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Audouin Dollfus

The Great Refractor of Meudon Observatory

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The Great Refractor of Meudon Observatory

Translated by Richard McKim

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Audouin Dollfus†
Paris, France

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Cover illustration: The great Meudon refractor, 2002.
Photo: Paris Observatory/Gérard Servajean

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Foreword

Engaged in the construction and use of telescopes of greater and greater aperture, favoured by mountain and desert sites, astronomers have little by little abandoned the Grande Lunette of Meudon.

The aging dome had ceased to revolve. Injured by the great storm of 1999, it was a sorry sight.

In 2005 the Paris Observatory, with the blessing of its guardian Ministry of National Education, wished to begin a new era for this spectacular instrument, with the renovation of the great dome.

At the beginning of the 21st Century, the stakes have changed: astronomers no longer count upon the Grande Lunette to open the way to new discoveries, but wish above all to utilise it to share with the largest number of people the passion of observation, the fascination with planets and nebulae: that will be the new career of this fantastic instrument.

Audouin Dollfus, witness to an epoch particularly rich in scientific advances, is a precious story-teller for evoking in a living and historically documented manner, the adventures of the Grande Lunette of Meudon. He knows how to make the thirst for scientific knowledge come alive again, and he capably describes the technical developments which enabled, often by means of remarkable feats, the research objectives to be reached.

Reader, in opening this book, let yourself be guided through the evocation of a scientific and technical adventure which has left its mark on history, discover with us the clever resources employed in mechanics and optics, and marvel in the discoveries patiently awaited and finally revealed.

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Technology has changed: information and automation have taken an increasing role for controlling astronomical instruments—but the curiosity, spirit of discovery, the fascination with the unknown, and the thirst for knowledge are always there.

Thanks to Audouin Dollfus for opening the gates of this dream.

Daniel Egret
President, Paris Observatory

Preface

Audouin Dollfus, an astronomer of worldwide repute, is the author of numerous works which are always authoritative. In the 1960s he was entrusted with the Presidency of the Planetary Commission of the International Astronomical Union (IAU), and then plenty of other international responsibilities.

He is now the only active witness of the great years of the Meudon refractor. He worked with Baldet, Camichel, Focas, Bertaud. . . . and above all with Bernard Lyot of whom he had been a pupil.

The writer remains a living memory of the history of the Grande Lunette. That is to say that this book comes at just the right time to make its turbulent history come alive again.

The book is remarkable for its very complete documentation and the attention to detail in retracing the origins and then the construction of the instrument with the material and human problems so well evoked. For example, the citation of the somewhat caustic comments of Eiffel, whose project of the floating dome had been discarded (it was carried out at Nice).

The details of the researches performed with the great equatorial leave nothing to chance, the author being in his element. All the works cited were the objects of Theses or Memoirs published here and there by numerous and prestigious researchers, sometimes less well known. The author has compiled all of this to the greatest advantage of the historian. On the other hand, he stresses the post-war modifications by Paul Muller who departed for Nice in 1974 and gave full rein to the author who would become the unique and precious depositary for the destiny of the instrument.

The great refractors of the late 19th Century, of which Meudon was a part—being the third largest in the world after those of Yerkes and Lick—are the testimony to the gigantism of the instruments of that epoch. Their principal virtue resides in the quality of the images that they present to the eye of the astronomer: they reach the resolving power of their apertures, permitting high definition observations upon planets, satellites and double stars. Besides, was it not Antoniadi who, thanks to the Meudon refractor, put an end to the quarrel aroused by the famous canals of Mars, the *canali* of Schiaparelli?

It is a shame that the funds allotted to the maintenance of these instruments did not allow for a larger number of them to be saved: some retired from scientific service or frankly just disappeared. However, the refractors of Washington (66 cm) and of Nice (76 cm), saved from the ravages of time, still make their contributions to the observation of close double stars. They are like the Meudon refractor, which is a jewel of French scientific heritage.

The principal driving force of the restoration and maintenance of these giant refractors was always a person whose passion, tenacity and competence have saved and kept in working order these sacred monsters, the pride of opticians of another age.

Audouin Dollfus is one of those pioneers, whose tenacity, whose good sense which is sometimes lacking in the younger generation, and his knowledge of history of the heritage bequeathed by the great artists, assures their durability. I lived through that situation with the great refractor of Nice (18 m long), judged an irreparable wreck in 1951.

The great refractors always have their place in modern astronomical observation, through the purity and quality of their images. At Meudon, beneath the great dome, a resolving power of fourteen hundredths of an arcsecond awaits the observer. Very few institutions in France can offer as much.

Paul Couteau
Honorary astronomer, Côte d'Azur Observatory

Acknowledgements

I would especially like to thank the members of the scientific heritage group of Meudon Observatory who, over numerous years, cooperated in order to retrieve, rearrange, preserve and catalogue the equipment, documents, instruments, photographs, observations and laboratory notebooks which have marked the scientific activity of the observatory and which have served as the basis of the present study.

Numerous colleagues and observatory staff contributed to document, illustrate and to improve this work, amongst whom are Jean-Eudes Arlot, Suzanne Débarbat, Philippe Demange, Christine Etienne, Françoise Launay, Gérard Servajean, Philippe Véron and Claude Zeippen.

Christine Etienne, Gérard Servajean, Laurence Bobis, Françoise Launay, Pascal Rouleau and Marie Bellosta gave very special care to the editing of this book and its numerous illustrations.

Paul Couteau was happy to offer a Preface, as the astronomer most qualified to do so. The book begins with a Foreword that Daniel Egret, President of the Paris Observatory, was keen to write.

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Part I The Largest Refractor in Europe

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Preamble

The Grande Lunette of Meudon has become legendary. When it was conceived, a little after 1870, the entire science of Astronomy was no more than a visual one. Knowledge of the sky was limited to what one could see with the human eye, assisted by telescopes. The Grande Lunette would show it larger, closer. The discoveries upon the sky would fall like so many victories. In 1909, Antoniadi, astronomer at Meudon, could exclaim: "I saw Mars closer than anybody!"

At Meudon, which became a highpoint of visual observation, the planets could be examined in a manner no other great telescope could ever photograph. One could study the states of their atmospheres; their surfaces could be mapped. Their dimensions could be measured. Eye at the eyepiece, one could see what the photographic emulsion could not show in the heads of comets: their very tiny nuclei. Always at the eyepiece one could measure numerous double stars, a status symbol for telescopic observation. With a marvellous little instrument, the polarimeter, one could identify the nature of clouds in planetary atmospheres, discover the constitution of the terrains covering their surfaces. So many of the results are true discoveries.

And this while photography, universally adopted elsewhere, revolutionised other knowledge of the world. The sensitive emulsion, associated with the great reflecting telescopes, would reveal the Universe as rich and profound as Cosmology.

Throughout the century reviewed, telescopic photography could never surpass certain results of visual observation. The photographic emulsion could not attain the resolving power of the retina. The dazzling progress of Astronomy could not bypass the discoveries offered by observation at the eyepiece with large refractors. The Meudon instrument, the largest in Europe, had become a symbol. Its speciality, visual observation, had made it unavoidable. Throughout a century it was the matchless servant for the progress of Astronomy.

Now, after a pause, the renovated Grande Lunette offers us a new adventure. It will make us dream differently. Widely open to the public, accompanied by a presentation evoking the epic nature of astronomical research and its future, it will be a living legend of a period highly symbolic of the history of the conquest of the sky. It will show how discoveries were built upon the work of the constructors and artisans who created exceptional instruments, and then upon the subtle dexterity and talent of some nocturnal observers featured in the story.

Part I
The Largest Refractor in Europe

The end of the 19th Century was the time of the *Belle Epoque*, and it included the *savants*. Great spirits cultivated the Sciences. They sought to understand the world. The *savants* of Astronomy discovered other stars, other worlds.

Life thrilled with new knowledge. The mysteries of the sky were brought to everyone's door. Camille Flammarion was preparing for the publication of his *L'Astronomie Populaire* whose title signified the spirit of the work. One marvelled in the distances to the stars, their number and diversity. The planets could be inhabited. Great refracting telescopes allowed them to be seen from close up. Mars revealed the geography of its surface and its changing lands seemed to indicate vegetation. It was believed that there had been discovered artificial streaks, a kind of canal, perhaps of human origin.

One could think of the dawn of a new Astronomy, based upon the physical study of celestial bodies. One could get to know the properties of stars, even the nature of their constituents. Photography in its first faltering steps offered the chance to probe the immensity of the sky beyond that which the eye could see. One learnt that the *savants* had at their disposal a new instrument, the spectroscope, which gave the composition of stars. With that device behind a refracting telescope, the Englishman Huggins, the Italian Secchi, these *savants* announced astonishing results, simply through the examination of the faint coloured streaks, a kind of spectral vision left by the star in the eyepiece of the instrument.

Behind the spectroscope, one could try to replace the human eye by the photographic plate, in order to preserve the trace of the coloured bands, to examine them at leisure. In this way much fainter stars could be studied, the diffuse glimmer of faint nebulae, and those mysterious spirits the comets. But there had to be, above all, more powerful telescopes.

Already, several great instruments offered talented observers the analysis of celestial objects. In *L'Astronomie Populaire*, Flammarion always praised the colossal Washington refractor, the most powerful in the world, with its diameter of 66 centimeters, which had been inaugurated in 1873. In Vienna, an even larger refractor would go into service in 1878. Its diameter would reach 69 cm.

When, after the Franco-Prussian war of 1870 and the defeat of France, the astronomer Jules Janssen entered the field to equip French astronomy with a powerful observatory, the road towards giant refractors was thereby opened, justified by the incredible attraction for the mysteries of the sky. France had to be an important player in the concert of astronomical research.

So, after the foundation of the Meudon Observatory in 1875, its creator Jules Janssen decided to equip that new institution with an exceptional refracting telescope. The audacious manner of its realisation had to appeal to the remarkable resources available in France, to the art of glassmaking and to the great opticians, to the techniques of ironworking and mechanics, and to the applications of electricity.

The idea was much copied. At Pulkovo in Russia, and at Nice in France, two immense refractors were in preparation, both of 76 cm aperture. They would be inaugurated in 1886 and 1887, a little before that of Meudon. Equally the United States wanted to give *savants* instruments worthy of their talents. The patron who created the Lick Observatory in California, which carries his name, began (at the same time that the Meudon refractor was being made) the building of an instrument of 91 cm aperture which would enter into service in 1888. Another patron supported the University of Chicago in offering them the Yerkes Observatory, and prepared for the construction of another giant, of 102 cm diameter, definitely the largest astronomical eye open in the world. The eye would be opened in 1897, a little after the first peeps at the sky of our 83 cm refractor of the Meudon Observatory.

Thus, when our Grande Lunette of Meudon entered active service in 1896, the instrument was in terms of its size the second largest in the world, the largest in Europe, and so it has remained until our times. Moreover, in a duplication of its functions, it is at the same time both a visual and photographic instrument.

The description of that exceptional instrument, the deciphering of the stages in its creation, then its transformations, and the analysis of the functioning of the great instrument, comprise the first part of the present work. To write it, the author of these lines had the necessary qualifications. Entering Meudon as a young astronomer in 1945, he lived for sixty years in the wake of this impressive instrument. At the time of his first observations, the instrument had been practically unaltered since its creation, being in the condition in which it had been used from the first years. Following the transformations of the 1960s, the author used it and kept it running for more than 20 years in its function as the great and faithful servant of science.

Chapter 1
The Project, its Realisation and the Dome

The Site

We are in 1870. It is War. The French military defeat brings the Prussians to the gates of Paris. The terrace of Meudon offers the enemy a remarkable site for surveillance of the besieged capital. Artillery pieces are positioned all along the terrace and can take aim at the Parisian landmarks. By means of its slightly withdrawn position in the locality, the Château Neuf, a magnificent royal residence built in 1705 by the architect Jules Hardoin Mansart for the Grand Dauphin, eldest son of Louis XIV, seems a highly appropriate place for storing the gunpowder and munitions necessary for supplying the gunners.

On 1871 January 28, Armistice Day, the residence still charged with powder and canons is restored to the French. But two days later, on the morning of January 31, the Château explodes and then catches fire. The two wings are destroyed.

The basement of the building and the central part should be recoverable, but no project for it exists to justify the great cost estimated to put things back into order. There is talk of demolition.

There then appears a person of great character, energetic and creative: Pierre Jules César Janssen, known as Jules Janssen (1824–1907). He has just witnessed his reputation as an astronomer and a *savant* grow. On 1870 December 2, he had left besieged Paris aboard a balloon, the *Volta*, to go to Algeria to observe an eclipse of the Sun.

The astronomical spectroscopic works of Janssen are already known, his researches upon the physical state of the Sun, his distant and courageous expeditions across the world, schemes for analysing the Sun in eclipse [1].

Jules Janssen had analysed the absorption spectrum of the Earth's atmosphere and that of water vapour. In 1867, he went to Italy, at Tauri, to study the total eclipse of the Sun of March 6 and to observe with the spectroscope from the summit of Mount Etna. The following year, he was in the Indes, at Guntoor, for the eclipse of 1868 August 18. He discovered then, at the same time as the Englishman Norman Lockyer (1836–1920), an unknown spectral line, later attributed to a new element, helium. Immediately after the eclipse, he thought of the procedure for enabling the

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observation of solar prominences around the periphery of the Sun without the need for an eclipse.

On 1870 December 22, Janssen found himself at Biskra, in Algeria, without seeing the eclipse due to clouds. In 1871, he returned to the Indes, to Shoolor, for the eclipse of December 12. In 1874, with his *photographic revolver*, the ancestor of the cinematograph, a trip to Japan enabled him to study the transit of Venus across the Sun. In 1875, the year where, from Paris, the Minister gave him the use of Meudon for the creation of his observatory, Janssen was in Siam, for the eclipse of April 9 at Singapore.

Later again, Janssen would observe the solar eclipse of 1879 July 19 from Marseilles, then that of 1883 May 6 from the Caroline Islands in the Pacific. The same year the transit of Venus across the Sun would find him in Algeria. In 1896 when the Grande Lunette at Meudon would yield its first observations, Janssen would be excited with his new observatory at the summit of Mont Blanc, to which he would make the ascent several times. In 1905, aged 81, two years before his death, he would be in Spain for the eclipse of August 30 at Alcosèbre.

That is the man who would create the Meudon Observatory. To provide France with a scientific establishment entirely devoted to the study of the physics of stars, here was a project worthy of his ardent disposition.

Analysing celestial bodies by means of their actual properties, through the possibilities of spectroscopy, photography and telescopic observation, actual research had already seen the light of day in our neighbouring countries, in Italy, in England, in Germany, and in the United States. But in France, nothing of that sort had previously existed. The Paris Observatory, with Urbain Le Verrier (1811–1877), owed its reputation for Astronomy above all to celestial mechanics, relating to the motions of stars.

Since 1869, concerned to develop the new approach in science that would later come to be called *astrophysics*, Jules Janssen, strongly supported by Victor Duruy had approached the moment of decision. In 1871, exploiting the still warm post-War dynamics, he newly buttonholed Ministers. Convinced by Janssen, with the favourable opinion of the French Academy of Sciences, the Minister of Public Instruction decided to provide our country with an *Observatoire d'Astronomie Physique*, of which Janssen would be the Director.

First of all a site had to be found to establish the institution. In 1869, attention had been focused upon the Pavillon de Breteuil at Sèvres. But the Franco-Prussian War had ruined the project. In 1875, Janssen saw fit to make two possibilities, each as famous as they were dilapidated, either the ruined residence in the estate of Malmaison, or the destroyed château upon the terrace at Meudon.

The latter place was much better suited. The architects considered that the central body of the château could be preserved. A thick circular wall could support a dome, even for a large astronomical instrument. The project would give the historic château a prestigious destiny, in continuation of the earlier uses of the Meudon site, which since the Revolution had been devoted to advanced technical research.

Jules Janssen carried out Astronomy at that time in a small site along the boulevard d'Ornano in Paris, where he used his telescopes. In 1876, he was given permission to occupy the building at Meudon running alongside the entrance to the terrace, that is to

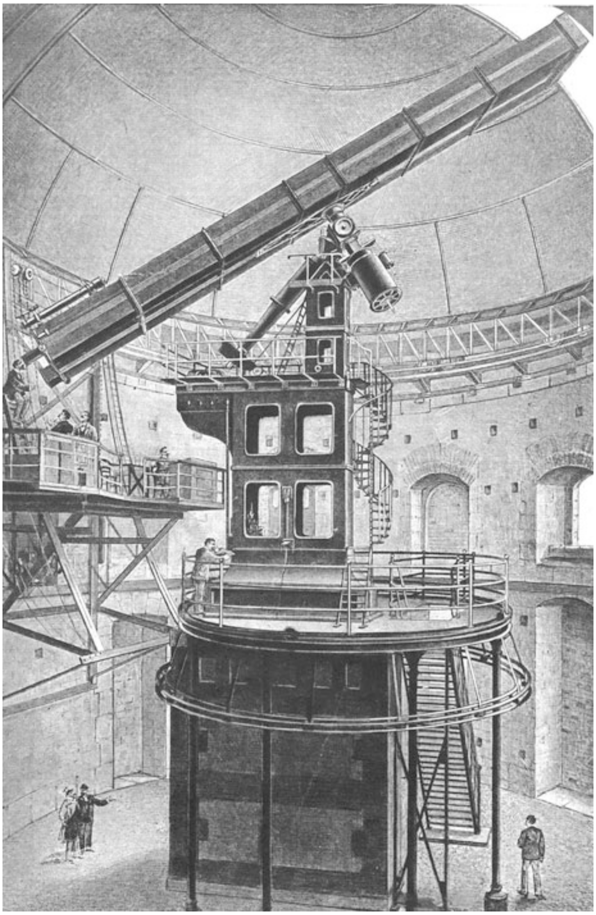

Fig. 1.1 The Grande Lunette of the Meudon Observatory during its commissioning in 1896. (Heliogravure by Dujardin after a number of photographs.)

say the outbuildings containing the large stables of the ancient Château de Louvois, razed after the fire of 1795. These stables were being restored by the Prince Jérôme-Napoléon, and Janssen could live there, although the ruins of the Château Neuf, at the other end of the great terrace, were still being used by the Army as barracks [2].

However, the preservation of the remains of the Château Neuf was always the focus of attention. In 1879, a Government Bill was voted to allocate the entire building to Jules Janssen, tasking him with saving it from destruction and placing there a powerful astronomical research instrument [3].

Finance

The instrument would be constructed, but not without difficulty. Eighteen years later, in 1896, astronomers at Meudon could finally make use of the largest refracting telescope in Europe, a double telescope for simultaneous visual and photographic work (Fig. 1.1).

The enterprise, simply put, would not be at all easy to conduct. The technical difficulties, very significant for that time, would on the whole be satisfactorily resolved. But the financial resources would not be forthcoming at a sufficient rate or to the level needed.

In 1895, when the impending start of the active service of the refractor was finally announced, the scientific and Ministerial milieu would come to enquire about the cause of the delays. At a meeting of the French Academy of Sciences on 1895 June 10, Janssen would justify them solely in terms of financial difficulties:

> [. . .] If that creation was held up in this way, it is because it happened to pass through two very different financial periods: the first still favourable where the funds for building had been approved; a second where financial difficulties became more and more marked and in which not only were the necessary resources for the works unable to be given, but where we suffered heavily from cruel budget cuts, reductions which, unable to fall upon the personnel, made our publications and our works suffer. The funds assigned by the *Pouvoirs Publics à l'administration des bâtiments civils* for the restoration of the building, its allocation for the erection of the great dome having been insufficient and supplementary funds not having been allowed, we duly took from our funds for instruments and publications the cost of the great dome and that which covers the 1 m reflector and the photographic refractor. [4]

The astronomer Henri Deslandres (1852–1948), who came from the Paris Observatory to settle at Meudon on 1898 January 1, had contributed personally to certain expenses for putting the instrument into operation. He benefitted from a significant personal fortune. In that way, Deslandres would come to be one of the first users of the Grande Lunette, although, at Meudon, he simultaneously developed solar research with the instrument known as the *spectroheliograph*, of his own invention. After the death of Janssen, on 1907 December 23, Deslandres would become the new Director of the Observatory.

Janssen, certain of seeing the completion of the great astronomical installation, was very much absorbed in putting into practice his new observatory at the summit of Mont Blanc, and may then have felt more disengaged from the Meudon project. We have no photographic record of Janssen at the side of the Grande Lunette. He had a view of the surface of the Moon on 1893 December 18, during one of the first trials of the instrument. Again, in 1896, he had seen the planet Jupiter during one of the first observations with the now operational instrument. Aged 72, he sadly had a fall beneath the dome, which prevented his next climb on Mont Blanc. Later, the instrument would essentially be found in the hands of Deslandres.

The Building

Building works upon the ruins of the château began in 1880, under the chief of works, C. Moyaux, architect of the Meudon Observatory, and continued for five years. It was a case of demolishing the remains of the two wings of the château in their upper parts, then to restore all of the ground floor as well as the central forepart, by preserving the sculpted pediments by Jules Hadouin Massart dating from 1706, on the park and garden sides [5].

Then, in 1886, Moyaux had constructed, around the central part and integrated with the sculpted pediments, a strong masonry cylinder 20 m in diameter, with a thick circular wall, raised up to the ancient roof level, for supporting the dome. A metal chain system was made at the top of the wall to avoid it spreading under the weight of the dome. This precaution is however quite useless, since contrary to the sort of domes familiar to architects, the rotating dome, resting upon bearings, exerts no other pressure upon the wall than the vertical pressure due to its weight.

The contract for the production of the rotating dome which had to cover the building would not be drawn up until 1889. Meanwhile, the largest components needed to construct the refractor were stored at château, upon the paving at the base of the great circular wall, which was covered over at the top by a temporary roof.

The Construction of the Dome

The great dome of Meudon, having an internal diameter of 18.5 m, is considered to be a masterpiece of carpentry in ironwork. It is a perfect example of the method of light iron girder construction, characteristic of the time.

After submission of tenders, a deal concluded by an Act dated 1886 September 30 awarded the contract for building the dome to the Anciens Établissements Cail, an institution founded by Jean-Francois Cail and taken up later by his son after his father's death in 1871. This public company with a capital of 10 million, whose principal factory was at Denain, specialised in large-scale metal construction, producing locomotives, iron ships, canons and framework for scaffolding. The Paris head office, at 15 quai de Grenelle, ran the agencies in the principal capitals of Europe, in the Orient and Latin America. For the production of astronomical domes, operations were entrusted to the branch in the rue Jean Dollfus in Paris.

Under the impetus of its delegated supervisor M. Bourdet, a former pupil of the École Centrale, the company had already delivered an astronomical dome of 9.6 m diameter to the Rio de Janeiro Observatory and had made another of 12.5 m. The company had designed a model dome 7.5 m in diameter, of which two examples had already been delivered to the park at Meudon to house, not far from the great dome, the 1 m reflecting telescope and the Eichens equatorial. Other domes to the same design had been made, notably for the observatories in Buenos Aires, of Santiago in Chile, of Cadiz in Spain. Later, the company would become the Établissements Five-Cail-Babcock, or FCB, particularly well known for its locomotives [6].

The concept for the Meudon dome had resulted from an earlier study requested by Admiral Ernest Mouchez (1821–1892) for a 20 m astronomical dome destined for the Paris Observatory, a project later abandoned. The Ministry of Public Works had opened in 1881 October a competition for the construction of that dome. The Anciens Établissements Cail had been selected and their study prevailed.

One can be surprised that Gustave Eiffel had not been retained for this project. He had effectively come to construct the large dome at Nice Observatory and he was a personal friend of Jules Janssen, who had called upon him for his observatory on Mont Blanc. Very probably consulted, Eiffel must doubtless have prioritized his project of the great tower which would be opened in the centre of Paris on 1889 March 31 [7].

Assembling the ironwork above the high walls of the chateau was no easy task. Construction accidents were reported. In 1892 April, a worker from the Établissements Cail, Eugene Einard, broke an arm; from the insurance, Janssen had to give him 100 francs in compensation. In December of the same year, a laboratory assistant retired from the Observatory, M. Cousin, broke a leg; a monthly allowance of 100 francs was given to him until it healed. Later, a roofing worker slipped upon the complicated convex surface of the dome, whose slope increased with distance from the top, resulting in a mortal fall [8].

The technical on-site approvals were spread out over three stages, on 1891 September 5, then on 1892 April 12, and finally on 1894 March 5. In the course of the last one, several new modifications were asked for, delaying the provisional operation by a year [9].

On 1895 June 14, the final signing-off took place on site, "between, from one party M. Janssen in the name of the State, assisted by M. Lévy, member of the Institute, of M. Berthot, civil engineer and adviser for the dome and of M. Gautier, constructor of the refractor (absent on the day), and for the other party M. Bougeault representing the Établissements Cail" [10].

The fifth and final part of the payments, authorized by the provisional agreement of 1895 June 14, was settled with Établissements Cail for a total of 8,400 francs, on 1895 July 15, in return for some items still to be finished (laterally positioned bearings). For his services, M. Berthot received several bonuses of 300 francs [11].

Meanwhile, the refractor, whose components had first been left in the château beneath a temporary roof, had been mounted under the incomplete dome and it had been ready for service since 1893. Some trials had even been made upon stars crossing the opening of the slit of the immobile (or hardly mobile) dome. Finally, in 1896, all was ready. Janssen had brought to Meudon the astronomer J. Perrotin, from the Nice Observatory, to check the performance of the Grande Lunette by carrying out test observations. The first scientific publication, by Perrotin, was presented by Janssen to the Academy of Sciences on 1897 February 15. It concerned the detailed observation of the surface of Mars [12], of which we shall speak later.

The Framework of the Dome

In the *Annales* of the Observatory, Janssen described the structure which would come to fruition:

> The backbone of the dome is formed from a system of radial beams (in fact, 26 beams), applied upon two great main beams which are parallel to one another, spaced about 2.60 m apart and support the two opposing sides of the dome. They are destined to form the opening for observation, and to support the mechanisms that control that opening. These two great beams, as well as the radial beams which come to join together, are bound by the horizontal rings formed into parallels, like those showing the meridians of the hemisphere. [13]

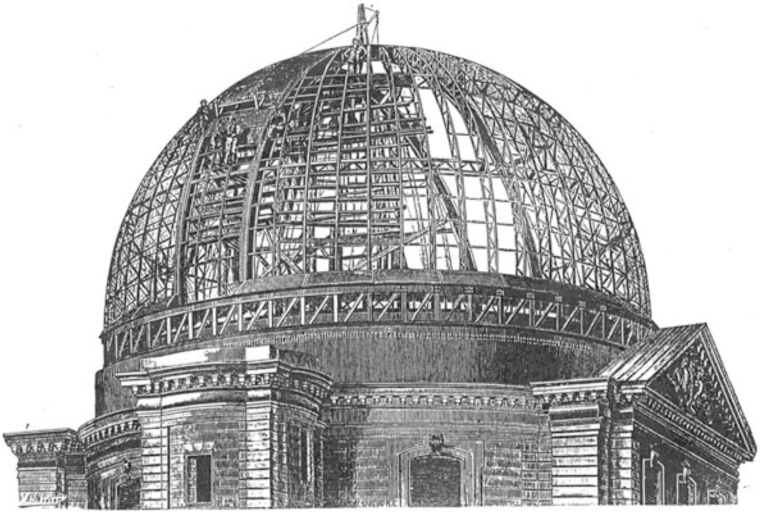

Fig. 1.2 Iron framework of the great dome of Meudon during its construction by the Anciens Établissements Cail in 1892

The entire structure was fixed to the base of a large metallic ring, high and rigid, made from two concentric girders, joined together by cross-beams, clearly visible upon Figs. 1.2 and 1.3 [14].

All the backbone is faced externally by a covering of sheet steel of 1 mm thickness, riveted upon all the beams and cross-beams, forming in that way a waterproof covering. Internally, wooden sheathing made of fir leaves between the two layers a cushion of air which is destined to limit the change in temperature of the interior of the dome when the Sun warms the sheets.

Other details appear in the photograph of Fig. 1.4, taken 70 years later, but all has stayed the same, except for the removal of the sheathing in 1961.

The Revolving Rail

The dome carries at its base and beneath the large circular girder a thick iron track which is wide, flat, smooth, horizontal and circular. This girder sits upon a system of twelve huge roller bearings, of 1 m diameter and 60 cm thickness, each weighing 1,500 kg, kept in place by a ring. These bearings themselves roll upon a flat metal rail sitting on the upper part of the circular wall [15].

According to Janssen:

> One of the conditions essential to the correct functioning of domes, in general, is to make sure that the revolving rail is perfectly flat. That there was one of the biggest difficulties which the revolving rail for the new dome presented, being close to 70 m in extent, carrying a shifting weight of 120 tonnes and reposing upon the perimeter of a very high circular-walled tower, finally resting upon an ancient chateau suited, as well as might be expected,

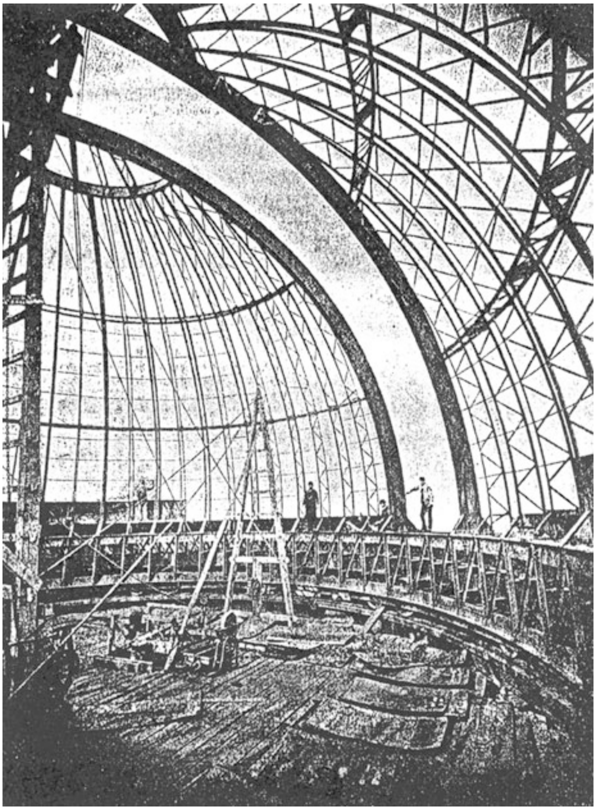

Fig. 1.3 Assembling the great dome upon the chateau of Meudon in 1892

> for that purpose. That condition was obtained in the following manner: the inner revolving girder rests upon a system of jacks, 70 in number [16], whose loading points are upon wide, thick, double cast iron plates, in order to spread the load over a large surface of the masonry and to not compromise its solidity. It can be seen that through the averaging of these jacks, it is easy to regulate the precise horizontality of that girder in a very exact manner. [17]

Lateral bearings keep the dome centred, as well as the intermediate ring carrying the large roller bearings. These bearings also maintain the circular form of the base of the dome, itself supple and pliable, within a tolerance of 5 cm.

The Rotation of the Dome

An endless metal cable surrounds the exterior of the dome in its lower part. This cable fits a wooden groove arranged upon the external perimeter of the ring forming the base of the dome. It is pinned to the groove by tension and drives the rotation of the dome by friction. The two strands of the cable leave the groove radially between two pulleys and then descend vertically into the machinery at the foot of the building.

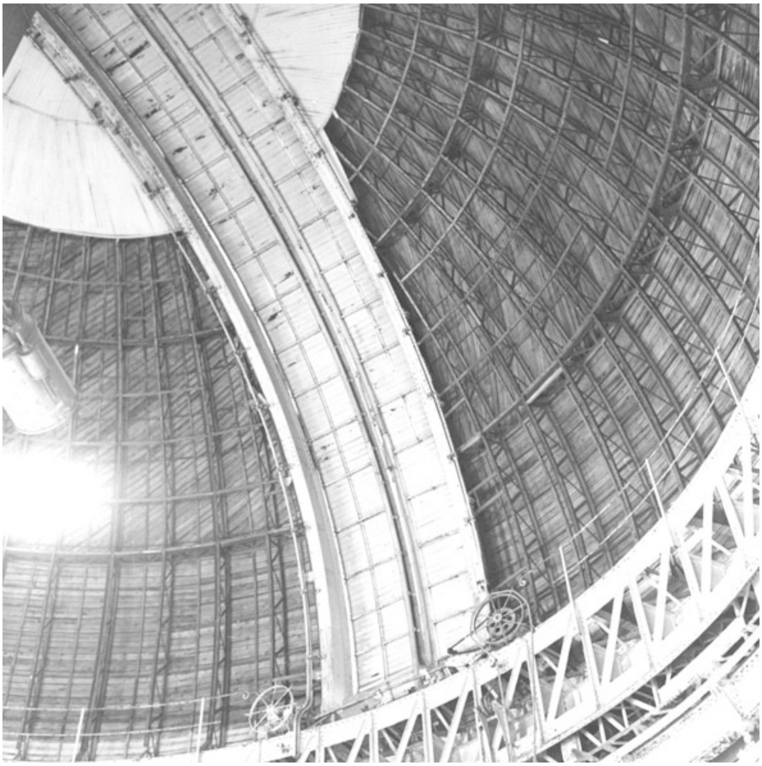

Fig. 1.4 Appearance of the panelling of the great dome and its opening slit in 1961

The mechanical drive comprises two large cast iron wheels in grooves, vertical and parallel, each driven in one sense, in order to ensure the rotation of the dome in the two directions. The endless cable which descends from the dome is wound round one of these wheels in its groove, rises up via pulleys to a counterpoised cable-strainer, redescends, and is wound around the other large wheel to reascend towards the dome.

The motive power is supplied by a car dynamo working on the mains supply and acting upon a large toothed ring, limiting the torque upon each of the two large wheels. A hand control allows the dome to be moved in case of failure of the electric drive.

The Opening of The Slit

A slit is installed in the dome, between the two great diametrical girders spaced 2.80 m apart (Figs. 1.3 and 1.4). This opening ends in a semicircle at the top, in such a way as to enable the refractor to reach the zenith. It is closed in the middle by two shutters having the full height of the slit and which join at the middle. These shutters are mounted on slide channels and were originally moved by hand by means of two endless cords each upon a large capstan wheel controlling the opening. The cords hang down and their lower loops nearly reach the ground, at the bottom of the high wall which supports the dome.

The two capstans can be seen in Fig. 1.4: the right-hand one carries the motor unit added later. For those who had to manipulate the shutters with the cord, the operation was long and laborious.

The watertightness of the shutters had never given satisfaction. Always, after rain, pools of water spread upon the ground at the bottom of the building, then evaporating. The difficulty did not become significant until the 1960s, when the observing platform had been replaced by the great area of the moving floor which covered the whole surface. The water then accumulated upon the moving floor. The reason for these intrusions of water is found in the long and narrow gap between the lip of each shutter and the body of the dome. The wind blows horizontally on the film of water covering the dome during rain, and forces it through the gap.

The Exterior Platform

On this subject, Janssen wrote in the *Annales de l'Observatoire*: "There was built, on top of the dome, a platform surrounding the opening at the zenith, and to which access was by an exterior ladder fixed to the dome. From the height of this platform, the view is comparable to that which one can enjoy from the Eiffel tower. It spreads over the entire panorama which forms the immense city, above the heights which it dominates and a large part of the *départements* of the Seine and the Seine-et-Oise [18]."

The Observing Platform

The arrangement giving access to the eyepiece of the refractor, very original and practical, differed from the solution often adopted elsewhere, consisting of a large platform occupying the entire surface beneath the refractor, and which could be moved upwards or downwards.

The astronomer is carried by a platform directly joined to the side of the dome, and shares its rotation (Fig. 1.1). This platform can be raised and lowered by a vertical movement. Moreover, it slides upon two parallel rails which press upon two circular slide channels (Figs. 1.1 and 1.5) which, in changing the height, a horizontal movement serves to maintain a constant distance with the centre of rotation of the refractor.

According to Max de Nansouty: "These movements are obtained simply by the touch of an electric button; the enormous platform with a weight of 6,000 kg rises immediately with all the observatory staff and their assistants, which can reach up to fifteen or twenty persons [19]."

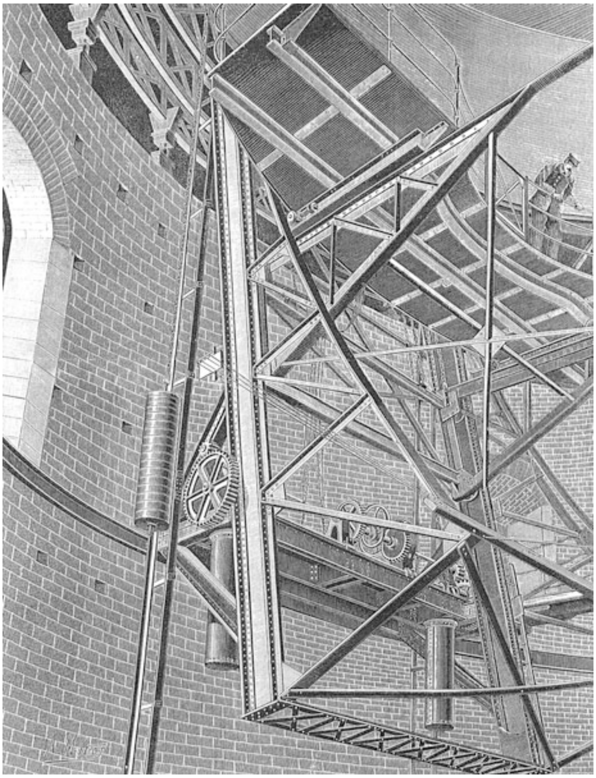

Fig. 1.5 The structure supporting the observing platform, attached to the rotating part of the dome. (Seen from underneath)

The platform measures 8 m in width and 2 m in depth. To reach the moving platform, a large metallic ladder gives access from the floor to a fixed circular terrace which surrounds the pier of the instrument (Fig. 1.1). From that terrace, entry is direct and upon the same level as the mobile platform at its lowest level.

The terrace equally gives access to a spiral staircase which climbs up along the pier carrying the refractor and gives access to the mechanism of the equatorial (Fig. 1.1).

When the observer is on the moving platform, a metal ladder fixed to one of the slide channels (visible upon Fig. 1.1, to the right of the platform) enables him to climb up to the walkway at the inner edge of the base of the dome and to reach the mechanism for moving the shutter as well as the objective of the refractor when it itself has first to be brought into a horizontal position.

All these arrangements, logical and well-designed, allow for easy observation. Subsequently, they were unjustly criticised, doubtless because they depart from concepts adopted elsewhere. The writer of these lines had the use of the equipment in its original form many times, before the modifications of the 1960s, always finding it to be efficient and problem-free.

The platform, suspended in the air, submerges the observer in a very special atmosphere, as soon as he steps onto its edge. The arrangement recalls, in being much more comfortable, those prime focus cages now used at the other ends of our great modern telescopes.

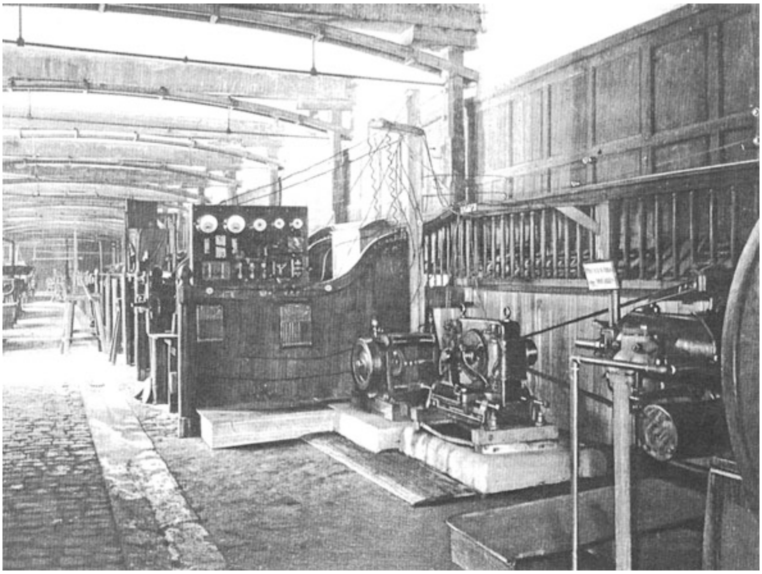

Fig. 1.6 The system for supplying the great dome with a direct 500 V electricity supply

Utilising the Space Beneath the Dome

The vast circular space close to 18 m in diameter and 15 m in height covered by the dome, and surrounding the central column carrying the instrument, was only used in its upper parts. The apparatus of the observing platform only descends as far as 5 m above the ground, leaving a vast unused space (about 200 m^2) over the entire floor surface around the column (Fig. 1.1).

It is odd that Jules Janssen never reckoned upon using this space for offices and laboratories. His successor Henri Deslandres would want them after 1920, but did not succeed in developing them [20]. We shall see that they would be constructed in 1965, at the initiative of Paul Muller.

The Electrical Supply

The motive force needed for moving the dome and the observing platform was provided by electricity. A gas-powered motor, of the Otto design and of 8 horsepower was installed in the laboratory associated with the observatory, in the large stables of the ancient château, located 600 m away on the opposite side of the terrace. The motor drove a dynamo generating a direct current of 500 volts, and had a power rating of 4,000 watts. Moreover, the installation was combined with powerful accumulator batteries supplied by the Dujardin Company.

The electrical setup in the stables can be seen in Fig. 1.6. The electrical switchboard mounted upon one of the stalls allowed the switching, at will, from the current supplied by the dynamo or that provided by the accumulators. The current was supplied by a double electrical cable, visible all along the wall above the stalls. These two cables, protected against lightning, then ran in the open air all along the terrace, carried upon poles, up to the great dome.

Beneath the dome, the direct current acted upon demand on a Gramme-type motor for the rotation of the dome as well as upon another of the same sort for elevating the platform, both being reversible and equipped with rheostats. All the commands were made from the mobile observing platform. The current reached the platform by means of an electrical trolley with brush contacts, which could circulate around the wall (Fig. 1.1).

In 1919, the observatory Director, Henri Deslandres, wrote in his annual report: "The accumulator batteries which make the great dome and the platform turn, already in poor condition before the War, are currently out of action. These batteries will be replaced by a group of electric motors which have been ordered from the Thomson-Houston Company [21]."

In 1932, the arrangement for providing the direct 500 volt supply was transferred from the stables of the chateau to beneath the dome itself, under the care of M. Burson. This generator, then powered by the 110 volt mains supply was placed upon a column close to the entrance, and could thereby be put into operation from there at the moment of observation.

Reflections

From 1902, the covering of the dome in sheet steel showed some weaknesses. In 1905, Gustave Eiffel was consulted. In December he prepared a five-page manuscript document upon the state of the dome, whose appearance is somewhat surprising and overloaded with deletions. In particular one can read:

"The result of the examination that I made upon the dome on December 16 last (1905) is that the steel covering of 1 mm thickness is invaded by rust which, in certain points, has completely eaten away the borders of the sheets over great lengths. [. . .] The thickness of the sheeting is very thin [. . .] There have not been more than three coats (of paint) laid down, of which two are of minium of iron. There should have been at least four coats (of paint), two of which of minium of lead [yellow lead oxide, or PbO – *translator*] and the two others of cerium white [cerium oxide, CeO_2 – *translator*] [. . .]. In proceeding thus, one should have reapplied a final general layer of cerium (white) about every five years. [. . .] I would have preferred that the sheets had at least a thickness of a millimetre and a half instead of one millimetre. That increases, it is true, the weight of the dome a little, but in an insignificant proportion. Indeed, that increase is only 4.5 kg per square metre, or for 614 m^2, around 2,800 kg. The weight supported by the bearings being around 70,000 kg, this increase is quite negligible [22]."

The estimate of the cost, after numerous scratchings-out and corrections, can be finally read thus:

Covering in sheet steel	9,400 francs (in 1905)
Repair of the interior panelling	4,200
Scraping and painting the framework	1,200
Putting the mechanism into operation	2,000
Unforseen expenses, repair of the floor	400
	17,000

The Council for Civil Buildings, meeting at Meudon, decided in favour of the repair but the finances were not obtained immediately. Meanwhile, in 1906 the architect J. Monduit replaced C. Moyaux in the office of architect of the Observatory. He was content with a caulking and painting operation, carried out in 1907. Then came the First World War.

After the conflict, Deslandres wrote in his annual report of the Director for 1919: "The metallic dome, which is pierced with holes, does not adequately protect the great instrument which it covers, and the Director thinks that it will be wise to request for it *un crédit extraordinaire spécial* (about 100,000 francs) [23]."

Then, in 1921: "Currently, the expenditure must exceed 150,000 francs (in 1921). There is serious talk of discarding the iron sheeting and adopting copper for the covering which is a little more costly but which has a long life, is easy to maintain and does not require painting [24]."

Finally, in 1922, the Director for Civil Buildings decided in favour of a budget appropriation and the repair was carried out with a coating of copper. Upon completion of the works, in 1924, observations could be taken up again at the time of the very close approach of Mars to the Earth. Eugène-Michel Antoniadi then made numerous drawings of the planet, in remarkable detail, while Bernard Lyot carried out completely innovative polarimetric analyses.

The dome at that time exhibited a brassy colour, upon which the Sun cast a brilliant reflection. Then, with time, the copper oxidised and the great dome would took on a green colour, which has now become familiar.

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Chapter 2
The Optics, the Mounting, the Refractor

The Optical Work

Astronomical objectives are generally made to compensate for the effects of unwanted colour, by reducing the coloured fringe at the side of the image. These objectives, called achromats, are made by the unison of two lenses, one convergent, the other divergent, consisting of glasses of a different sort. One of the types of glass, the crown, is made from potassium and sodium silicates and lime, and produces weak colour dispersion. The other, flint glass, is of potassium and lead silicates, producing a strong dispersion. The two lenses are combined so that their dispersions mutually annul one another. In this manner, the dispersion can be made perfect for a particular colour, generally chosen from the middle of the visible spectrum, and it becomes progressively worse towards its ends [1].

To make each of the two large lenses of crown and flint necessary for the fabrication of the achromatic objective, one must first of all produce sufficiently large and homogeneous glass blocks. Then, they are made into lenticular form and polished with an optical precision. All these operations require a very skilful craftsmanship.

The production of very large blocks of sufficiently homogeneous glass was at the time a near-exclusive speciality of French know-how. The mastery of the art, in the hands of Édouard Mantois, in his workshop in the rue Lebrun in Paris, made him the sole manufacturer in the world able to produce large enough glass blocks of the required size and homogeneity for the needs of large-scale Astronomy then [2].

The trade was the result of a long accumulated practise. Pierre-Louis Guinand, born in Switzerland in 1749, had been the inventor of the homogenisation of the molten glass by mixing, then of melting and casting. His son, Henry Guinand, perfected the processes with Georges Bontemps. He installed a workshop in rue Mouffetard in Paris, and finally in rue Lebrun. The grandson of Henry Guinand, Charles Feil, would direct the workshop in rue Lebrun for 35 years. Then his son in law, Édouard Mantois, would continue the work and perfect the knack. After making the optics for Meudon, a parent of Édouard Mantois, Numa Parra, would transfer the enterprise to Vésinet in 1902, and, in 1925 the family business would become the more impersonally named Société Parra-Mantois [3].

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_2, © Springer Science+Business Media New York 2013

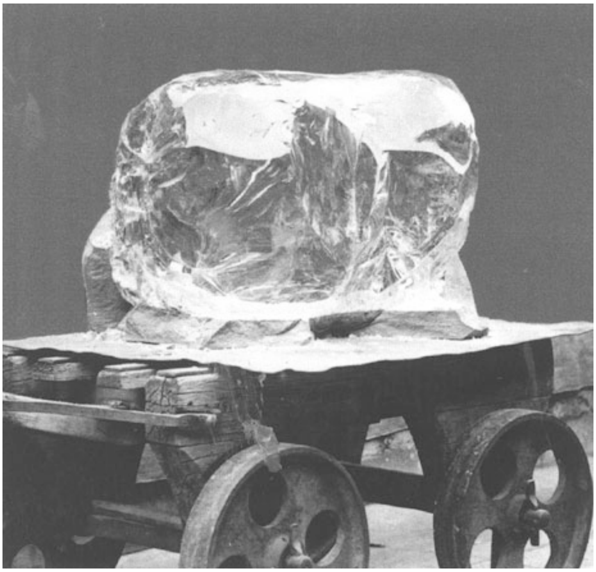


Fig. 2.1 Block of crown glass leaving the furnace

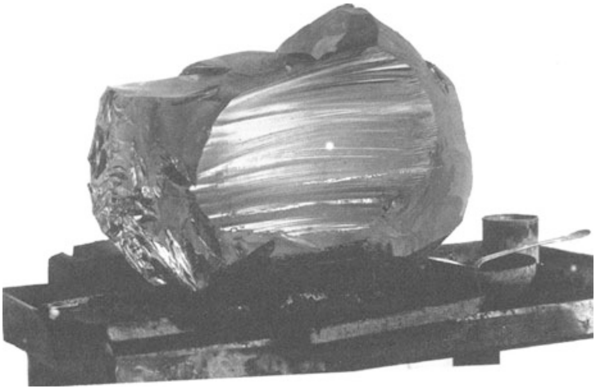


Fig. 2.2 Block of crown glass with one face sawn and polished, ready for examination for optical homogeneity

In *l'Astronomie* for 1894 one can read an article from the pen of Édouard Mantois [4], providing a remarkable description of the manufacture of large lenses, consisting of the melting, the mixing, the grinding and polishing, the examination and the casting, and then the examinations of the new piece, the new castings, a second and often a third, with casting, and at last the final testing and final reheating at high temperature (Figs. 2.1, 2.2 and 2.3).

The big disks of crown and of flint would be given to the optician accompanied by prisms made in the same manner. These prisms, placed upon a Babinet goniometer, enabled their refractive indices to be determined and of the dispersion of colours by each of the two glasses making up the achromatic combination for each objective. This was in order to calculate the radius of curvature to give to the surfaces for obtaining the required focal length with the best possible chromatic correction.

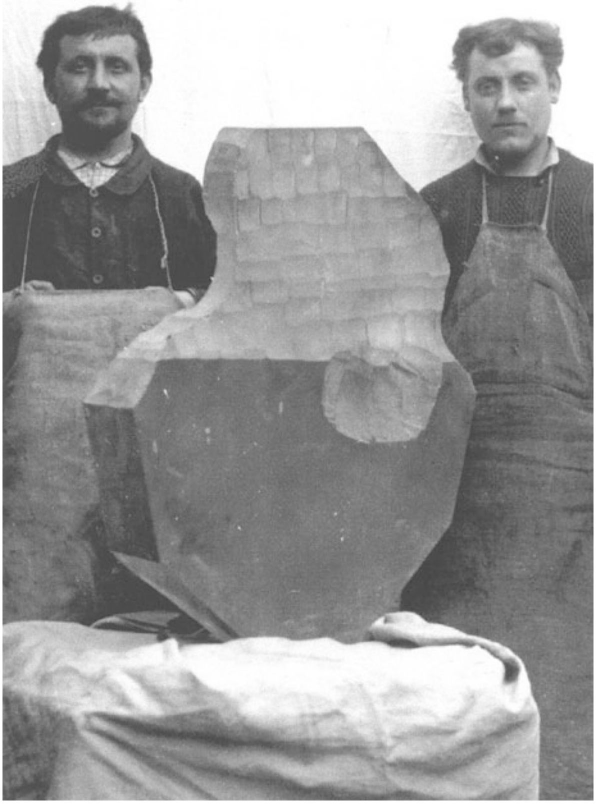


Fig. 2.3 Block after elimination of the defective parts by carefully grinding them away. The remaining material would be remelted and cast in a decagonal shape, then re-examined optically. The residual defects would again be ground out. The piece of glass left, having passed the tests, would again be remelted and then formed into its final shape after leaving the oven

The task of producing an optical surface was well known at that epoch, since the time that numerous private astronomers made for themselves their telescope mirrors. Developed initially in the 17th Century, essentially in Italy and Holland, the art was practised in the19th Century in several towns in Europe and America.

In France, the Henry brothers controlled the practice for large optical components, and it was to them that Janssen entrusted the job of manufacture for the observatories of Meudon and Mont Blanc [5].

In 1882, the Henry brothers' operations consisted of an optical workshop adjacent to their home, employing several people. Then installed at Montrouge, they were essentially devoted to the production of large objectives and mirrors.

One owes to the Henry brothers in particular the photographic objectives destined to be used in the international project inaugurated in 1887 known as the *Carte du Ciel* (11 objectives of 33 cm aperture), the 1 m mirror of the large Meudon reflector and that of the 83 cm of Toulouse brought into service in 1887, the objective of the 76 cm Nice refractor used from the same year onwards, the two 60 cm visual and photographic objectives of the great Paris coudé instrument (1892), and then the great objectives for Meudon and others later.

An article in *l'Astronomie* in 1894 from the constructor R. Mailhat revealed the procedures used for the manufacture of large objectives. These included shaping the objective by rubbing with diamond powder upon slabs or metal bowls, achieving the centering and parallelism of the axes of the two faces, smoothing with emery, polishing with paper coated with Tripoli powder, examination by the Foucault test, then successive retouching [6].

The Objective for Visual Observation

The achromat devoted to visual observation is made from two glasses in the optical combination known as the Littrow objective, in order to compensate for the effects of colour and to minimalise them in the yellow.

The two large lenses have a diameter of 82.95 cm which, once encased by the cell, leaves a clear aperture of 80.6 cm. The focal length is 1,639.7 cm for the green line of mercury. The chromatic correction optimised for a wavelength of $\lambda = 594$ nm leaves a blue aureola around the image, which disappears through the use of a yellow filter.

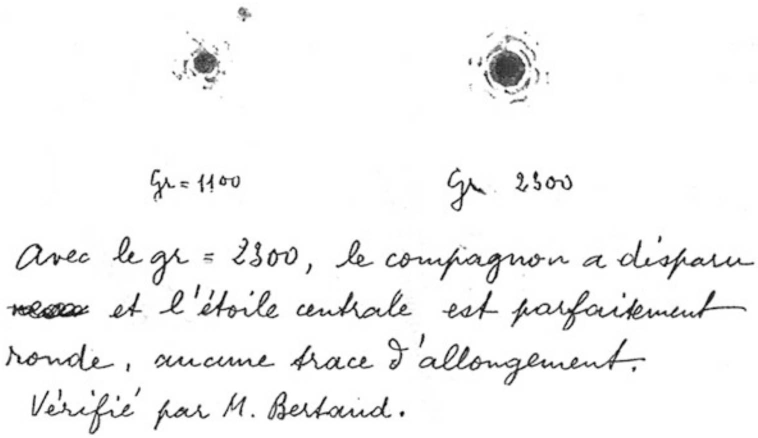
The assembled objective was mounted in the tube of the refractor in 1893, three years before the completion of the dome covering the instrument. The optical performance upon the night sky could be practised by pointing it at various stars crossing the slit of the motionless dome. Meudon Observatory possesses a second crown lens, kept in reserve, and presumably of a less fine quality.

In 1929, after having carried out star testing, Bernard Lyot, whose experience of such matters was considerable, could write: "When the atmospheric conditions are favourable, the objective gives perfect images, necessitating a magnification of 800 [7]."

On a very still night, 1937 May 22, Fernand Baldet examined a star of magnitude 6.3 and stepped the magnification up to 2,300 × x. He saw a perfectly circular diffraction pattern surrounded by broken, moving rings (Fig. 2.4) [8].

In 1956, the lenses had been dismounted for optical examination. Paul Muller wrote in his notebooks: "The lenses, apparently mounted in a cell with no lateral play, had been subject to stresses, notably at their N. and S. points where due to condensation rust had accumulated, as a result of the location of the refractor in one or other of two usual positions with respect to the meridian. It was necessary to saw through the rust with thin blades to get out the lenses. Decisions were taken: (1) to slightly loosen the cell; (2) to remount the lenses with a circular Teflon joint [9]."

Jean Texereau, optician at the Paris Observatory, checked the quality of the objective by optical laboratory testing. The objective was shown to be perfect over a diameter of 68 cm. Wave-testing revealed a slight turned-down edge over the outer 5.5 cm, which reached $\lambda/4$ at the very edge (perhaps resulting from prolonged stresses in the cell). Consequently, around 20 % of the light in total is a little less well focused.



Avec le gr = 2300, le compagnon a disparu ~~[illegible]~~ et l'étoile centrale est parfaitement ronde, aucune trace d'allongement.
Vérifié par M. Bertaud.

Fig. 2.4 Examination of the 83 cm objective upon the double star OΣ 192 by Fernand Baldet, May 22, 1937. On a night with an exceptionally calm atmosphere, the central part of the diffraction pattern of the stellar point is seen to be quite circular, and the first and second diffraction rings (broken and moving) were present

The glass of the lenses shows a slight residue of quenching, which can affect the first diffraction ring [10].

Paul Muller, between 1966 and 1975, examined numerous very close double stars and could tell they were double at a separation of 0.15 arcseconds, which corresponds to the theoretical resolution of the objective. An elongation was still perceptible when the components were even separated by only 0.12 arcseconds [11].

The objective of the Grande Lunette of Meudon must be counted among the great achievements in astronomical optics of the 19th Century, besides the objectives of the Yerkes refractor of 102 cm dating from 1897, of that of Lick, 91 cm, dating from 1888, of Poulkovo, 76 cm, put into operation in 1886, and of Nice, 76 cm, in 1887. The double refractor of Potsdam, 1889, had a 50 cm visual objective and a photographic one of 80 cm.

The Photographic Objective

The first gelatine-silver bromide photographic emulsions were sensitive only to blue and violet light, essentially from 320 to 410 nm. The orthochromatic plates sensitive to green, then the panchromatic plates sensitive to red did not make their appearance in astronomy until around 1905. The great 83 cm objective, corrected for visible light, could not serve for astronomical photography at that epoch. Janssen therefore decided to have a second objective – a photographic one – made, and corrected appropriate to the sensitivity of the emulsions then [12].

The photographic objective measures 62 cm in diameter and its focal length is 15.90 m. It is made from the same crown and flint glasses as the main objective, but the curvatures of the lenses are calculated to give an optimum chromatic correction at 430 nm.

The photographic objective of the Grande Lunette began its celestial service in 1898, and was used mainly by Henri Deslandres with the assistance of Millochau and Burson. The early long-focus photographs notably concerned globular clusters (variable stars in those clusters in 1898), planetary surfaces, and the bright parts of nebulae. Then the objective served to record numerous spectra, in particular for the detection of spectroscopic binaries, for Nova Persei in 1901, for the rotation of Uranus by means of the Doppler effect in 1902 and for comet Borelly in 1903.

Later, in less frequent use, the objective was removed from the refractor before the repair work carried out on the great dome, which was completed in 1924. The lens was not remounted until later. In 1956, it was dismounted when Paul Muller took charge of the works to build a new moving floor.

In examining the photographic objective of the refractor in 1972, together with Paul Muller we found that the cell, now very rusty, strongly compressed the lenses. By lengthy contact with the nail at the edge of the glass in contact with the cell, coinciding with a point of rusting, a thin conchoidal flake had broken off the front face of the crown component, covering 2.5 cm^2. This fragment could have been optically rejoined. But it seemed best to mask it off, the light loss not exceeding one part in a thousand.

The Mechanics of the Refractor

All the working parts of the Grande Lunette had come from the Paris workshops of P. Gautier, the constructor of astronomical instruments at 56 boulevard Arago. Paul Gautier (1842–1909) had in 1881 taken up the business of the constructor Wilhelm Eichens (1818–1884). The latter had founded his business in 1876, his establishment at 41 rue Saint-Jacques was famous, and Gautier had been his pupil.

Gautier, whose workshops around 1900 employed some 40 staff, had come to be the manufacturer of mechanical parts for all the large astronomical instruments with which France had equipped itself after the Franco–Prussian War of 1870. This uniformity in mechanical construction would give French astronomical instruments a particular character.

Gautier's firm should in particular be credited with three examples of the double equatorial refractors called *Carte du Ciel* instruments, an enlarged version of this instrument for the Pic du Midi, a widened version for the Meudon 1 m reflector, the 83 cm reflector for Toulouse, the 120 cm reflector for the Paris Observatory, and seven instruments known as *equatorial coudés*, of which the Great Paris coudé has a diameter of 60 cm.

To him is also due the Great Foucault siderostat of the Meudon Observatory, the mechanical parts for the refractor of the Paris Exhibition of 1900 known as *La Lune à 1 mètre*, and plenty of other instruments of lesser dimensions. In 1887 Gautier had made the mounting for the great 76 cm refractor of the Nice Observatory, of which that of Meudon is a close replica.

The Equatorial Mounting

From the beginning of the 19th Century until the close of the 20th, astronomical refractors and reflectors were in general carried by what are called equatorial mountings. The principle is to be able to move the instrument around two perpendicular axes, one of these being aligned parallel to the axis of the Earth's rotation. A mechanical drive exerts a slow rotation of the instrument around that axis, at a rate of one circuit in 24 hours. The sense is opposite to that of the rotation of the Earth. Therefore, a star sighted in the refractor remains stationary, in spite of the movement resulting from the rotation of the Earth.

The equatorial mounting at Meudon is a copy of that which Gautier had already made for the 76 cm refractor at Nice. The refractor of Janssen, indeed, had initially been envisaged as being similar to that of Nice, with a single objective and a tube of circular section.

But later Janssen would prefer a double refractor, more powerful and enabling photography, although much heavier. The diameter of the visual objective was chosen to be 83 cm, probably because Mantois had at his disposal slabs of glass allowing for that actual diameter after making the mirror for the Toulouse reflector having the same size. But the equatorial mounting was found to be too weak for the increase in mass and inertia.

The right ascension shaft is parallel to the Earth's, in a vertical north-south plane inclined at an angle corresponding to the latitude of the place. It is composed of two hollow parts in bolted circular sections (Fig. 2.5). This axis rotates between two landings at its extremities. The bearings are smooth, the axles are in steel, the ball-bearing housings in bronze with neither grease-cups nor oil grooves, being lubricated at the edge. The upper landing carries nearly all the weight of the refractor but the friction is relieved by massive weights housed in the pylon carrying the north landing. The weights are held by cables and pulleys upon a strong arched hinge carrying two wheels applied against a circlet surrounding the shaft.

The lower end of the RA shaft presses upon a cylindrical steel bearing serving as a stop and enabling adjustments. The upper part is terminated by a cube traversed by a perpendicular axis, known as the declination shaft (Fig. 2.6). A bulky cylindrical counterweight balances the tube of the refractor. Systems of weights, levers and bearings relieve the load upon the bearings of the shafts, reducing the friction [13].

Fig. 2.5 The equatorial mounting, with the pylon carrying the upper landing, the footbridge surrounding the mounting and the upper footbridge above around the landing

The Tube of the Refractor

The instrument being double, the two refractors are combined in the same tube of a rectangular cross-section, in accordance with a familiar arrangement of the manufacturer, Gautier. The cross-section is 0.90 m in width and 1.70 m in height, over a total length around 17 m.

This very heavy tube aligns seven parallelopided sections in sheet iron joined by flanges, each having 28 bolts (Fig. 2.6). The very short central section, in thicker sheet iron, joins the declination shaft concentrically. All the bolts throughout the instrument are threaded 'with Gautier's footprint' in a non-standard type, used by the manufacturer to preserve his monopoly in any maintenance operations upon his products.

The tube of the refractor turns around the declination shaft. To keep it from moving, a large 2 m long arm, stiffened by struts, balanced by counterweights, surrounds a sleeve on the shaft. Once pointed at a star, the arm is connected with the shaft by tightening the clamp worked by a wheel near the eyepiece.

For fine control of the declination angle, the arm working as a lever carries at its end a bronze part pierced by a threaded hole. This element can go along an endless screw linked to the tube of the refractor. A control rod with a handle allows the screw to be turned at the eyepiece and to move the star in a north-south direction at will in the field of view of the instrument. A small auxiliary refractor allows the value of the declination angle to be read upon a graduated circle.

Fig. 2.6 The astronomical set-up during an observing session in 1926. Behind the telescope, upon the movable platform, is Fernand Baldet. To the *left*, Eugene-Michel Antoniadi. Reproduced from photographs made in true colour

The Pillar and Foundations

The mounting of the refractor is erected upon a pedestal of cast iron, which itself rests upon a very high masonry pier (Fig. 1.1).

This pier has a 4.10 m × 2.70 m cross-section and measures nearly 18 m in height. Its foundations lie in the soil of the lower terrace. Upon its upper flat surface this high masonry pier carries the two large superposed castings which constitute the foundation upon which the mounting of the instrument rests. In itself increasing the height of the mounting, the shaft of the instrument is located nearly 28 metres above the ground. This considerable height is masked by the architectural device of the chateau which surrounds the installation without touching it at any point.

In spite of this great height above the foundations, astronomical observation does not disclose any vibrations, oscillations or sagging ascribable to these arrangements.

A footbridge with railings encircles the upper part of the foundation, surrounding the mounting of the refractor (Figs. 2.5 and 2.6). Access to it is via a spiral metal ladder. It can be folded into parts along the pier to clear the refractor when it is pointing in the region of the zenith. Another smaller footbridge encircles the top part of the mounting, at the top of the north pylon (Fig. 2.5). It is generally folded, as shown in Fig. 2.6.

This whole ensemble had been set up at the start of the 1890s. The constructor Gautier only asked for settlement of his fee in 1895 June and September, in five separate bills for a total sum of 5,870 francs in the currency of that time [14].

Initially the tube was painted in a remarkable wine colour. The foundation was darker, the declination axis and the counterweights had a coppery tone (Fig. 2.6). At night, inside the dome, the effect gave an atmosphere of mystery. With time, the colours faded. After 1960, they were replaced by light colours, necessitating frequent cleanings and dustings.

The Right Ascension Drive

The diurnal motion was supplied by a toothed sector, centred upon the right ascension shaft, against which was applied an endless tangent screw (or worm) moved by a weight-driven clockwork mechanism, whose speed was stabilised.

The radius of the toothed sector reached 1 m, whose size minimises the jolts and flexing of the tangent screw. The great sector covers an angle of 30°, which ensures two hours of movement. An alarm announces the end of its course. One must then interrupt the observation to replace the sector at the start of its travel, a significant constraint.

The threaded steel tangent screw is engaged upon the sector. It is secured at its conical ends between two cup-like recesses mounted upon a sturdy rod. A system of adjustment, the *système Gautier*, adjusts the pressure upon the cones. The device must have taken considerable pressures from the great instrument, without which there would have been play between the teeth, longitudinal flexure and backlash of the tangent screw. Plenty of equatorials constructed by Gautier have revealed weakness in these aspects.

The tangent screw is held by a jointed slider to be able to bring the threads into contact with the teeth of the sector, as well as the contrary pushing back the device and disengaging the sector. A camshaft and a lever allow this operation at the location of the device above the equatorial mounting. One can, though it is difficult, control operations from the observing position by means of a cord.

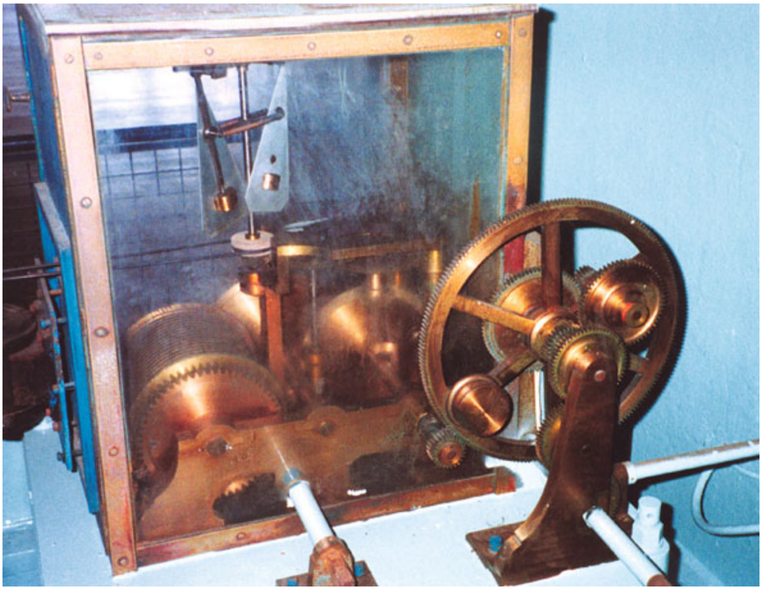


Fig. 2.7 The box of the Foucault regulator and the differential gearing, at the bottom of the pier of the telescope

The Speed Regulator

The clockwork mechanism control, located at the base of the refractor, makes the tangent screw turn slowly and regularly. It is driven by a heavy cylindrical weight held by a metal cable wound upon a drum, which slowly descends in a shaft installed in the pier. After observing, the weights must be rewound with the aid of a large crank with two symmetrical handles, a laborious operation.

The speed of rotation is stabilised by a Foucault regulator, whose design is found in all of the French equatorials of that epoch (Fig. 2.7). The original Foucault device is still in service upon the Grande Lunette after more than a century of use and still gives satisfaction.

Two paddles with dampers are fixed on either side of a vertical axis. The falling weights rapidly rotate that axis. Centrifugal force causes the paddles to move outwards, and a spring brings them back together. The air resistance, acting upon the paddles, brakes the rotation. An increase in speed forces the paddles outwards, which augments the braking action, from which stabilisation arises, and that covers a wide range of situations.

The driving shaft leaving the regulator box carries a gear mechanism faces a rotating circlet (Fig. 2.7). The device constitutes a differential mechanism. The action upon the circlet, with the help of lateral gearing, acts upon the position where the drive shaft leaves, in one sense or another, in relation to the shaft from the regulator.

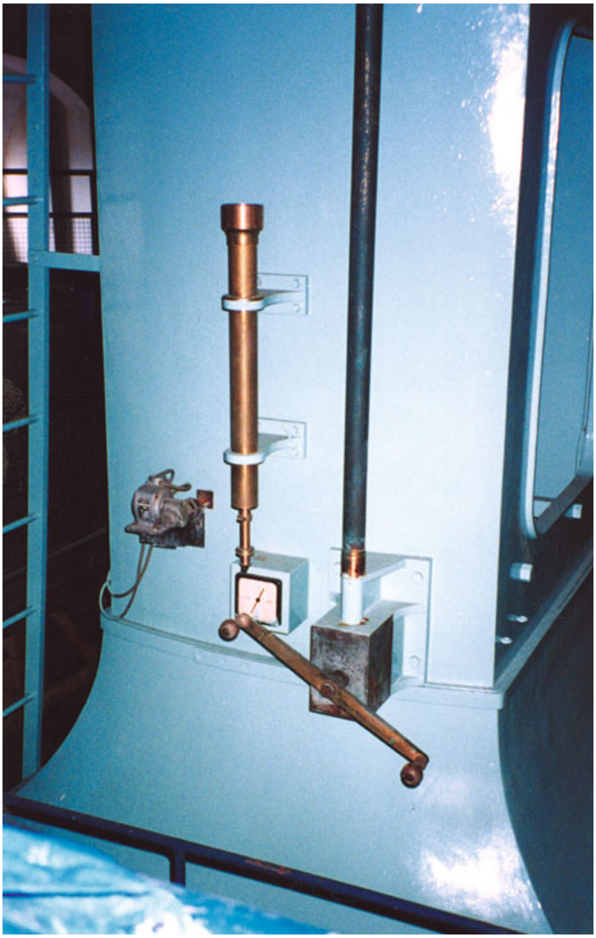


Fig. 2.8 The controls for the hour angle beneath the lower terrace, upon the south face of the pillar. The clock for the hour angle was added in 1965. The manual control handle for the hour angle was replaced by an electric motor (at *left*)

Thus, the observer is able to move the position of a star in the field of the refractor by controlling the gearing at the foot of the instrument.

The motion is transmitted to the tangent screw above the pillar by a shaft which traverses the full height of the foundations. At the top end, a second differential gear is interposed. It is controlled at a distance by two endless cords which hang vertically along the whole length of the foundation, up to the lower circular platform (one of the two is visible in Fig. 2.6).

Thus the observer, before gaining the moving platform, takes hold of the most accessible cord according to whether the refractor is to the east or west of the pier. Positioned behind the eyepiece, it is a matter of adjusting the cord the fine control of the telescope drive.

Pointing in Right Ascension

On the other hand, the general setup does not make it easy to read the hour angle from the mobile observing platform. It seemed preferable to control the position of the refractor in right ascension before observing, from the circular platform at the bottom of the instrument. Figure 2.8 shows this arrangement.

The lower part of the RA shaft of the equatorial carries a circular toothed wheel 115 cm in diameter, as well as a circle divided by a vernier scale giving the hour angle. At the foot of the pier, against the south wall, from the circular platform and at a man's height, a large crank with two handles via a vertical shaft enabled the toothed RA wheel to move the refractor to the desired position. The hour angle was read from the divided scale by means of a small refractor. The control for the differential mechanism associated with the Foucault regulator was held in the hand, for precise adjustment (replaced by an electric motor in Fig. 2.8).

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3. P. Véron, *Histoire du verre d'optique (a paraitre)*, Bernard Lyot exhibition "La verrerie au service de l'astronomie", Le Vésinet, 1997 November 13–23.
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5. After training as opticians, the two brothers Paul Henry (1848–1905) and Prosper Henry (1849–1905) had started at the Paris Observatory, both aged 16. Coming to be astronomers' assistants at the same time in 1868, then to the post of *astronome adjoint* (deputy astronomer) in 1876, being relentless observers, they had set up a private observatory at Neuilly. Between 1872 and 1882, they had 14 asteroid discoveries and one comet discovery to their names. Pioneers in the employment of photography, they discovered the nebulosity around the stars of the Pleiades in 1885. See J. Fort, "Opticines et astronomes: les frères Henry", Société Astronomique de France, *Observations et Travaux*, No. 46 (1996).
6. R. Mailhat, "Sur les objectifs astronomiques", *l'Astronomie*, **8**, 123–126 (1894).
7. B. Lyot, *Recherches sur la polarisation de la lumière des planètes et de quelques substances terrestres*, Thesis, Faculty of Sciences, Paris University, 1929, also published in *Les Annales de l'Observatoire d'astronomie physique de Paris, sis à Meudon*, **8**, part 1 (1929).
8. All the observational logbooks of Fernand Baldet and Charles Bertaud for the Grande Lunette and the equatorial table are preserved in the archives of the Observatory.
9. Meudon Observatory Archives (Paris Observatory Library, D-216).
10. Meudon Observatory Archives (Paris Observatory Library, D-216).
11. P. Muller, "La rénovation de la grande coupole de Meudon", *l'Astronomie,* **78,** 397–407 (1964), and P. Muller, "La grande coupole de Meudon", *Annales du Bureau des Longitudes pour 1966*.
12. J. Janssen, *Oeuvres scientifiques*, collected and published by Henri Dehérain, Éditions géographiques, maritimes et colonials, Paris, volume 1 (1929) and volume 2 (1930).
13. Meudon Observatory Archives (Paris Observatory Library), and French National Archives, F17 3745 and 3750.
14. In 1927, a sagging was noticed in the pylon carrying the upper landing, which brought the polar axis to scrape upon a particular spot. Two braces were added, on either side of the pylon, of whose effectiveness Fernand Baldet knew. See the observational notebooks of Fernand Baldet, preserved in the observatory's archives.

Chapter 3
Using the Telescope; Its Later Renovations

Behind the Refractor

The astronomer who gets up to the observing platform to undertake some study has the use of a large eyepiece holder upon a rack mount behind the visual objective, at the rear of the great instrument. He also has the use of a plate holder at the rear of the photographic objective (Fig. 3.1).

A powerful refractor of 15 cm aperture is at hand, mounted in parallel along the tube of the large instrument. This refractor, the *finder*, offers a much wide field of view upon the sky than does the main instrument. It allows the target star to be found and brought into the limited field of view of the large instrument. A second smaller finder offers a still wider field of view.

The observer has a handle, the declination control, for gently moving the star in a north-south direction and a cord for movement in the east-west sense. These devices allow for fine control of the refractor to position the star precisely in the field of the eyepiece and to keep it in the exact centre.

The moving platform contains the lights and the supplementary means of observation.

The Observational Equipment

The drawtube can take six large eyepieces giving magnifications from 220–540×, as well as six smaller eyepieces giving a maximum magnification of 2,300×, in stages (Fig. 3.2). Its rack mount allows for accurate focus.

A second very fine sleeve provided with a rack mount can be substituted, and carries a large-format eyepiece for giving low-power views of starfields, nebulae and comets (Fig. 3.2). The diameter of this beautiful device is fully 180 mm, of a type whose field of view is more extensive than the Full Moon. Its magnification is 150×. The device, giving bright images, can be mounted upon a large plate with two rectangular micrometer sliders able to travel up to 150 mm. The eyepiece can thus be shifted in order to explore an even wider field.

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_3, © Springer Science+Business Media New York 2013

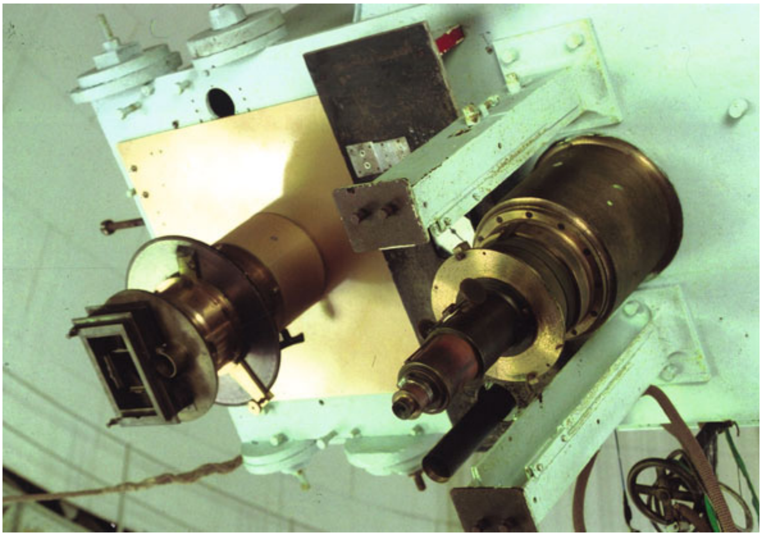

Fig. 3.1 The mounting plate behind the Grande Lunette. To the *right*, the eyepiece holder for visual observation with the 83 cm objective. To the *left*, the plateholder for photographic exposures with the 62 cm objective

Fig. 3.2 The eyepiece box for the Grande Lunette, the set of eyepieces (the four smallest ones are not originals) and the large rack mount holding the eyepiece giving a wide, bright field

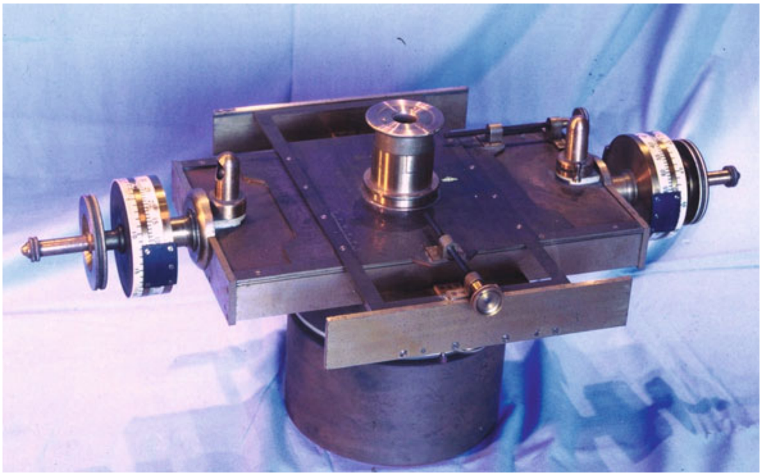

Fig. 3.3 The large bifilar micrometer made by P. Gautier for the Grande Lunette of Meudon

For precise measurements of planetary diameters, or equally the separation of a double star, the adaptor is able to accommodate two micrometers with moveable wires. The first, a very fine precision instrument made by P. Gautier (Fig. 3.3), covers by virtue of its large dimensions a field of 30 arcminutes, here also more extensive than the Full Moon. Its two moveable wires are of platinum and they are controlled by two divided drums allowing a precision of a fraction of an arcsecond to be attained. The second micrometer, of more classical dimensions, and with spider webs, was made by Mailhat. It covers a field of 16 arcminutes and its two moveable threads are associated with several fixed wires forming a precise quadrilateral in the field of view.

Behind the photographic refractor, the large-scale plateholder takes sensitive glass plates in 24 × 24 cm square format, covering a field of 43 arcminutes (Fig. 3.1). Adaptors enable smaller format plates to be accommodated. Focusing is achieved by a device like a lathe's capstan consisting of two threaded plates which can be moved to and fro. The plate can be orientated in azimuth. A lateral eyepiece allows for viewing a star near the field to be photographed. That star is used for guiding the instrument during the exposure. The observer keeps it upon the crossing point of two fine wires, and uses the north-south and east-west controls in order to correct for the movements of the image throughout the duration of the exposure.

Carrying Out the Observations

During the early years of using the instrument, from 1896 and during more than 30 years, little in the way of modification would come to be made to the initial state of installation of the instrument, such as it was described earlier. The appearance of the instrument was as in Fig. 3.4.

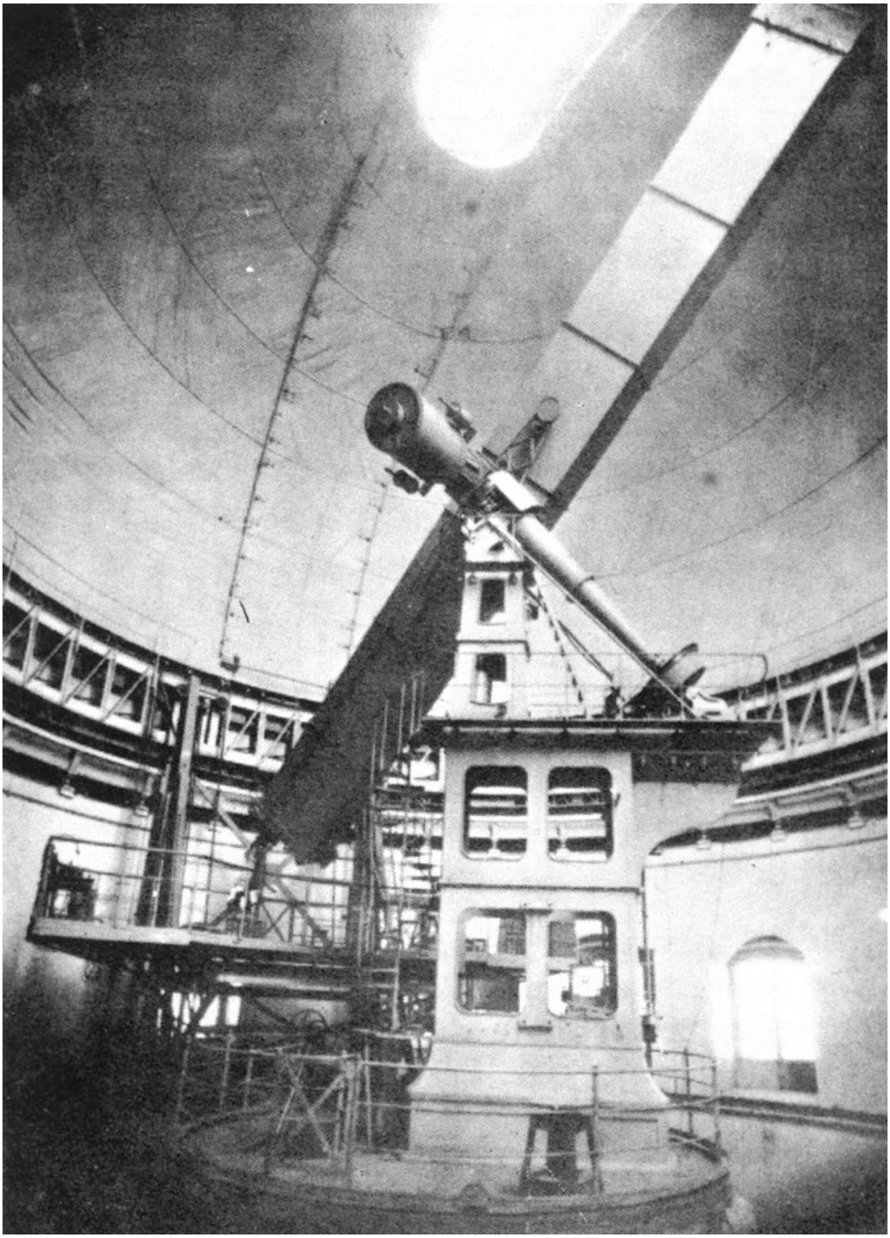

Fig. 3.4 The Grande Lunette of Meudon as it was in the days of the first observations

The astronomer accesses the dome through the door from the terrace opening straight onto the floor of the vast interior. The electricity generator previously turned on in the basement of the chateau provides the light. The first job is to open the dome shutters, by pulling on each of two thick endless cords which hang from the pulleys of each of the levers.

Then, by a metal ladder with 30 steps, the observer reaches the circular terrace which encircles the pedestal of the instrument (Figs. 3.4 and 1.1). From there, at the crank, he winds up the weights activating the operation of the Foucault regulator and the drive of the equatorial.

Next, the observer comes round on foot to the south wall of the pedestal of the refractor and takes up his position for moving the instrument in order to point it through the correct ‘hour angle’ necessary to aim it towards the star to be observed. He uses the crank with two handles shown in Fig. 2.8. The value of the hour angle is read upon a graduated circle by means of a viewing telescope. Corrections are made by turning the crank by hand, the rod of which acts upon the differential gearing of the Foucault regulator.

After having thereby aimed the telescope in hour angle, the astronomer has to climb the metal spiral staircase to the north of the pier (Fig. 2.6) to reach the footbridge at the level of the equatorial (Fig. 3.4). From there, he brings the toothed sector back to the start of its course, then engages the tangent screw (or worm) against the sector in order to transmit the diurnal motion to the refractor. It is possible for him, but difficult, to carry out these operations without having climbed the staircase, by pulling on the cordlets from the base of the instrument.

Next, after having grasped the double cordlette serving for fine control in hour angle and keeping it in the hand, the astronomer enters upon the moving platform. After closing the gate, the action of a large rheostat contact mounted on a white marble plinth controls the rising of the platform. The rise in the semi-darkness is steady, and the author of these lines there very often felt, amidst the loud noise of chains, slight jolts at times.

Arriving at the level behind the refractor (Fig. 3.4), the astronomer grabs the instrument already pointing along one axis, then, in playing with the electrical control rheostats, without letting go of the refractor, he adapts the platform to the appropriate height and also to the correct orientation, in order to bring the instrument to point to the correct angle of declination. The value of this angle is read upon a graduated circle with the help of a viewing telescope attached to the tube of the instrument. It is finely adjusted by the action of the declination control.

The platform is interdependent of the dome and is fixed opposite to the slit opening onto the sky, so that the objective is facing the opening. If the hour angle and declination were accurate, the star to be studied will already be found in the field of the finder.

Amongst the stars visible in the eyepiece of the finder with the extended field of view, it remains to identify the one desired, then to bring it to the centre of a square formed by four fine crosswires. It is adjusted in declination by the control handle, and in hour angle by the cordlet between the fingers like holding the reins of a horse. The star then enters into the field of the large instrument.

When the object needs to be observed over several nights or several times consecutively, the astronomer can leave the refractor aligned. It is sufficient, for the following observation, to move the toothed sector back to the start of its course and to reset the hour angle.

For bright stars, and particularly with planets, the alignment can be made easier, by positioning the platform directly in the azimuth provided by a scale. To this effect, large vertical marks are painted in black upon the circular wall of the dome, every 10°, numbered from 1 to 35. The dome is turned until a vertical stroke painted at its base is aligned with regard to the mark upon the wall indicated by the scale.

In the same way, the height to be given to the platform can be read upon a large scale painted in black upon the framework supporting it. The scale recommends, according to whether the observation is made seated, standing, upon a stool or a stepladder; it gives the appropriate height of the platform. When all is positioned from suitable reference points, the part of the starry sky which appears by prolonging the tube of the refractor across the slit of the dome contains the target star.

Generally, the astronomer will be accompanied by an assistant, although it is certainly possible to observe alone, particularly for planetary studies.

In 1920, after having intensively used the instrument himself since it was brought into operation and for more than fifteen years, Henri Deslandres, then aged 67, in his report upon the activity of the Observatory, could conclude: “In summary, the Grande Lunette is again usable for several lines of research. It only needs young and active astronomers [1].”

Safety

When, in the course of an observation, it is necessary to leave the platform, one could perhaps descend by electrical command as far as the level giving direct access to the terrace. Contrary to the case with the direct focus cages in plenty of our present telescopes, it is not necessary to move the instrument from its target. The refractor is left in operation. To continue the observation later, one has only to climb back to the platform.

In the case of electrical breakdown, or even if one should leave an observer to continue an observation in progress, one can exit the platform without any change in its height by following a small metal ladder laterally attached to the framework, to the right of the platform, visible upon Fig. 2.6. The descent emerges onto a narrow footbridge which leads to a vertical metal ladder also fixed to the framework supporting the platform. The final bar almost touches the ground eight metres lower.

If one has to leave the platform avoiding the illumination of the dome in order not to disturb an observation in progress, one has to work in the dark. The descent along the length of the vertical ladder needs both hands, in a way that makes it impossible to hold a portable lamp. From personal experience, one thus has to walk down the ladder in the dark, until one’s feet are on the ground. The climb back up is easier since the desk upon the platform can throw a light towards the top of the ladder, marking the destination of the ascent.

Successive Alterations

After its being brought into service in 1896, the instrument benefited from the resources of industry, craftsmen and the most advanced techniques of the time. Its creation had reached the limits of possibility then. The refractor was suited to the needs of astronomical research and its use responded to the way in which science was carried out. Therefore, during the first quarter-century of its use, it was neither necessary, nor possible, to bring about significant modifications.

After the First World War, developments in industrial and domestic electricity offered new resources. In 1923 Bernard Lyot (1897–1952), then a young assistant who had recently entered the Observatory, replaced the crank for rewinding the driving weights by an electric motor.

In 1932, as we have seen, the generator had been removed from the chateau stables in order for it to be transferred under the dome itself. Supplied by the domestic 110 volt line, it is now put into operation on the spot at the start of the observations.

In 1935, Bernard Lyot motorised the opening of the dome shutters [2]. The same year, Henri Camichel (1907–2002), a newcomer to the Observatory, was given the task of improving the ease of use of the instrument. He replaced the falling weight drive by an electric motor attached directly to the Foucault regulator. A hand-held rheostat allowed for fine adjustment of the speed of the motor, in order to refine the guiding [3].

Then Camichel replaced the handle controlling the declination by an electric motor operated by a joystick with keys. It was no longer necessary to place a hand upon the instrument, which is very sensitive to oscillations [4].

The motion of the refractor in hour angle had been made, up till then, by applying the tangent screw against the toothed sector with the aid of a lever placed above the instrument. It was necessary, we have seen, to access the mechanism by a spiral staircase. Camichel equipped the lever with an electromechanical device controlled by a commutator from the observing platform. Likewise, the engagement of the sector with the drive could be electrically operated.

It then became possible to carry out all the pointing operations from the eyepiece, except the initial positioning in hour angle, always carried out from the terrace before having entered upon the platform.

In a souvenir memorandum, Camichel would write in 1993: "Although when I had made my debut I was helped by an assistant and arrived in the dome half an hour before the time of the observation, I could arrive just a quarter of an hour before starting work, and work alone, without assistance. The refractor worked in this way in a satisfying manner [5]."

The Improvements of Paul Muller

In 1956 April, at the instigation of André Danjon, then the Director of Paris Observatory, Paul Muller (1910–2001), an astronomer from Strasbourg Observatory, came to Meudon with a mission to bring the necessary changes to the Grande Lunette to enable it to conduct a programme of double star measurement. He would later lead this programme.

The refractor had initially been designed for prolonged observation of a single object. It was hardly suited to the successive viewing of a large number of stars in the course of a single night. It was not possible to read the hour angle from the observing platform and each new target required descending to make some adjustment at the pedestal of the instrument.

Paul Muller took up an old suggestion of Henri Deslandres from the 1920s, which consisted of replacing the solid floor of the dome with a mobile floor able to move vertically, covering the entire circular surface of the building. This modification moreover allowed the development of the space lost beneath the moving floor, for offices and laboratories [6].

Andre Danjon obtained the necessary finance, and the building work for fitting out the premises was begun in 1960 September. The rooms were available from the end of 1961. The following year, a contract was signed with the S.F.A.C. Schneider Company for making the moving floor with the electrical operating systems, as well as other developments beneath the dome, notably putting a lift in the south turret of the basement. All these works were complete by the end of 1964, under the direction of the architect in charge of civil buildings and national palaces, André Remondet, assisted by the architect P. Odoul. Observations upon double stars commenced at the end of the same year.

The new arrangements beneath the dome would be described by Paul Muller in the magazine *l'Astronomie* for 1964 November [7], then in the *L'Annuaire du Bureau des Longitudes* for 1966 [8].

The great moving floor, 16.86 m in diameter and with a weight of 21 tonnes is suspended in 16 places by cables upon counterweighted pulleys. Four of the suspension points enable vertical motion by means of Galle chains and two 6.5 CV electric motors provide a vertical speed of 2 metres per second.

In its lowest position, the floor descends as far as the base of the pedestal of the refractor (Fig. 3.5). In its uppermost position, it nearly reaches the inner edge of the dome, giving access to the parts of the mounting and of the dome and enable their maintenance. A fixed gallery encircles the circular wall under the base of the dome, for the maintenance of a circulation path and to offer to visitors a bird's-eye view of the instrument.

Upon the moving floor, a control desk allows the electrical operations of opening the slit and rotating the dome, as well as the elevation of the floor. Angular sensors display the hour angle and the declination upon two indicators. These arrangements are visible in Fig. 3.5.

It was necessary to do away with the spiral staircase giving access to the gangways around the equatorial mounting. It would now become necessary to elevate the moving floor to the highest level to gain access to the toothed sector which drives the instrument, requiring the refractor to be placed in a horizontal position. Although a vertical metal ladder without guardrail allowed this access, it was dangerous.

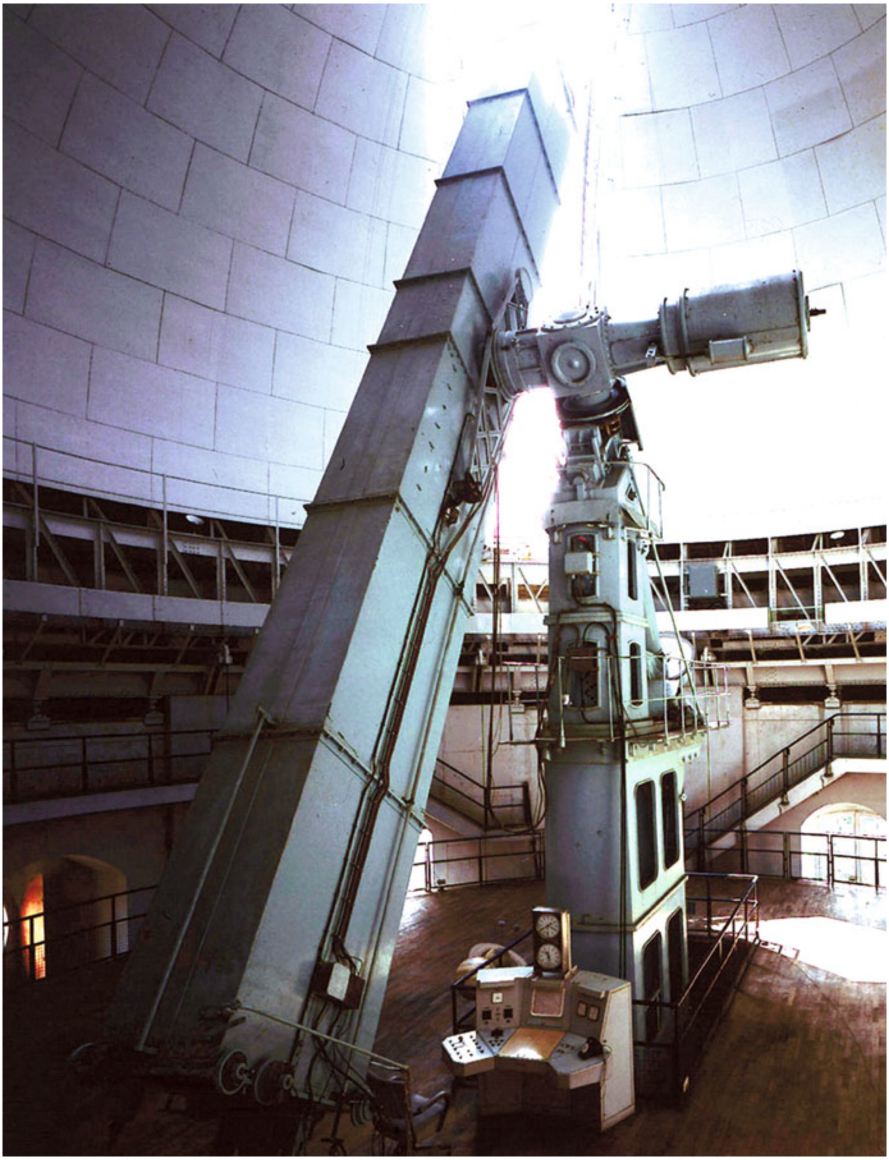

Fig. 3.5 The Grande Lunette in 1966, following the renovation work by Paul Muller. The telescope remains unchanged. The spiral staircase up the pedestal has been removed. The observing platform was replaced by a moveable floor covering the whole surface. A control desk allows for the opening and rotation of the dome, as well as the elevation of the platform. The hour angle and the declination are displayed

The renovations of the 1960s were not accompanied by improvements in the refractor itself, despite the progress of mechanical and electrical technology. Apart from the angular sensors displaying the hour angle and the declination, the entire instrument remained in the state left by Henri Camichel in 1936, with the electrical supply the normal 110 volts (mains voltage).

A maintenance contract with the firm of J. Heurguer at first guaranteed the good working of the new installation, without fault, for 20 years. But, in the 1980s, the contract with the successor was terminated. The setup progressively deteriorated, making observations more difficult. In 1991, the dome ceased to rotate, interrupting the use of the instrument for a long time, up till the renovations undertaken in 2003.

During the great storm of 1999 December 26 the dome of the Grande Lunette sustained significant damage, with the plates of the copper covering being torn off. The incident coincided with the launch of a study of the repair of the building, of the dome and of the instrument. The building was classified, the study being made by the chief architect of historic monuments, Pierre-Antoine Gatier, in collaboration with the Paris Observatory.

The developments in the scope of the renovation programme concerned the reestablishment of the rotation of the dome, its copper covering, and the restoration of the refractor, in order to allow observations to be restarted. The work of Mansart, the chateau containing the refractor could offer its spaces to the public to present to them experiences in Astronomy, History and their discoveries, and the science in the act of making them, the whole being dominated by that prestigious shining beacon which the Grande Lunette represents.

The Capabilities of the Instrument

Since being put into operation, the principal quality of the instrument has always been in the exquisite quality of its focal image, allowing magnifications which could not be realised by the other refractors and reflectors then available. Few instruments in the world demand a power of 800 × in order to show all the detail available in their images. The Grande Lunette of Meudon was the vanguard of what would later become Astronomy at high angular resolution.

This specific great quality is however accompanied by a mechanical defect. The refractor oscillates easily. From the beginnings of the use of the great instrument Henri Deslandres noted down, in his observing logbooks, an oscillation in the sense of the clockwork motion. The amplitude could reach several seconds of arc, with a period of 1 or 2 seconds [9].

These image movements do not hamper visual observation. The eye unconsciously follows the displacements of the image in the field of the instrument. Thus, the refractor is perfectly suited to observations of the planets and did pioneering work in this field. It enables measures of double stars by the double image method and has provided innumerable such data. It allows polarimetric analysis of planetary surfaces through a method which was innovative. The timing of eclipses and occultations can provide all the requisite precision, as much as for satellites as for asteroids. All this work is effected visually upon images often of great quality, an incontestable privilege accorded by the great instrument.

The slight swinging of the refractor would not be too much for spectroscopy at the beginning of the discipline of astrophysics. The slit was oriented in the east-west direction; the undulations would spread out the spectra by a slight amount, which rendered the spectral lines better visible. The undulations were hardly a nuisance again with the long photographic exposures upon nebulae and globular clusters. The preserved photographs show the stars sufficiently well separated in the arms to satisfy the astronomical research then in progress.

For photographic exposures upon the planets and the Moon, which are brief, exposures had to be made at the moments of greatest image excursion. One could also counteract the oscillations by a light rhythmic finger touch upon the end of the tube. Dexterity helps, and can in that way cushion or even cancel out for a time the movement of the star in the field [10].

The needs of astrophysics have become more stringent. But new methods of obtaining images by using diodes as detectors have made their appearance, as well as the procedures for digital image processing, by rapidly making many short exposures and then realigning each image before finally combining them together. This new method of carrying out astronomical photography has made it possible to completely freeze the drifts and oscillations of the instrument. These techniques offer to old equipment new possibilities for science, education and the media.

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Part II
Observations and Discoveries

Since the Grande Lunette of Meudon was first turned upon the sky, in 1896, the instrument has produced brilliant discoveries. The planets were examined with high magnifications. From 1898, the astronomer Henri Deslandres carried out long-focus astronomical photographs: more detailed ones had never then been obtained in the whole world. He developed astronomical spectrography, then a very new technique. He studied the rotation of the planet Uranus in 1902, the spectrum of Nova Persei in 1901, and that of comet Borelly in 1903. A little later, in 1909, the remarkable observer Eugène-Michel Antoniadi destroyed the myth of the martian canals.

It was there that, in 1924, Bernard Lyot inaugurated an ingenious method of observation which would become the technique of astronomical polarimetry. There again Henri Camichel in 1935 studied the spectrum of the exploding star, Nova Herculis, then that of Nova Lacertae. Fernand Baldet determined the dimensions of the nuclei of comets. In 1963 and in the following years, Paul Muller made more than a thousand micrometrical measurements from Meudon of double stars, and determined stellar masses.

There again, the Greek observer Jean Focas carried out a polarimetric surveillance of the planets, and studied of the question of life on the surface of Mars. With the Grande Lunette, observers of the Société Astronomique de France caught the ejections of dust from comet Halley in 1986, and analysed the veils and clouds in the atmosphere of Mars in 1988.

A Century after coming into operation, the Grande Lunette of Meudon continues to serve the progress of Astronomy. With renovation programmes agreed, the legendary instrument again begins a new career in serving the needs of astronomical culture, and will now be open to the public.

Of its observations, its works and its discoveries, the Meudon Observatory has preserved the evidence. As an *aide-mèmoire*, these documents enabled the episodes in its astronomical life to be reconstructed. A working group brought together the equipment, the logbooks, the observational notes, the notes left by astronomers who had used the refractor. A significant point was that numerous original photographs, often large format glass negatives, were able to be conserved. An entire Century was not enough to cause deterioration.

These negatives were able to be reproduced with modern digital image treatment facilities. Much finer details and more subtle tones could therefore be reproduced from the photographs of the planets, spectra, star fields and nebulae than their originators a century ago could have achieved, which would have astonished them.

In this way, the second part of the book retraces the vibrant scientific use of the Grande Lunette, by generations of astronomers who had succeeded one another to the observing platform, behind that powerful eye, open for new discoveries.

Chapter 4
The First Observations and Photographs (1898–1904)

Commissioning the Visual Refractor (1896)

When, in 1896, astronomical observations began, the equatorial had already been assembled beneath the dome for three years. But, in 1893, as we have seen, the great dome could not yet be moved. Several preliminary technical observations had been carried out through the still fixed slit, to check out the various parts of the instrument.

Jules Janssen had invested heavily to put this exceptional project into working operation [1]. In 1896, at the time of its first phase of active service, he was found to be fully occupied in the creation of his new observatory at the summit of Mont Blanc.

Nevertheless, as soon as the instrument was functioning correctly, he wished to check the suitability of the Grande Lunette by means of visual observation, in order to prove the high quality of its images.

The astronomer Joseph Perrotin (1846–1904), from the Nice Observatory, had already made plenty of planetary observations. He had a good experience of the 76 cm refractor which had been in operation at Nice since 1887, and of that of its high altitude branch of Mont Mounier. He came to an arrangement with Janssen who paid him to come to observe from Meudon for several months and to compare the merits of the three instruments [2].

At the end of 1896, the planet Mars made a close approach to the Earth. Upon the surface of the planet, it had already been possible to recognise the threadlike streaks; the very enigmatic ‘canals’. Moreover, the patches and mottlings upon the surface had shown evidence of change.

In 1896 December and 1897 January, Perrotin made use of nine favourable nights for observing Mars. His results were presented to the French Academy of Sciences at its meeting of 1897 February 15 [3] and also in *l’Astronomie*.

The drawings of Perrotin are not very skilfull and their analysis remains descriptive. But from their evidence, in spite of the great distance of the planet from the Earth, he saw really very fine details upon Mars (Fig. 4.1). Janssen, satisfied, emphasised the favourable diagnosis by means of remarks made later in an academic communication.

A little later, in 1898 January, as we have seen, the young and ardent student of the Ecole polytechnique Henri Deslandres was named as the astronomer at Meudon

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_4,

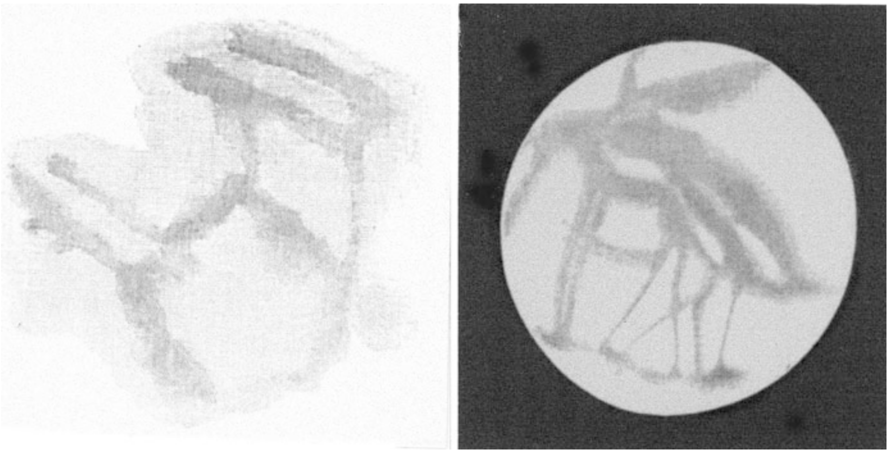

Fig. 4.1 The surface of Mars in 1896. Drawing by J. Perrotin. First observation with the Grande Lunette of Meudon. To the *left*, the region of Elysium, December 15, 1896, at 01 h 00 m, under high magnification. To the *right*, a whole disk drawing from January 3, 1897. (*Translator's note*: unless stated to the contrary, south is uppermost in this and in all the other telescopic images in this book.)

and came to live there. He had carried out spectroscopic research upon stars and the Sun at the Paris Observatory, and had become known through his invention of the spectroheliscope at the same time as the American, George Ellery Hale (1868–1938). Very interested in the Grande Lunette, he had contributed towards the final cost of putting it into operation out of his own pocket. He succeeded in being entrusted with the management of the instrument. He would play a remarkable part in all its aspects and would remain its principal user up till 1904.

Gaston Millochau (1866–after 1919), assistant to Deslandres at the Paris Observatory, had followed his boss to Meudon. He made use of the instrument in 1898 April and May to make four drawings of Jupiter, published in *l'Astronomie* in 1899 October (Fig. 4.2). Other observations of Jupiter would follow in 1904: "In several instances, at Meudon, in spite of the immediate vicinity of a great city and most notably on 1904 October 15, I was able to make upon Jupiter, with M. [Monsieur] Hansky, observations to the contrary, under conditions of such still images that one could have thought to have been observing a drawing illuminated by artificial light [4]."

The young Russian A. Hansky, from the Odessa Observatory, had come to Meudon to train in Astronomy under Janssen. He had shown himself as a talented artist, even to reproduce all the detail seen at the eyepiece (Fig. 4.3). He made remarkable drawings in 1904, published the following year in *l'Astronomie* [5].

Thus, the first years were marked by an intense activity which would become all-round. Between 1897 and 1903, ten communications would be presented to the Academy of Sciences. Besides the planets, observations would involve photography and spectroscopy. Their authors were J. Perrotin, G. Millochau, G. Tikhoff, A. Hansky and six communications were from H. Deslandres. Other articles and results would appear in the *Bulletin astronomique* of the Paris Observatory as well as in the review *l'Astronomie*.

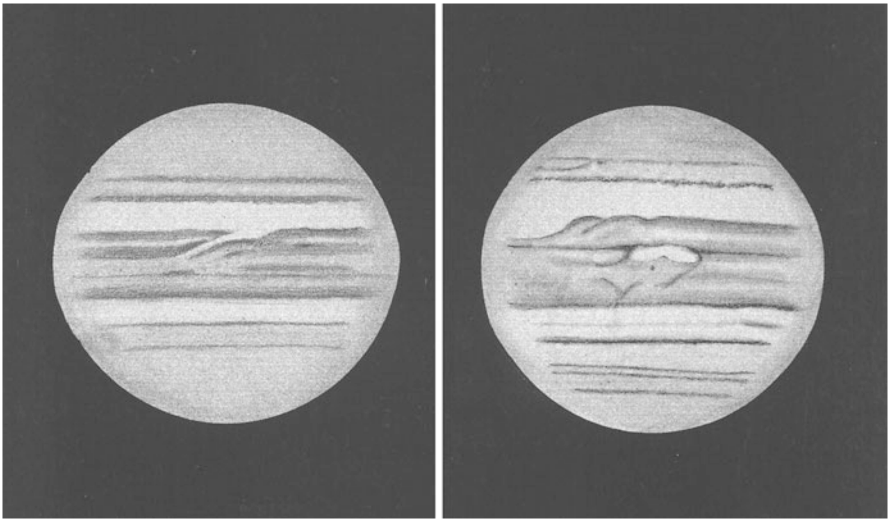

Fig. 4.2 Jupiter in 1898. Grande Lunette of Meudon. Drawing by G. Millochau. At *left*, May 9, 1898 at 22 h 35 m. *Right*, April 6, 1898 at 21 h 35 m

Fig. 4.3 Jupiter in 1904. Grande Lunette of Meudon. Drawings by A. Hansky. *Left*, October 14, 1904, 23 h 40 m. *Right*, October 15, 1904, 23 h 20 m, in excellent seeing

Analysis of the Surface of Mars (1901–1903)

At the start of the 20th Century, the study of planets was essentially left to visual observation at the eyepiece. The planet Mars, in this context, offered a special interest. The surface of the planet was directly visible. There one could study characteristics attributable to the present of life.

The Italian Giovanni Virginio Schiaparelli (1835–1910) in 1877 had thought that he had seen fine streaks upon the planet's surface, of a character that was hardly natural. In America, Percival Lowell (1855–1916) had studied the properties of these canals. Numerous other observers had confirmed them. Interpretations circulated, invoking signs of an intelligent life. In France, Camille Flammarion (1842–1925) had developed the subject in his great monograph *La Planète Mars* [6] and in numerous articles which had appeared in *l'Astronomie*. In 1898 he had come to produce a Mars globe, fixing the surface features as well as the positions of a great number of canals.

At Meudon too, Léopold Trouvelot (1827–1895) had studied the mottlings of the planet's surface and their variations, with a 38 cm refractor [7]. He had helped to recognise in such changes a seasonal character. He proposed, at the same time as Émile Liais, Director of the Rio de Janeiro Observatory in Brazil, to attribute them to expanses of vegetation.

Deslandres came to decide upon the replacement at Meudon for Trouvelot, who had recently died. He could do no better than to encourage Millochau to re-examine these problems of Mars with the Grande Lunette, more powerful than that of Trouvelot and all the other refractors in Europe.

Mars approached the Earth in 1901, although it again remained rather distant. But the planet had a very high altitude in the sky, which favoured stable images and the use of a high power. Millochau made four observations [8]. The following opposition came in 1903, with a disk diameter reaching 16 arcseconds. Seven nights were used to advantage, from which the Meudon Observatory has preserved 18 drawings [9].

The drawings of Millochau do not convey the full detail of the telescopic image. He could see much finer details than he was able to draw. From this acuity, he extracted an important conclusion:

> The canals which, in refractors of average power, are seen as weak lines, very narrow, but a little fuzzy, lose that appearance in the Grande Lunette; they then seem composed of dark broken masses, with irregular borders, formed like a string of beads which are lined up by the eye when the vision is not concentrated upon a point. [...] This aspect [...] must stem from the great separating power of the objective, which allows to better define the tiny details. [10]

Commissioning the Photographic Refractor (1898)

In 1898 January, from taking up his position as astronomer at Meudon, Deslandres quickly gave priority to the commissioning of the photographic refractor coupled to the visual instrument. The great device, whose objective measures 62 cm in diameter, offers a remarkably long focal length of 15.9 m.

From February, Deslandres carried out long exposure photographs with the instrument. These could exceed one hour, although: "With these large instruments, the least wind is a nuisance, as also is the slightest pressure upon the extremities [11]."

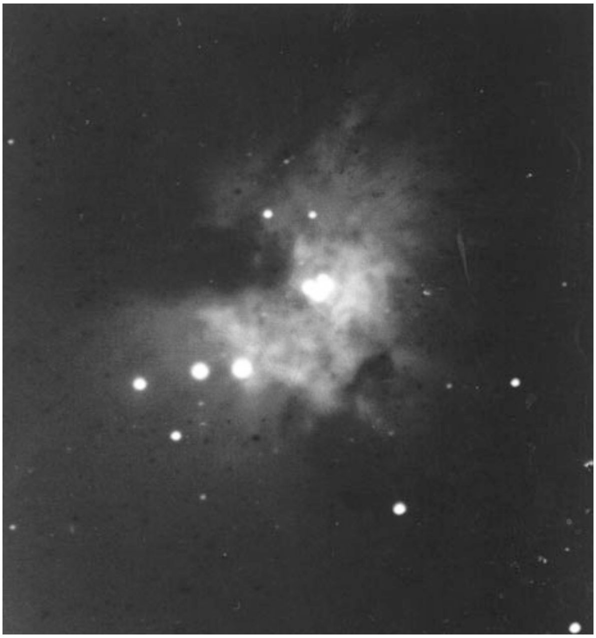

Fig. 4.4 The central part of the Orion Nebula. Photograph taken with the photographic objective of the great Meudon equatorial, February 22, 1909

Deslandres first attacked the great nebula in Orion, M42. He obtained three plates of the central part, then another very remarkable photograph the following year (Fig. 4.4) [12].

The invention of the gelatine-silver bromide photographic plate goes back to 1871. But the first pictures in silver of the Orion Nebula had not made their appearance until 1881, under the signature of Jules Janssen, then a little afterwards by Henry Draper. A very beautiful image had been obtained on 1883 February 28 by Andrew Ainslie Common (1841–1903), then came others by Isaac Roberts. All these images were obtained with very short focal lengths. They only showed the nebulosity as a whole.

Several larger images had allowed closer study of the central part. In 1895 the Harvard Observatory had published a print by Pickering, with a focal length of 4.50 m. Then in 1898 Sheiner at Potsdam came to produce an image of 3.0 m focus.

The Meudon images, with a 15.9 m focal length, were much bigger than all those that had preceded them. They were incomparably more detailed. According to Deslandres, preoccupied with the questions of Astronomy of the time: “These large plates thus seem to tell how to decide the longtime controversial question of variations in the nebulae [13].” New photographs of M42 would be taken for comparison purposes in 1909.

The Photography of Planetary Surfaces (1898–1899)

Above all else the photography of planets demands an extremely fine grain with very short exposures. Deslandres carried it out as follows: “A simple shutter mechanism was adopted, the lightweight shutter moved by the help of a foam rubber bulb. The observer follows the planet with the eyepiece of the Grande Lunette and squeezes the bulb when the image is least affected by the atmospheric undulations and the vibrations of the refractor [14].”

The first attempts were made with the Moon, at the prime focus, with the photographic emulsion coated upon glass plates of 18 × 24 cm format. The first plate was secured on 1898 February 26. The image of the Moon had a diameter of 14 cm. Six other plates are preserved at Meudon [15].

The detail upon the photographs is at least comparable with the best plates obtained at the Paris Observatory by Loewy and Puiseux. The great coudé instrument used at Paris from 1894–1907 to make their *Photographic Atlas of the Moon*, was of comparable power (60 cm objective, 18 m focal length) but was much less well situated. From Meudon, the photographic objective towers above the site, above the atmospheric disturbances caused in the vicinity of the ground.

For planetary photography, in 1898, the technique was again faltering. A first photograph of Jupiter had been obtained by Common on 1878 September 3 and showed a dark band and the Great Red Spot. On 1885 December 11, the brothers Paul and Prosper Henry had captured Saturn with its rings well separated from the globe [16]. On 1890 April 9 and 10, William H. Pickering obtained very small images of the disk of Mars [17]. The same year, at Lick Observatory, William Wallace Campbell sought to organise a photographic surveillance of planetary surfaces [18].

At the prime focus of the Grande Lunette, Jupiter measures 2 mm in diameter. Deslandres made attempts with different enlargements of the image. Between 1898 March 21 and May 13, twenty-one photographs were made, of which 15 plates have been preserved today. Modern prints from them are reproduced in Fig. 4.5.

Millochau drew the planet through the visual objective at the same time as Deslandres made the photographs behind the photographic objective. The prints of the photographs in Fig. 4.5 may be compared with the visual observations of Fig. 4.2.

According to Deslandres: “[The prints] were very good, and certainly superior to those of Lick Observatory, whose positives had been published by the Royal Astronomical Society of London [19].”

For Saturn, the exposure times were three to four times longer. Between 1898 May and July, four photographs were made, but the length of the exposures rendered them mediocre (Fig. 4.6, above). Nevertheless they show the exterior ring darker than the inner ring. Then, the angle of opening of the rings decreased. At the same time, the sensitivity of the emulsions improved. In 1909, a very good print was obtained, probably by Millochau (Fig. 4.6, below), although he had left Meudon for the Paris Observatory in 1907.

In 1899, the planet Mars was photographed on five occasions. But the image on the plate did not exceed 1.3 mm in diameter. Attempts were made with Venus, on four

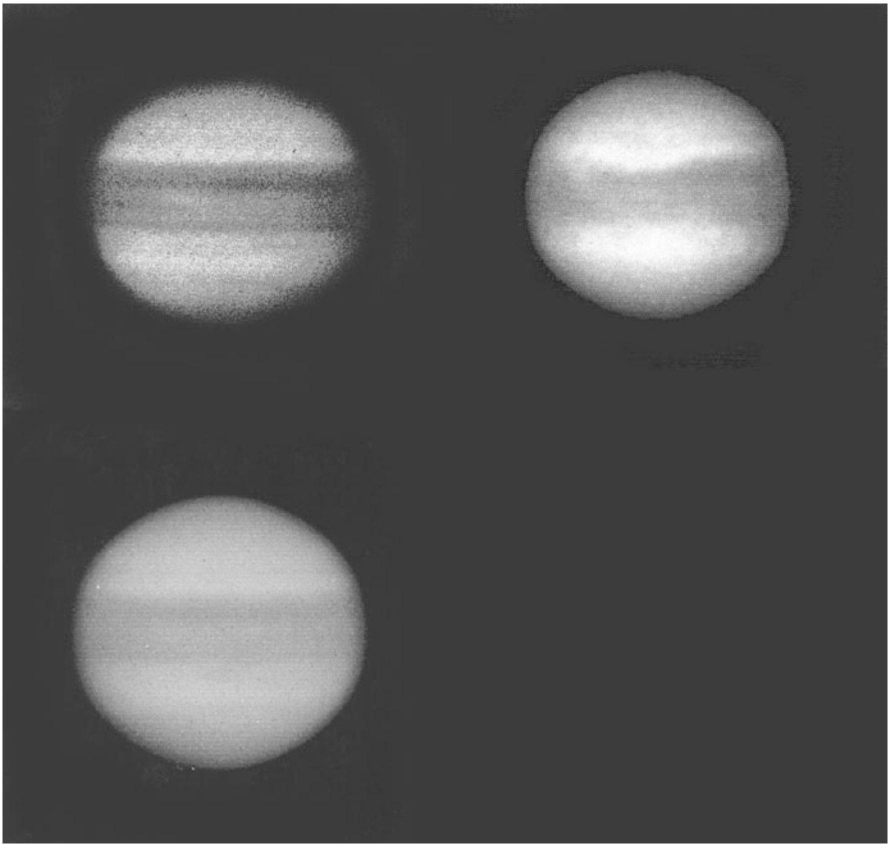

Fig. 4.5 Jupiter in 1898. Photographs made with the photographic objective of the great Meudon equatorial. Above, April 6, 1898 (*left*) and May 13, 1898, LB plate (*right*). Prints on paper from negatives obtained at the prime focus made by combining two images in order to reduce the grain of the photographic plate, a method unknown at the time the photos were taken. *Below*, April 13, 1898. Print taken from a single, prime focus image enlarged 4x. The grain is much weaker, but the duration of the exposure was 16 times longer

occasions, in full daylight or in twilight, but the dome heated by the Sun disturbed the images.

Deslandres presented his planetary photographs to the French Academy of Sciences [20]. Four prints of Jupiter and two of Saturn were reproduced by heliogravure in the *Bulletin astronomique de l'Observatoire de Paris* [21], as well as in the *Notice sur les titres et travaux scientifiques* of Deslandres of 1902 [22]. In spite of these presentations, these images of planets, nevertheless among the best of that epoch, would remain little known.

These fine results allowed consideration to be given to a systematic surveillance of planetary surfaces within the framework of the observatory's operations. But Meudon did not possess the necessary means. For Deslandres: "A regular and continuous study

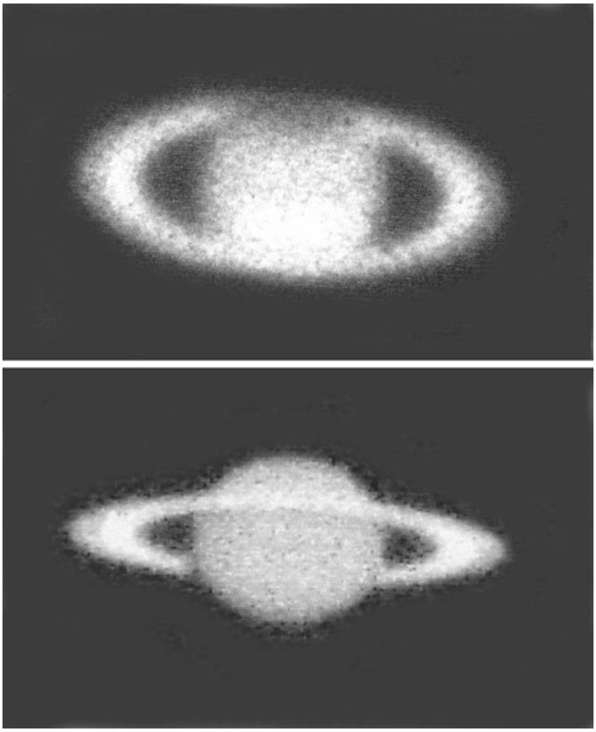

Fig. 4.6 Saturn in July, 1898 (*above*) and in 1909 (*below*). North is uppermost. Photos with the photographic objective of the great Meudon equatorial. Plates sensitive to blue and violet light. The improvement in image quality between the two dates is noticeable. (*Translator's note*: North is uppermost in these two pictures.)

of the planets by photography seems to me to be reserved for those observatories of which the stellar images are always steady [23].” The systematic study of the planets by photography would for years to come to be left to the privilege of the Lick Observatory in the USA.

All the photographs from that epoch showed the planets in blue and violet light, for which the emulsions then were alone sensitive. These aspects are different from the eyepiece impression. Jupiter, in particular, shows much more contrasty belts. Some years later, photographic emulsions would become sensitive for all colours of the visual waveband. Planetary photography no longer needed a refractor specially designed for blue light, like that of Meudon; it could be carried out with a normal refractor whose objective is optimised for the sensitivity of the eye. It would become practicable at numerous observatories.

In 1907, Lowell Observatory began in the USA a long-term planetary photographic program, in the visual waveband and in blue light. From 1941 onwards, planetary photography would become the privilege of the Pic du Midi Observatory, where the altitude of the mountain favoured obtaining very high quality telescopic images.

Fig. 4.7 The global cluster Messier 92 (NGC 6341) in Hercules, May 19, 1909. Photo with the photographic objective. Plate LΣ. Exposure 2 h 00 m

The Photography of Star Clusters (1898–1909)

At the end of the 19th Century, great concentrations of stars called *globular clusters* had been identified in the sky thanks to observations at the eyepiece with the great reflecting telescopes with metallic mirrors of Herschel, Rosse and Lassell [24].

Several photographs of short focal length began to be attempted. At Meudon, Louis Rabourdine (1858–1936) conducted a programme of photography of stellar and nebular objects with the Janssen reflecting telescope, an instrument of high light-gathering power, of 1 m aperture and 3 m focal length. The small image scale did not enable stars to be resolved in the hearts of star clusters [25].

Deslandres profitably employed the great focal length of the photographic refractor to attempt to partially or completely resolve the concentration of stars around the centres of the clusters [26].

Assisted by Millochau, Deslandres first photographed the globular cluster in Hercules, M13 (NGC 6205), upon the large-scale 24 × 24 cm LZ plates. In 1898, then in 1899, exposures reached 90 minutes. The nucleus, of which the integrated magnitude is 5.5, gathered numerous separate stars in a space 3 arcminutes in diameter (a tenth of that of the Full Moon).

Other exposures were obtained upon the clusters M3 in Canes Venatici (NGC 5272), M56 in Lyra (NGC 6779) and M11 in Scutum. In 1899 July and August, four plates were exposed on M92 in Hercules (NGC 6341).

The observations upon global clusters were taken up again in 1909, with even better results, upon the more sensitive LΣ and HΣ plates, of 13 × 18 cm format. Three plates would be obtained upon the globular cluster in Hercules, M92 (Fig. 4.7)

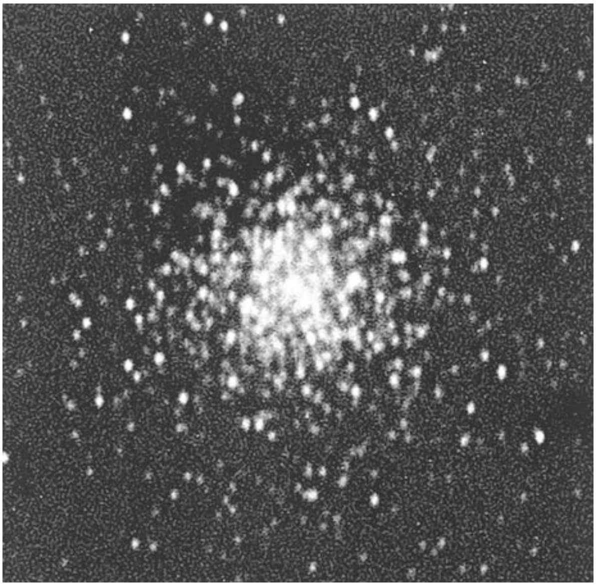

Fig. 4.8 The central part of the Messier 3 (NGC 4272) cluster in Canes Venatici, May 8, 1909. Photographic objective. Plate LΣ. Exposure 2 h 00 m

and four upon M3 in Canes Venatici, of which one was exposed for two hours (Fig. 4.8).

In 1895, from the Arequipa (Peru) branch of the Harvard Observatory, M. S. Bailey had showed that 3 % of the stars of the globular cluster in Centaurus were variable in brightness. Then William H. Pickering from Harvard had recognised more than 14 % of the stars of M3 were variable, although he had noted only 0.2 % as the case for M13. These results concerned the majority of stars in the cluster, excepting those of the centre which were unresolved.

The detailed photographs of Deslandres allowed research in stellar populations to be extended even to the hearts of the clusters. In M13, four variables were discovered in the central part, out of 300 stars counted, or 1.3 %. The result confirmed a strong increase in the proportion of variables towards the centre of the cluster [27].

The importance that the study of variables in clusters would later take on is well known, leading the American Miss Leavitt to discover in 1912 the relation between the period and absolute magnitude, for the class of stars called Cepheids, a relationship which allowed the determination of the distances of stars.

The Photography of Nebulous Stars (1898–1899)

Certain stars had been recognised as being enveloped in nebular material. Discovered by William Herschel (1738–1822), and called by him *planetary nebulae*, they could only be examined visually, at the eyepieces of the great reflecting telescopes with metallic mirrors.

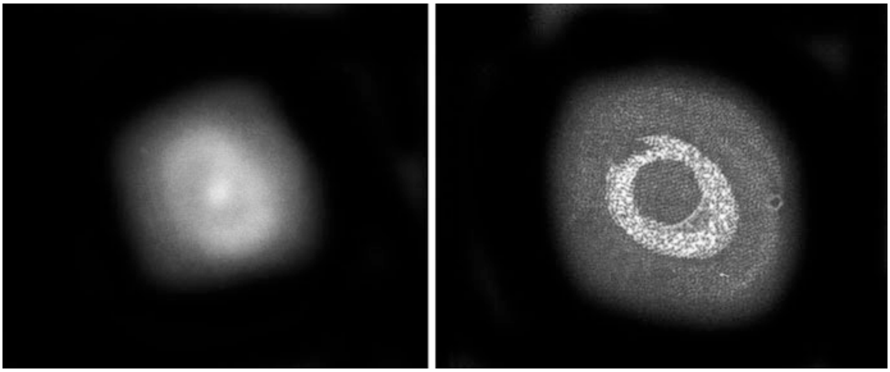

Fig. 4.9 The planetary nebula NGC 7662 in Andromeda, September 12, 1899. To the *left*, photograph with the photographic objective of the great Meudon equatorial. Plate LB. Exposure 1 h 53 m. To the *right*, the visual appearance through the great 183 cm reflector of Lord Rosse

It was generally thought that it was a case of stars in formation, at the stage where the material assembles around the nascent star and converges to increase its mass. We now know that contrarily it is a question of the final phase in the life of a star, when the explosion of the star propels its constituents into space.

For Deslandres, with the Meudon refractor, these stars surrounded by material were "all the more interesting since they escape, by reason of their small dimensions, from small and medium instruments [28]."

The planetary nebula NGC 7662 in Andromeda, of magnitude 8, covers a diameter of 30 arcseconds, a little less than the apparent disk of Jupiter. It was recorded photographically at Meudon on three occasions. We must note that these were the first known photographs taken of that object. Figure 4.9 compares the photographic image obtained with the best previous visual representation, by Lord Rosse (1800–1867). The central star, very blue, does not show up in the visual examination.

The object NGC 6523 in Saggitarius (wrongly identified by Deslandres as NGC 6543 in Draco) is now known under the name of the *Lagoon Nebula*. It was also photographed by him for the first time on 1899 May 30. The nebulous patch, of magnitude 4, is hardly larger than the preceding one.

It was the turn of the *Saturn Nebula*, NGC 7009, in Aquarius, very similar, on 1898 August 19. In Hercules, NGC 6229, a small fuzzy patch, reveals a weak neighbouring component.

NGC 7027 in Cygnus shows no more than faint extensions. NGC 6210 in Hercules, as well as NGC 6570 in Ophiuchus, in comparison with nearby stars, are revealed to be quasi-stellar. NGC 6905 in Delphinus, of magnitude 12, is too faint.

Much larger and brighter, the Ring Nebula in Lyra had been photographed with less powerful instruments. At Meudon the photographs showed around its centre the luminous filaments previously seen visually by Lord Rosse (Fig. 4.10).

These photographs, completely novel for their time, were presented at a meeting of the Academy of Sciences [29]. Two planetary nebulae were illustrated in the

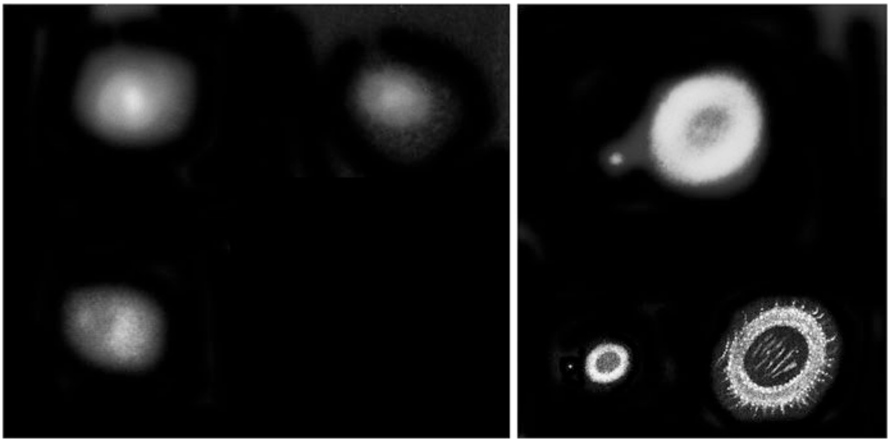

Fig. 4.10 The Ring Nebula in Lyra. *Above*, a print from a glass copy negative, date unknown, Grande Lunette of Meudon. *Below*, the visual aspect drawn by W. Herschel (*left*) and by Lord Rosse (*right*)

Bulletin astronomique de l'Observatoire de Paris [30] and then in the *Notice sur les titres et travaux scientifiques of Deslandres* in 1902 [31]. But these results too would very rarely be cited.

Deslandres did not draw any conclusions about the physics of planetary nebulae. It was more a question of proving the capabilities of the great instrument. His aim was to explore new fields of research in which the power of the great equatorial was bound to break new ground.

Final Stellar Photography (1909)

In 1898 and 1899, the photographic observing campaign had been intense. But Deslandres did not follow this line of research any further. He was above all a spectroscopist, and his invention of the spectroheliograph had pushed him to the forefront of solar physics [32]. As a result, he would use the resources of the Observatory for developing these two fields.

A new series of photographs would again be obtained in 1909, probably again under the coordination of Millochau, in spite of his differences with Deslandres. They concerned Mars, Saturn, the Orion Nebula, and the globular clusters mentioned earlier. These results would profit from the considerable improvement in the performance of the new photographic plates over the past decade.

From 1905 onwards, we have seen that for planetary photography, the new photographic emulsions would become sensitive to the same range of wavelengths as the human eye. They would permit long exposures with ordinary refractors, designed for visual observation, like the great instruments of the Lick, Yerkes and Lowell

Observatories in the USA, and plenty of others, destroying the specificity of he great photographic objective of Meudon.

In 1896, Common's old 90 cm reflector, which had been a little more powerful than the Meudon instrument, had been transferred from England to the Lick Observatory in America, under the name of the Crossley reflector. From 1898 onwards, James E. Keeler (1858–1900), then Charles D. Perrine and later Hubert D. Curtis (1872–1942) would make remarkable use of the instrument for the photographic exploration of distant objects. They would essentially lead the research in this field [33].

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8. The drawings by Millochau in 1901 are reproduced in C. Flammarion, *ibid.*, **2**, p. 529.
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10. G. Millochau, "Observations de Mars a la grande lunette de l'Observatoire de Meudon", *Comptes rendus de l'Académie des Sciences*, **137**, 1903 October 27.
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12. The photograph in Fig. 4.4 is from 1909. One of the photographs from 1898 is reproduced in "Photographies stellaires avec la Grande Lunette de l'Observatoire de Meudon", *Bulletin astronomique de l'Observatoire de Paris*, 1900 February, pp. 69–73, and in H. Deslandres, *Notice sur les titres et travaux scientifiques de M. H. Deslandres*, Gauthier-Villars, Paris, 1902. The negatives taken in 1909, preserved at Meudon, have never been previously published.
13. H. Deslandres, "Photographies stellaires avec la Grande Lunette de l'Observatoire de Meudon", *Comptes rendus de l'Académie des Sciences, op. cit.*
14. *Ibid.*
15. The labels upon the photographic plates are in the hand of Lucien d'Azambuja. In 1898, Deslandres proposed to a school, the Écoles des Frères de Bellevue, to pay a young pupil for some practical tasks at the Observatory. Lucien d'Azambuja (1884–1970) was recruited in that way in 1899, at the age of 15 for, in his words "affixing the labels at the top and to the right of the glass plates". D'Azambuja finished his astronomical career as *astronome titulaire* of the Observatory, and President of the Solar Commission of the International Astronomical Union.
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18. The majority of photographic images collected at the various observatories of the world from 1905 until 1975 have been assembled by the IAU at Meudon. (The database can be consulted at: http://megasn.obspm.fr/bdip.html)
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29. H. Deslandres, "Photographies stellaires avec la Grande Lunette de l'Observatoire de Meudon", *Comptes rendus de l'Académie des Sciences, op. cit.*
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Chapter 5
The Beginnings of Spectroscopy (1898–1904)

First Spectroscopic Observations

Before moving to Meudon, Deslandres had acquired considerable practical experience of spectroscopy. It is a technique for analysing stars through the splitting up of their light by means of prisms. Deslandres had created the Spectroscopy Service of the Paris Observatory, founded a specialist laboratory, and invented an instrument—the *spectroheliograph*—for studying the Sun [1].

Deslandres had carried out stellar spectroscopic measures of radial velocities with the 120 cm reflector in Paris. His method was to detect and to measure the displacements of the absorption lines in the spectra of certain stars. The physicists Doppler and Fizeau had shown that the actual displacements of the wavelengths of light indicated motion away from or towards the light source, in this case of the star with respect to the Earth. These displacements could reveal periodicities, and in that case, they indicated the presence of two stars in mutual orbits, leading to an alternating movement. It was then a case of *spectroscopic double stars*.

After the close of the photographic campaign with the Grande Lunette, Deslandres put into action a programme of spectroscopic studies (Fig. 5.1). The instrument collected less light than the Paris reflector but it was much more convenient to use.

Deslandres modified the observing platform and added the mountings for attaching the spectroscope behind the refractor [2]. He assigned a spectroscope appropriate for measuring stellar radial velocities.

For the production of the *radial velocity spectroscope*, or *spectroscope des vitesses*, the resources of the Observatory supplied numerous object glasses, lenses, spectroscopic slits, and sets of prisms left over from eclipse expeditions. Trains of prisms of dense flint glass, crown and light flint were found. For Deslandres, spectroscopic instruments were constantly modified, and would each time be adapted to the specific observation proposed.

The radial velocity spectroscope consisted of a wooden box produced by the instrument-maker Mailhat. This chassis carried, in its preliminary version, a Steinheil lens of 52.5 cm focal length, a set of two glass prisms, one of crown and one of flint and a chamber in bronze 58 cm in length [3].

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_5,

Fig. 5.1 Henri Deslandres on the observing platform of the Grande Lunette in 1910, in the company of Weisler

The determination of radial velocities is made by measuring the displacement of spectral lines, and demands a precise reference scale of wavelengths by comparison with a reference source.

According to Deslandres: “The terrestrial source is an arc lamp of iron and titanium, kindly provided by M.Moissan. It is projected upon the slit, on each side of the star, in the middle of the exposure; it is also projected at the start and the end of the exposure upon another part of the slit, in such a way so that the three spectra thus obtained are juxtaposed. These latter form the spectra called controls, which record all the accidental displacements of the spectrum, other than the true displacement to be measured [4].”

The apparatus, weighing 21.6 kg, was fixed behind the photographic refractor. It was put into action in 1898 June together with the calibration source. The first photograph of a stellar spectrum was obtained on 1899 October 15. The precision of the radial velocities was of the order of several km/sec.

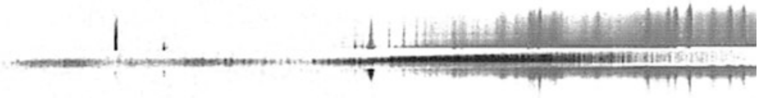

Fig. 5.2 Spectrum of Betelgeuse (α Orionis), a red star of spectral type M, framed by the lines of the reference spectra. The spectrum extends from $\lambda = 650$ nm (at *left*) to $\lambda = 430$ nm (*right*). Grande Lunette, visual objective, February 23, 1904, plate PL, exposure 30 m

Magnitude 4.5 was reached in a one hour exposure. The new photographic plates, Lumière PL, in 6 × 9 cm format, were sensitive from the violet up to the green. Longer exposures allowed them to reach the orange part of the spectrum.

Numerous other spectra would follow (Fig. 5.2). On 1900 February 12, the results communicated to the French Academy of Sciences gave an inventory of sixty spectra already obtained (Deslandres perhaps included here the spectra obtained earlier at the Paris Observatory). An interesting result was announced: "I point out that the star δ d'Orion presents variations in radial velocity which are at the same time strong and rapid. [. . .] The variations in velocity are considerable, from + 85 km per second to −50 km per second and they agree well with a period of 1.92 days. This new spectroscopic double star, remarkable for the great variety of its velocities, is that which, up till now, has the shortest period [5]."

The remainder of the year 1900 was employed to record numerous other spectra. Logbook No. 4 records, between 1900 December 19 and 1901 February 21, thirty-two spectra obtained in the course of 16 nights of observation, for 13 different stars.

The long period variable 11 Monocerotis was observed seven times, the variable ε Aurigae five times, the irregular variable α Orionis five times, and the variable β Pegasi with a 40-day period three times. For π Orionis, of period 54.5 days, spectra were obtained twice, and for α Cassiopeia three times.

The Spectra of Nova Persei (1901)

On 1901 February 21, by chance, the Reverend T. D. Anderson discovered from Edinburgh a new star which had come to appear in the constellation of Perseus. It was an exploding star, Nova Perseus [6]. Its magnitude then was 2.7. The opportunity to analyse the spectrum and its modifications in the course of evolution of the nova, which is generally rapid, is exceptional.

From February 26–28, with the aid of Millochau and Burson, four spectra was obtained in the blue and the violet, upon CR plates. Then, the spectrograph was transferred behind the visual objective and adjusted for working in the green and yellow with the new Lumière and Edwards orthochromatic plates. The red end of the spectrum was not accessible to the emulsions of that time. Deslandres had to resort to visual observation. He reproduced by means of a drawing the spectrum that he had viewed at the eyepiece of the spectroscope (Fig. 5.3).

Upon the photographic spectra, Deslandres recognised the lines of the hydrogen series from Hβ up until Hε, as well as the two H and K lines of calcium. In the eye-

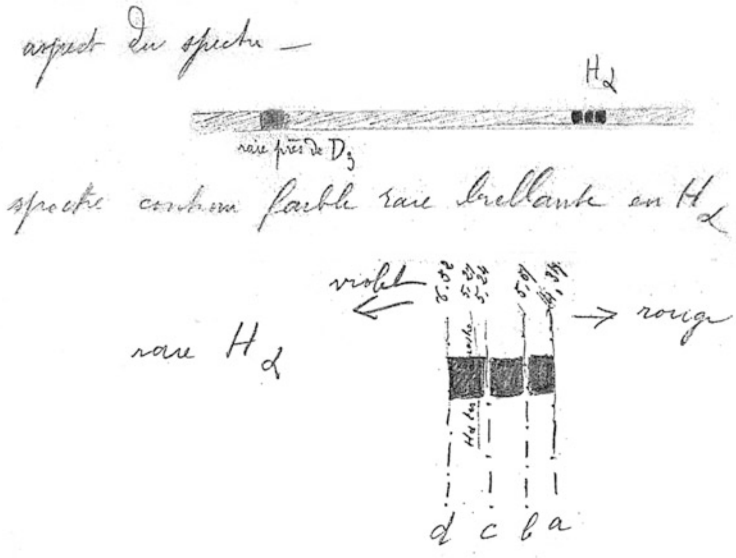

Fig. 5.3 Spectrum of Nova Persei, 1901 March 3. Montage of drawings by Henri Deslandres made with the spectroscope at the focus of the visual objective of the Grande Lunette

piece, he made out the Hα line of hydrogen as well as a faint band close to the sodium lines, attributed to helium. All these lines can be found with solar prominences.

According to Deslandres: "[The spectral lines] are very broad, diffuse and displaced more towards the red and, close to them, on the violet side, appear equally broad dark lines [7]."

On March 4, Deslandres communicated his results to the French Academy of Sciences [8]. Then, Nova Persei was fading and fluctuating in brightness. It spectrum was changing. The most interesting lines were located in the visible part of the spectrum. The radial velocity spectroscope then continued to be used behind the visual objective and observations were made by eye, with an eyepiece equipped with a micrometer allowing for measurement of wavelength. The colour correction of the objective was improved by the interposition of a lens of high refractive index, which reduced the effect of change of focus in the blue [9].

The Hα emission line, very widened, exhibited dark striations (b and e upon the drawing by Deslandres in Fig. 7.3). In the green, two broad emissions dominated the region of the continuum (AB and CD in Fig. 7.4). On March 3 and 5, micrometrical measurements, made at the eyepiece by comparison with the lines of the iron arc lamp, and of hydrogen and helium fixed the wavelengths for a, b, c and d (Fig. 7.3), as well as the limits of AB and CD (Fig. 7.4).

The visual measurements were again completed with the photographically obtained spectra for the green and the yellow, with the same spectrograph. To cover the blue and violet wavelengths, the spectrograph had to be dismounted, fit out a shorter chamber and the fix it behind the photographic objective. On March 8 and 12, spectra of that type were obtained upon the Lumière CR plates. All the results were newly communicated to the French Academy of Sciences [10].

The brightness of the star continued to fall. Nova Persei, very red and faint, was hardly visible to the naked eye. Deslandres replaced the spectrograph chamber by another, still shorter one, of 30 cm focus with a wooden tube. At the end of March, spectra were thereby retaken, behind the photographic objective.

Then Deslandres dismounted the spectrograph and put in its place, behind the photographic objective, the customary photographic plate-holder of 24 × 24 cm format, but preceded it by a direct vision prism, in order to form a tiny spectrum which could be photographed upon the emulsion. Between exposures, an eyepiece enabled him to follow the appearance of the spectrum visually, day after day, and to draw it (Fig. 7.5).

The spectrograph itself, with a short chamber, was replaced behind the visual objective and calibrated upon the stars α and β Persei. Eyepiece examination of the spectrum in the red still remained possible. The observations restarted on April 17 with the new instrumental arrangements.

In order to make visual measurements, Burson kept the image of the star on the entrance slit of the spectrograph by observing it through the eyepiece of a small sighting refractor. He held in his hand the cord for adjusting the clockwork movement and to correct for and to deaden the oscillations of the refractor At the same time, Deslandres observed the positions of the spectral lines in the micrometer eyepiece at the exit of the spectrograph. The two eyepieces were very close together, so Burson had to observe with the left eye, while Deslandres, at his left and against him, had to observe with the right eye. During the visual observation, the exposure was in progress with the twin photographic objective, in order to record the spectrum in the blue and violet.

Such observations were made on April 17, 19, 20, 22 and 23. Between the red and violet, the spectrum was drawn (Fig. 7.5). From the green to the blue, it was photographed. From blue to violet, it was recorded with the small prism of the photographic refractor. The wavelengths were determined to a precision of a fraction of an Angstrom unit.

The continuum had become more marked while the hydrogen lines faded. Three characteristic lines can be distinguished in the green, at 500.7, 495.9 and 486.4 nm, and those had already been observed in the nebulae.

On April 24, the star had become too faint for such exercises. It was nearing the horizon, which had limited the duration of the observation. Deslandres again dismounted his spectrograph and replaced it with a small spectroscope with a single flint prism made for stellar work, incomplete, but put into a state to work in a provisional manner. It was mounted on wood. The collimator and the chamber had focal lengths of 20 cm and 30 cm, respectively.

Between May 3 and the end of the month, spectra were obtained in the violet and blue with the small prism arrangement behind the photographic objective and from the green to the yellow with the new spectrograph behind the visual objective. To reach the red, eyepiece examination was becoming very difficult. On May 11, to compare with nebular spectra, Deslandres aimed at the planetary nebula in Draco.

On 1901 June 24 finally, definite conclusions were presented to the Academy of Sciences [11] and summarised thus: “The new star in Perseus, announced on 1901 February 23, was observed straightaway. The spectrum could be recognised as typical of the solar prominences, but with very broadened lines especially on

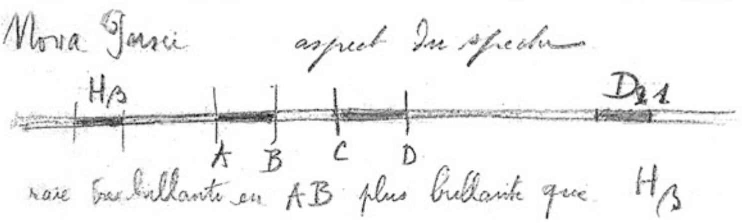

Fig. 5.4 Spectrum of Mova Persei, 1901 March 5. Drawing by Henri Deslandres with the spectroscope at the focus of the visual objective of the Grande Lunette

the red side, which can perhaps be explained by a very high gas pressure. The star was followed during its declining phase. The prominence spectrum decreased, and at the end of April appeared the spectrum characteristic of nebulae, a phenomenon already known with earlier temporary stars. The star, overall fading, had periodic variations in brightness; now, at maximum, the prominence wavelengths dominated; at minimum, the wavelengths of the nebulae were on the contrary the strongest. Finally, only the nebulae spectrum remained [12].”

At that epoch, the nature of the nova phenomenon was a complete mystery. From the point of view of his spectral results and the research conducted at other observatories, Deslandres risked some suggestions:

At the start of his observations:

> The temporary star is a star whose atmosphere was suddenly the site of phenomena analogous to solar prominences, but on a gigantic scale. [. . .] The particulars of the spectrum [. . .] lead us to accept two bodies charged with a high velocity which otherwise came to collide, to touch, or at least to pass very close to each other. The intense tidal phenomenon which would necessarily be produced under these conditions, explain very well the eruption of gas from the core and the incandescence suffered by the star. But how to explain the final transformation into the nebula? M. Seeliger, director of the Munich Observatory, proposed to accept that one of the two bodies which collided was a nebula. [13]

At the end of his study:

> An alternative explanation does not imply the intervention of the Doppler-Fizeau principle, or implies it only in a secondary manner. It supposes [. . .] a single gaseous mass at very high pressure which hardly moves with respect to the Sun and is suddenly the site of intense electrical phenomena. The high pressure [. . .] produced at the time widened the (spectral) lines and displaced the emission band towards the red. [. . .] That explanation perhaps allows us to bring back a single body, of great mass and great density, of which the solidified surface would be violently broken and would give access to gas and to the heat of the interior. [14]

Stellar Radial Velocities (1902)

Following these feats of instrumental virtuosity, Deslandres took up the spectroscopic study of stellar radial velocities with the large spectroscope behind the photographic objective. He was always aided by Millochau and Burson, to whom were added a young new assistant, Lucien d’Azambuja (1884–1970) (Figs. 5.4 and 5.5).

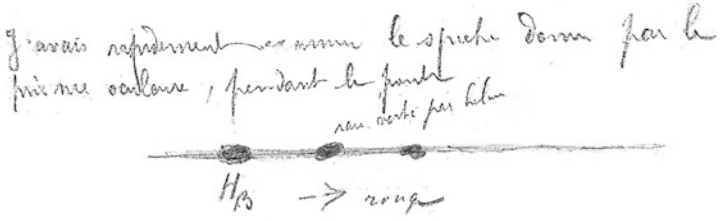

Fig. 5.5 Spectrum of Nova Persei, 1909 April 19. Drawn by Henri Deslandres at the eyepiece of the photographic refractor preceded by a direct vision prism

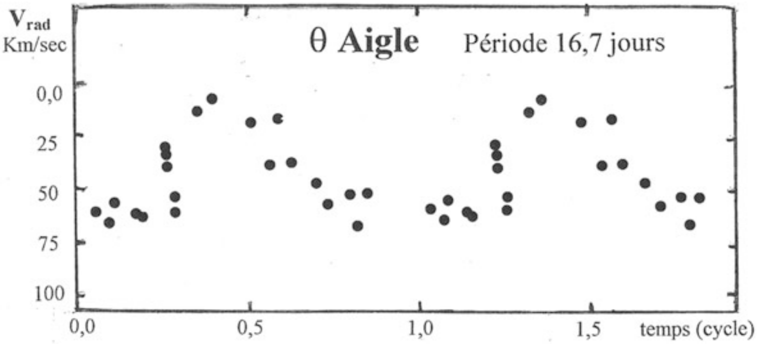

Fig. 5.6 Radial velocity curve for the star θ Aurigae, of period 16.7 days. Curve reconstructed by Audouin Dollfus from the table published by Henri Deslandres in 1903. The dispersion in the data indicates a second period of around 3 days

The results were presented to the Academy of Sciences at the start of 1903, and they concerned three stars. The white star θ Aquilae showed broad hydrogen lines and narrow metallic lines. Twenty-four spectra of the star could be obtained between 1902 August and December: "The variations in velocity are considerable [. . .] They were reduced to the same period estimated to equal 16.7 days and gave a [radial] velocity curve which, in general, appeared very regular [15]." Deslandres did not publish that curve, but his results allow it to be reconstructed (Fig. 5.6). "The star θ Aquilae, noted until now as being simple and non-variable, is at least double. It is the first white star of type VII (of Pickering's classification) that exhibits variations in velocity indicative of a spectroscopic double [16]."

The star ϕ Persei, observed six times between 1899 and the end of 1902, equally showed strong but variable radial velocities, ranging from $-20\,\mathrm{km\ h}^{-1}$ to $+11\,\mathrm{km\ h}^{-1}$. The hydrogen emission lines showed strong central absorptions, more pronounced than those of the solar chromosphere: "They herald an atmosphere relatively much thicker than that of our Sun [17]."

The star ψ Persei showed brilliant and wide hydrogen lines. They were striated with several black flutings and superposed upon wide black bands. This spectrum recalled that of Nova Persei in its initial phase, such as that drawn by Deslandres in Fig. 5.3.

The Rotation of the Planet Uranus (1902)

Since 1895, when working at the Paris Observatory, Deslandres had been attacking the problem of spectroscopically studying the rotation of planetary bodies [18]. The first to do so, he had used the method of inclination of the spectral lines.

When the entrance slit cuts a planet diametrically along its equator, the movement by rotation of the body deforms the spectral lines. In rotating, one edge of the planet approaches the Earth, which displaces the lines towards the blue, while the other edge displaces them towards the red. The lines are distorted, and thus appear inclined.

Deslandres, from Paris, was able to establish in this way the rotation of the rings of Saturn [19]. The Grande Lunette would enable him to extend his researches to Uranus and perhaps even to Neptune.

In 1898 December, a small experimental spectrograph with a single prism had been sketched out. The instrument had been used with some modifications for the study of Nova Persei, as described above. In 1901 July, the apparatus was modified with a new collimator of 27.5 cm and a chamber of 32.0 cm. The instrument was able to pivot around the axis of the collimator, in order to orientate the entry slit according to the desired position angle.

The idea was the use the apparatus with an entry slit 150 μm wide. At the prime focus of the Grande Lunette, the disk of Uranus subtends 300 μm, and that of Neptune 200 μm; the slit thus integrates the light over a certain height, which reduces the precision, but the lack of light renders the procedure necessary [20].

During the year 1901, Deslandres and Burson trialled the method by simulating the disk of Uranus. They used an auxiliary refractor to form a tiny image of Jupiter. The inclination of the lines conveys the rotation of the body. Then, on 1902 April 3, the spectrograph was tried upon Neptune at the prime focus of the visual objective of the great equatorial. Upon an LV plate, a suitable spectrum came to be produced with an exposure of two hours. But the spectral band was not high enough to show a significant inclination of the lines.

Uranus gives twice as much light and the spectrum is wider: "The planet, observed with the Grande Lunette, seemed to show a slight elongation in position angle 30°–40°. Also, the slit of the spectrograph was placed first in one direction, then in the opposite direction, and finally in the perpendicular direction [21]."

The spectra were obtained upon the planet in 1902 June and July, with exposures up to two hours and fifteen minutes (Fig. 5.7). Seven good prints were measured and enabled it to be established that a fact now well know, but totally new for the time: "It is very probable that the planet Uranus rotates in the retrograde sense, like its satellites [22]."

The Spectrum of Comet Borelly (1903)

The comet discovered by Borelly at the Marseille Observatory on 1903 June 21 appeared as a brilliant star [23]. "A special spectrograph had to be constructed of whose the chamber had a focal length of 0.12 m, much smaller than the collimator,

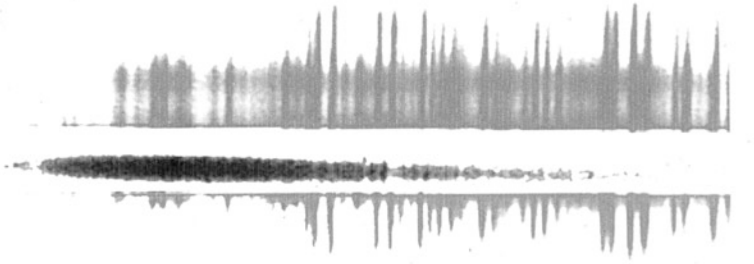

Fig. 5.7 The spectrum of Uranus, 1902 July 5, framed by reference spectra for the measurement of wavelengths. Plate PL, exposure 2 h 15 m by H. Deslandres and G. Millochau

of 0.55 m focus, the prism being in light flint with an angle of 60°. One thus obtained the concentration of light which, with a wide slit for the collimator, is necessary in the case of comets [24]."

Deslandres, assisted by Millochau and Jacques, used the spectrograph upon the comet on 1903 August 5, 6 and 7. Eyepiece examination gave the visible part of the spectrum and the photographic exposures of two hours reached the blue and the violet.

Twenty lines or bands showed up against the less intense continuum. The strongest of them corresponded to hydrocarbons and to cyanogen, already identified with earlier comets. The characteristic emission lines of hydrogen were not identified, nor were those of nitrogen.

For Deslandres:

> The hydrocarbons and cyanogen, electrically illuminated at low pressure in our laboratories, reproduce well the characteristics of cometary spectra, but they also give, with an appreciable intensity, the line spectrum of hydrogen and the bands of cyanogen, which are not shown in the comets. [. . .] The cause of the cometary light is electrical, but feeble; it is intense enough to illuminate the bodies of which they are composed, but insufficient for dissociation and to give rise to the spectra of the elements, hydrogen and nitrogen. [25]

For the spectrum of August 7, the slit was aligned along the tail of the comet opposite to the Sun. The displacements of the lines prove the motion of the tail with respect to the head as if there was a solar repulsive force: "The spectrum could be considered to be an experimental verification of that repulsion [26]."

The results upon Comet Borelly were to be the last obtained and published by Deslandres himself with the Grande Lunette. The new spectroheliographs which he had developed at Meudon for solar work now offered immense research possibilities. They would later come to absorb the research activities of Deslandres as well as the resources of the Observatory [27]. The Grande Lunette was to be left to other users.

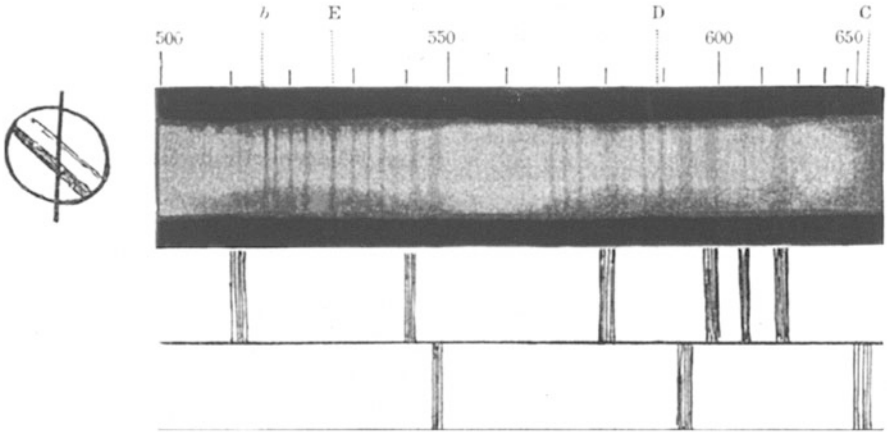

Fig. 5.8 Spectrum of Jupiter, January, 1904 16. By G. Millochau. Plate PL, exposure 1 h 30 m. Locations shown for those bands discovered in the jovian atmosphere as well as those due to water vapour

Spectroscopy of the Planet Jupiter (1903–1904)

Around this time, Millochau was getting on less well with Deslandres and was closer to Janssen. The latter, then aged 79, convinced Millochau to take up with the Grande Lunette the planetary spectroscopic studies which he had laid the foundations since 1862. Janssen had developed his researches notably from the summit of Mount Etna in 1867.

The new panchromatic PL plates could now reach the red end of the spectrum, in which the planetary spectral bands discerned visually were found in large number. Millochau adapted the spectrograph of Deslandres with a longer chamber, of 29.2 cm focus. On 1903 July 2 and 3, he recorded trial spectra of Venus and the Moon.

Between 1903 December 29 and 1904 January 29, six spectra of Jupiter of very high quality were obtained (Fig. 5.8). For comparison purposes, Millochau took two spectra of the Moon, one of α Tauri and three of α Orionis.

The conclusions were presented by Janssen to the Academy of Sciences on 1904 June 13: "The spectra obtained clearly show five absorption bands particular to the atmosphere of Jupiter; these bands are found at λ 618, 607, 600, 574 and 515 [millimicrons/nm] and correspond to the spectral bands reported in the spectrum of Uranus by Keeler. Moreover, the bands corresponding to water vapour and the band α were strongly reinforced [28]."

The presence of a new gas was confirmed, which does not exist upon the interior planets. This unknown gas could not be identified at that epoch. It would have to wait until 1921 for the Austrian Rupert Wildt to prove by means of these bands the existence of methane and ammonia in the atmosphere of Jupiter.

Millochau next announced his intentions to follow the same line of research under much more transparent and drier skies from a mountain site. He would make use of Janssen's astronomical station at the summit of Mont Blanc, to which he subsequently made several visits.

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3. H. Deslandres, “Variations rapides de la vitesse radiale de l’étoile δ d’Orion”, *Comptes rendus de l’Académie des Sciences*, **130,** 379 (1900). Meudon Observatory has preserved the laboratory notebook of Henri Deslandres, consisting of his projects and instrumental notes, as well as those of his collaborators, during the entire period of the spectroscopic programme, from 1898 December 29 until 1902 September 17.
4. H. Deslandres, “Résultats principaux obtenus en 1902 sur les vitesses radials des étoiles”, *Comptes rendus de l’Académie des Sciences*, **136,** 208 (1906). See also *Bulletin astronomique de l’Observatoire de Paris*, **20**, 129–136 (1903 April).
5. H. Deslandres, “Variations rapides de la vitesse radiale de l’étoile δ d’Orion”, *Comptes rendus de l’Académie des Sciences*, *op. cit.*
6. A journalistic description of the evolution of Nova Persei and the observations made from around the world, as well as their interpretations, can be found in a series of articles by Camille Flammarion in *l’Astronomie* for 1901.
7. H. Deslandres, “La nouvelle étoile de Persée”, *l’Astronomie*, **25**, 167–171 (1901).
8. H. Deslandres, “Observations de l’étoile nouvelle de Persée”, *Comptes rendus de l’Académie des Sciences*, **132,** 535 (1901).
9. The device for chromatic correction is described in the laboratory notebook of Henri Deslandres, recording his work and instrumental adjustments for the whole period of the spectroscopic programme, from 1898 December 29 to 1902 September 17.
10. H. Deslandres, “Details complémentaires sur la nouvelle étoile de Persée”, *Comptes rendus de l’Académie des Sciences*, **132,** 619 (1901).
11. H. Deslandres, “Troisième série d’observations de la nouvelle étoile de Persée”, *Comptes rendus de l’Académie des Sciences*, **132,** 1542 (1901).
12. H. Deslandres, *Notice sur les titres et travaux scientifiques de M.H.Deslandres*, Gauthier-Villars, Paris, 1902.
13. H. Deslandres, “La nouvelle étoile de Persée”, *l’Astronomie*, *op. cit.*
14. H. Deslandres, “Troisième série d’observations de la nouvelle étoile de Persée”, *Comptes rendus de l’Académie des Sciences*, *op. cit.*
15. H. Deslandres, “Résultats principaux obtenus en 1902 sur les vitesses radiales des étoiles”, *Comptes rendus de l’Académie des Sciences*, *op. cit.*, p. 205. See also *Bulletin astronomique de l’Observatoire de Paris*, **20**, 129–136 (1903 April).
16. H. Deslandres, “Résultats principaux obtenus en 1902 sur les vitesses radiales des étoiles”, *Comptes rendus de l’Académie des Sciences*, *op. cit.*, p. 205. See also *Bulletin astronomique de l’Observatoire de Paris*, **20**, 129–136 (1903 April).
17. H. Deslandres, “Résultats principaux obtenus en 1902 sur les vitesses radiales des étoiles”, *Comptes rendus de l’Académie des Sciences*, *op. cit.*, p. 205. See also *Bulletin astronomique de l’Observatoire de Paris*, **20**, 129–136 (1903 April).
18. H. Deslandres, “Recherches spectrales sur la rotation et les mouvements des planètes”, *Comptes rendus de l’Académie des Sciences*, **120**, 117 (1895).
19. H. Deslandres, “Recherches spectrales sur les anneaux de Saturne”, *Comptes rendus de l’Académie des Sciences*, **120**, 1155 (1895).
20. H. Deslandres, “Méthode spectrale capable de fournir la loi de rotation, encore inconnue, des planètes à faible éclat. Vérification de la methode. Premiers résultats”, *Comptes rendus de l’Académie des Sciences*, **135**, 228 (1902).

21. H. Deslandres, "Recherches spectrales sur la rotation de la planète Uranus", *Comptes rendus de l'Académie des Sciences*, **135**, 500 (1902), and *Notice sur les titres et travaux scientifiques de M.H.Deslandres*, Gauthier-Villars, Paris, 1902.
22. H. Deslandres, "Recherches spectrales sur la rotation de la planète Uranus", *Comptes rendus de l'Académie des Sciences*, *op. cit.*
23. Details of the discovery of and the first observations of comet Borelly can be found in *l'Astronomie*, **27**, (1903).
24. H. Deslandres, "Observations spectrales de la comète Borelly (1903)", *Comptes rendus de l'Académie des Sciences*, **137**, 393 (1903).
25. H. Deslandres, "Observations spectrales de la comète Borelly (1903)", *Comptes rendus de l'Académie des Sciences*, **137**, 393 (1903).
26. H. Deslandres, "Observations spectrales de la comète Borelly (1903)", *Comptes rendus de l'Académie des Sciences*, **137**, 393 (1903).
27. A history of the early solar work of Deslandres was given by A. Dollfus, "Henri Deslandres et le spectrohéliographie. L'épopée d'une recherche", *l'Astronomie*, *op. cit.*
28. G. Millochau, "Étude photographique du spectre de la planète Jupiter", *Comptes rendus de l'Académie des Sciences*, **138**, 1477 (1904). See also *l'Astronomie*, **28**, 469–472 (1904).

Chapter 6
Discoveries upon Other Worlds (1909 to 1935)

The Planet Mars in 1909

The year 1909 was that of a very favourable close approach of the planet Mars to the Earth. On September 24, at 56 million km away, the planet subtended an apparent diameter reaching 24 arcseconds. The previous equally favourable opposition was in 1892 and, at that time, no refracting telescope was as powerful as that of Meudon. The Grande Lunette thus enabled Mars to be better seen than on any of the previous occasions.

The planetary observer Eugène-Michel Antoniadi (1870–1944) knew this well, and made contact with Henri Deslandres, then Director of Meudon Observatory. Deslandres entrusted him with the great instrument and Antoniadi would make use of the circumstance in a revolutionary way.

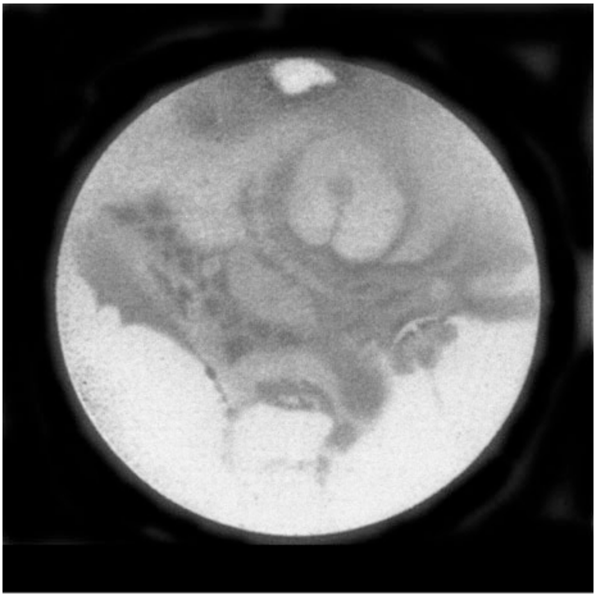
Eugène-Michel Antoniadi, born in Istanbul, of Greek nationality, a man of culture, and a well-read scholar and historian, was essentially an artist. In 1893, at the age of 23, he had come to live in France to apply his talent for drawing to the study of planetary surfaces. At the Flammarion Observatory in Juvisy, he would come to be recognised as an unrivalled observer [1]. In 1900, he would observe with the great refractor of the Universal Exhibition in Paris, known as ‘The Moon from 1 metre’, a horizontal instrument whose 1.25 metre objective was fed with light from a 2 metre plane siderostat mirror. It was then the largest refractor in the world. Even if the instrument was unable to attain the success anticipated for it, Antoniadi impressed upon it his reputation as an observer. Therefore Deslandres did not hesitate to accept his proposal to come and observe at Meudon under the title ‘Astronome volontaire’ (‘volunteer astronomer’).

According to several accounts, the night of 1909 September 20 revealed the planet Mars with a remarkable clarity. The red orb was at its closest to the Earth, and the fine detail in the image was exceptional. For Antoniadi, it was in the nature of a revelation: ‘The planet appeared covered with a vast and incredible amount of detail held steadily, all natural and logical, irregular and chequered, from which geometry was conspicuous by its complete absence [2].’

Antoniadi reproduced the appearance of the planet’s surface by means of a drawing which was to become well known, which subsequently would be widely shared

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_6,

Fig. 6.1 Mars on 1909 September 20. Grande Lunette, from the first observation of E. M. Antoniadi



20 septembre. $\omega = 279^\circ$; $\varphi = -20^\circ$.

among the scientific community (Fig. 6.1). An example of a pastel in natural colours would be sent a little later by its author to the Englishman Wilfrid J. W. Blunt; [A neighbour of Antoniadi, but not an observer—*translator*] today it resides in the archives of the Royal Astronomical Society.

Moreover, Antoniadi made other very beautiful drawings showing the whole disk. Those of September 30, October 6 and 11 are known [3], as well as those of November 5 and 17. For the attention of the American astronomer E. E. Barnard, he made a remarkable colour pastel showing the appearance of the planet on October 11, and sent it to his correspondent at the Yerkes Observatory at the end of 1909 (Fig. 6.2). He also made numerous partial drawings of the various martian features, of which four are reproduced in his synthesis of his Mars work published in 1930: *The Planet Mars* [4].

With his observations, Antoniadi drew up a Mercator projection chart of the planet, of an uncommonly high quality. He communicated this work to the French Academy of Sciences on 1909 November 15 [5], and published two descriptive articles in the journal *l'Astronomie* [6].

A remarkable fact is without doubt the absence of the famous canals of which Giovanni Schiaparelli (1835–1919) and Percival Lowell (1855–1916) had championed and whose artificial appearances had excited people in general.

> I observed with the beautiful Henry objective that the rectilinear 'canals' vanished when the most delicate details, inaccessible to the telescopes of Schiaparelli and Lowell, were evident

Fig. 6.2 Mars on 1909 October 11. Grande Lunette. Pastel drawing by E. M. Antoniadi, presented by its author to the American astronomer E. E. Barnard, of Yerkes Observatory

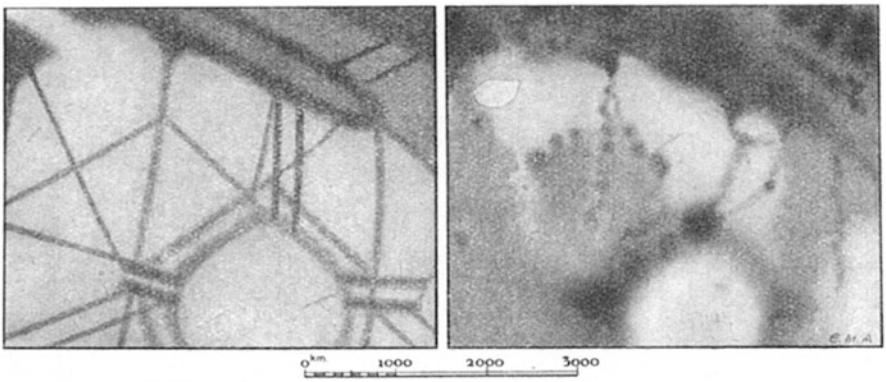
> and continually visible. It is that which is a fatal objection to the existence of the supposed geometrical network of the canals. [7]

Antoniadi illustrates this description by means of a convincing document, reproduced many times since (Fig. 6.3). He immediately took up an important scientific correspondence with the principal players in the field of Mars observation of that epoch, the Frenchman Camille Flammarion, the Italians G. V. Schiaparelli and Cerulli, the Americans P. Lowell, E. E. Barnard, G. E. Hale, the Secretary of the British Astronomical Association F. W. Levander and numerous members of the BAA, among them A. S. Williams and W. H. Wesley [8].

Antoniadi supplemented his artistic talents with a vigorous pen. His indictment against the martian canals was not published in the journal *l'Astronomie*, unlike his other works. Its editor, Flammarion, was an ardent defender of idea of the canals, and Antoniadi did not want to upset his old master. But he did publish in the Belgian journal *Ciel et Terre* [9]. After the death of Flammarion, he shared his thoughts openly in an article for *l'Astronomie* for 1926 August [10].

In his work *The Planet Mars*, which appeared in 1930, one can later read:

> The Grande Lunette of Meudon allowed the canal question to be settled once and for all. This is how it is: no-one ever saw a real canal upon Mars, and thus the more or less rectilinear 'canals', single or double, of Schiaparelli do not exist as canals, nor as geometrical lines; but they have a basis of reality since, at the location of one or other, the surface of the planet shows an irregular streak more or less continuous and speckled, or a greyish jagged border,



A. — « Canaux » linéaires sombres, entrevus par Schiaparelli, entre 1877 et 1890, dans la région d'Elysium.

B. — Résolution des mêmes détails en traînées et ombres irrégulières par l'auteur, entre 1909 et 1924.

— Aspect rudimentaire et en apparence artificiel de régions continentales de Mars dans des lunettes de $0^{m},218$ et $0^{m},490$, et sa transformation en taches complexes et naturelles dans l'objectif de $0^{m},83$ de Meudon.

Fig. 6.3 A martian region. Demonstration of the canal illusion

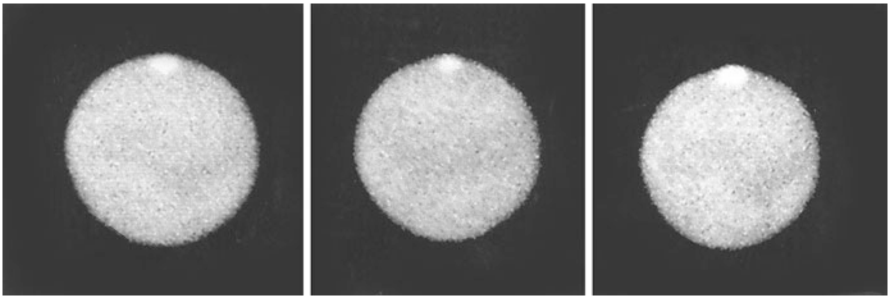


Fig. 6.4 Mars in 1909 in *blue light*. Photographic telescope of the great Meudon equatorial. From left to right: September 20, October 14 and October 20. The *left image* may be compared with the visual appearance viewed simultaneously by E.M. Antoniadi (Fig. 6.1). The photos were obtained in *blue light*. Note the reduction in contrast

> or again, a complex, isolated lake. Thus the details of the planet Mars everywhere exhibit an infinitely irregular and natural structure, so characteristic of the surface of the Earth. [11]

In 1909, while Antoniadi was always making visual observations, the photographic objective of the Grande Lunette was put to good use to make photographs of the planet (Fig. 6.4). These were probably taken by Milochau. A print is dated 1909 September 20, the same evening of the observation of Antoniadi in Fig. 6.1. The details appear very weakly contrasted in comparison with the striking configurations seen visually, with the exception of the polar cap. The reason is that the plates used, non chromatic ones, were sensitive only to blue and violet light.

During the time the Grande Lunette was being used at Meudon, the Count de la Baume Pluvinel (1860–1938) and Fernand Baldet (1885–1962) photographed the planet from the Pic du Midi with the new Baillaud equatorial which came into operation. Their excellent and numerous photographs made successively in yellow and blue light confirmed the faintness of the surface markings in the blue.

We now know that the reduction in contrast in blue light is not due to the martian atmosphere, as was thought at the time, which is transparent, but a response to the real reduction in contrasts of the surface features at that wavelength. Only the white clouds and snows are increased in contrast and appear brighter. The photographs from Meudon and Pic du Midi from 1909 September and October are characteristic of an especially cloud-free martian atmosphere.

It is odd that photographs of the planet in yellow light were not equally attempted at Meudon. The appropriate emulsions were available. At the Lowell Observatory in the USA, C. O. Lampland had photographed Mars in yellow light in 1905. In 1907, E. C. Slipher from Alianza in Chile had made a large number of excellent photographs of Mars in yellow and blue light [12]. In 1909, equally good photographs of Mars were taken through different coloured filters by G. E. Hale at Mount Wilson, by E. E. Barnard at Yerkes and by E. C. Slipher at Flagstaff. With the collection of photographs taken in 1907 and 1909, Glauco de Mottoni in 1967 would construct two planispheres of the martian markings for those years based entirely upon photography [13]. The work would later be extended for all the apparitions of Mars up to 1971 [14].

The Study of Mars in 1911

In 1910 the planet Mars was not observable from the Earth. Antoniadi, in a letter to Barnard of 1910 June 21, gave an account of his observations of the nucleus of Halley's Comet.

Martian observations were taken up again in 1911, at the next approach. Complete drawings were newly published, as well as numerous partial sketches [15].

To make his observations, Antoniadi installed himself behind the eyepiece of the refractor, in darkness. Fixing upon a particular region of the planet's disk, he watched the image, moving or quivering through the effects of atmospheric turbulence. He looked to seize upon the favourable moments, in order to furtively catch the finest details and to engrave them upon his memory. Thus he practised the exercise upon another nearby region. After having thereby memorised the different configurations, he arranged them with respect to each other. Finally, leaving the eyepiece, he placed himself behind a table with an empty desktop upon the observing platform. With pencil and eraser, he sketched upon paper at a single sitting all the memorised features of the planet.

The sketches of 1911, when compared with those of 1909 reveal modifications in certain martian regions as having occurred upon the planet's surface (Fig. 6.5). Other changes came from clouds in the martian atmosphere. "The Grande Lunette in 1911 showed me thick white clouds upon a white background, completely blotting out the

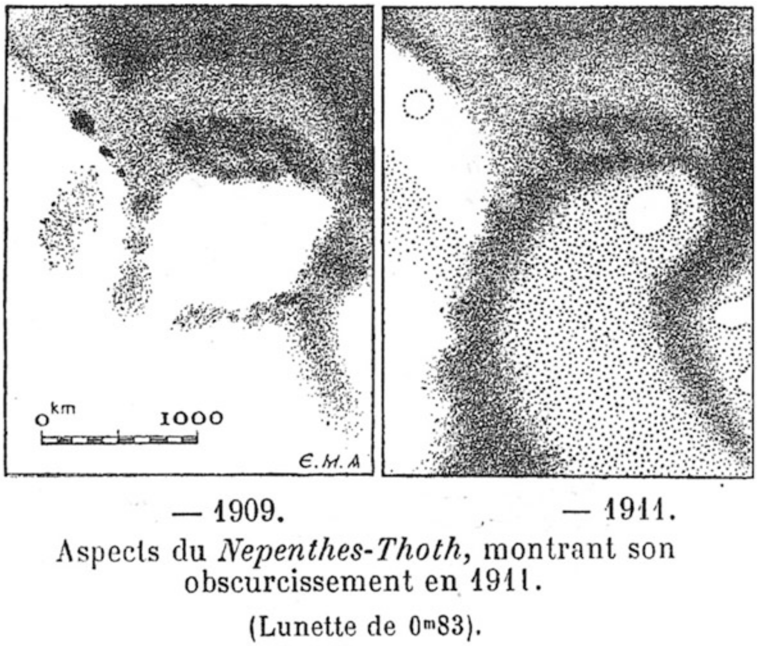


Fig. 6.5 Changes in the outlines of the martian features surveyed in 1909 and 1911, after E.M. Antoniadi

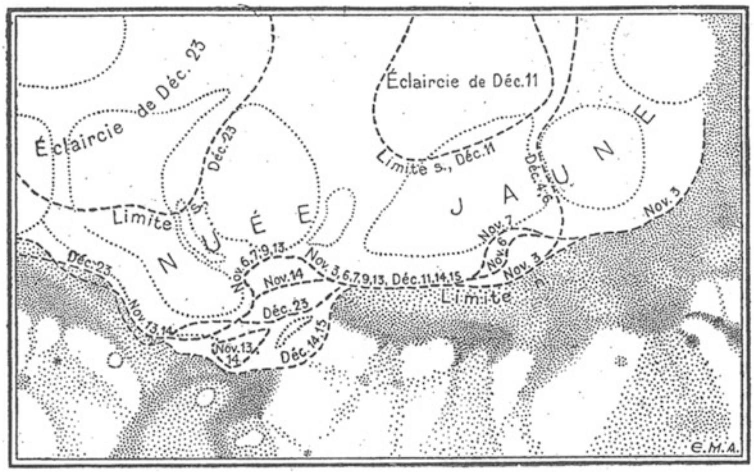
Mare Tyrrhenum, half of Hesperia and the following end of Mare Cimmerium.… I saw a great patch upon Libya, composed of disjointed white flakes, a kind of cirro-cumulus on a gigantic scale [16].”

The motions of the clouds signalled the presence of martian winds: “In 1911 the 0.83 m showed me a contra-alignment and a strong westerly air current in the high latitudes, exactly like upon the Earth [17].”

The atmosphere of the planet occasionally supports the evolution of dust clouds (Fig. 6.6): “I observed with the 0.83 mm that they could sometimes veil very extended regions for a long time. That was what happened in the Mare Eyrthraeum region in 1911 [18].”

Martin Studies Continued (1924 to 1929)

After operation in 1911, repair work upon the instrument and its dome necessitated an interruption of the observations. Then came the First World War. From 1914 to 1919 the instrument remained unused. After the conflict, the bad shape of the installation needed important work to be carried out [19]. The covering of the dome was replaced with sheets of copper. These works, begun in 1922, were completed just in time for the next favourable approach of the planet Mars in 1924.



— Immense voile jaune orangé, observé sur Mars du 3 novembre au 23 décembre 1911.

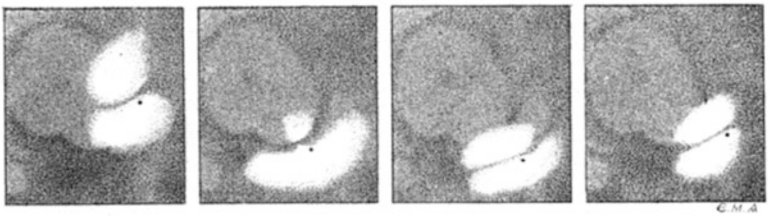
Fig. 6.6 Yellow clouds, attributable to veils of airborne dust, developing in the martian atmosphere in 1911 November and December. Observations by E. M. Antoniadi

The observation of this planet then led to a close collaboration between Antoniadi and Fernand Baldet, who had studied Mars by means of photography at the Pic du Midi in 1909. Between 1924 June 4 and December 31, Antoniadi made a point of mentioning 30 complete drawings of the planet, as well as around 30 partial drawings and charts. The gleanings from his observational logbook were published in eight consecutive instalments in the journal *l'Astronomie* [20]. Baldet made about 60 complete drawings, of which six were reproduced with his conclusions in *l'Astronomie* in 1925 January [21]. These drawings were comparable in technique with those of Antoniadi, a little more detailed, and the agreement was perfect [22].

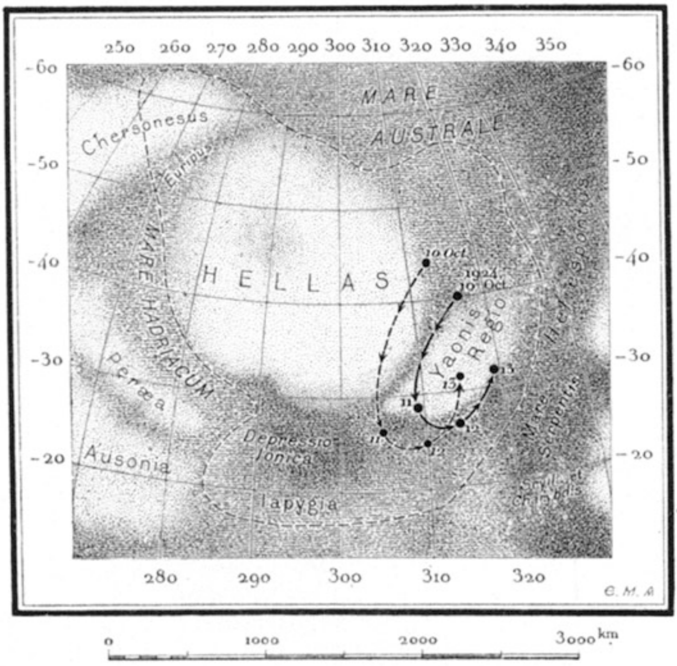
The great equatorial again revealed meteorological phenomena in the tenuous, transparent atmosphere surrounding the planet (Fig. 6.7). Antoniadi wrote of them: "In 1924 [. . . .] I noted a gyrating movement of the martian clouds carried out in an anti-clockwise direction, at latitude 30° South, exactly as in our north temperate regions [23]."

The two authors presented their results to the French Academy of Sciences, in four notes signed by either or both of them [24]. Special attention was given to the seasonal character of the changes observed upon the martian surface. It had been suggested from several quarters that the dark and variable stretches of the martian surface could be the result of vegetation. Taking up the idea again, Baldet and Antoniadi used it to address the occurrences witnessed with the Grande Lunette.

For Baldet: "The French astronomers Liais and Trouvelot were the first to attribute the albedo variations upon Mars to vegetation-based phenomena. This hypothesis seemed to me, up till now, the most satisfactory, and it does seem that the greater



Déplacement de deux masses nuageuses au-dessus d'*Hellas* et de *Yaonis Regio* sur Mars, les 10, 11, 12 et 13 octobre 1924.
(Lunette de $0^{m}83$).



Carte montrant le déplacement du point culminant et du centre des masses nuageuses observées comme des protubérances sur le terminateur de Mars, du 10 au 13 octobre 1924.

(Lunette de $0^{m}83$).

Les flèches continues indiquent la trajectoire du point le plus saillant, les flèches discontinues celle du centre des deux nuées.

Fig. 6.7 Clouds displaced by winds in the martian atmosphere. Drawings by E. M. Antoniadi, 1924 October

part of the dark markings, commonly called ‘seas’, contain vegetation since their colours have changed. There is water upon Mars, liquid or vaporised, at least the water originating from the polar caps [. . .], but it seems there is much less than on Earth [25].”

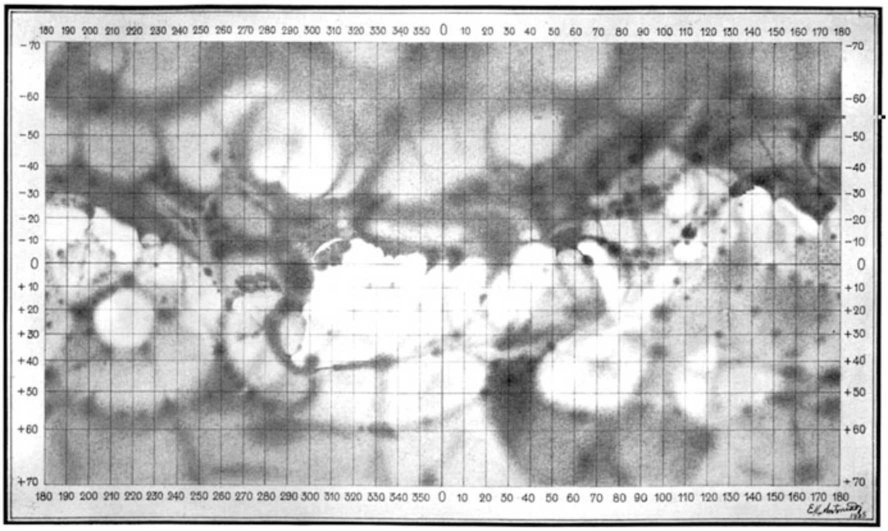


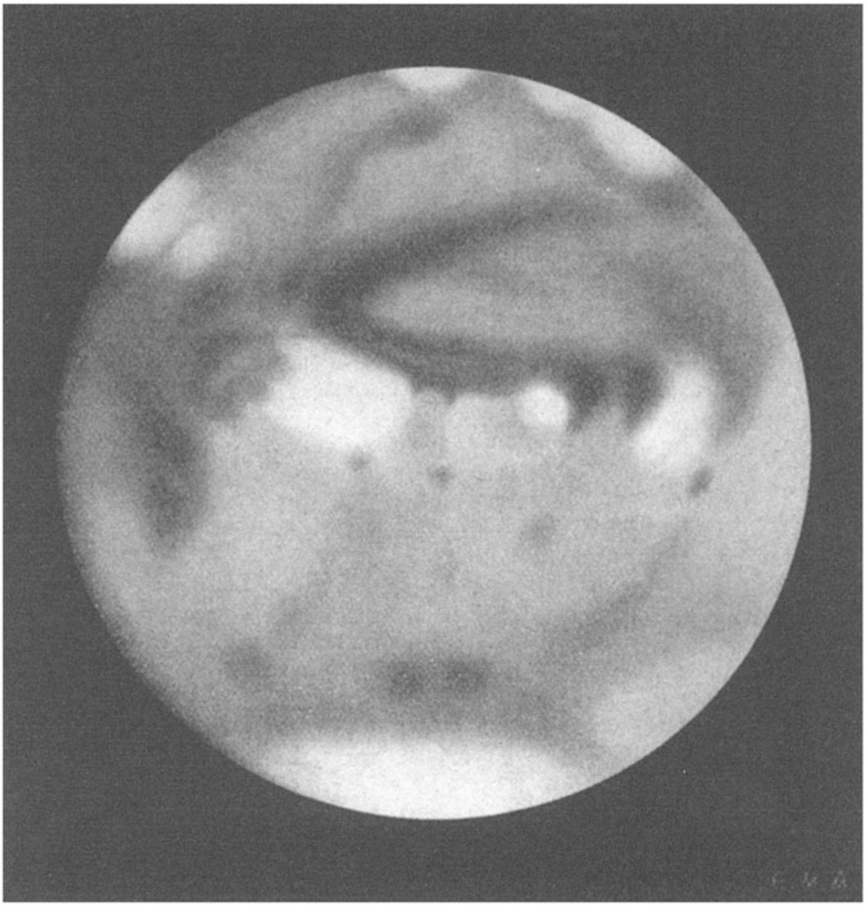
Fig. 6.8 Mars map drawn up from observations made by Antoniadi in 1909 and 1924, with the 83 cm Meudon refractor. Data for the high N. latitudes were supplemented by observations by Millochau made with the same instrument between 1898 and 1903

For Antoniadi: "Lowell and Douglas remarked in 1896–1897 that as the dark patches in the southern hemisphere approach the middle of summer, from October to January, their colour changes from green to brown and then to yellow. [. . .] This transition resembles that of our vegetation during dry summers and in autumn. In 1924, I was noticing with the Grande Lunette that the question is much more complex. I was witnessing then a decolouration coming from the south polar regions. [. . .] Not only the dark green patches, but also the grey and blue surface features, were turning under my eyes to brown, or lilac-brown, or even to carmine, whereas some other green or blue areas remained invariable. That there was almost exactly the colours of leaves fallen from the trees in summer and in autumn in our latitudes [26]."

At the end of 1924, Mars had moved away from the Earth. Antoniadi had sufficient data to hand to draw up a planisphere of the permanent markings of the surface of Mars (Fig. 6.8) [27], still more detailed than his chart of 1909 [28].

The next approach of Mars took place in 1926 under conditions nearly as favourable. Antoniadi published two articles in *l'Astronomie*, he described the new changes to the surface features and reproduced six drawings showing the planet under all longitudes [29].

In 1928, comparable results in number and quality were again obtained [30]. On December 8, the quality of the telescopic image was exceptional, allowing a drawing in great detail, despite the greater distance of the planet (Fig. 6.9, top). The four approaches of the planet in 1928–1929, 1930–1931, then those of 1933 and 1935 would again give rise to drawings, analyses and publications [31]. But Antoniadi already had the components of his conclusions.



Aspect exceptionnel de la planète Mars à Meudon, par les très belles images d'un léger brouillard, le 8 décembre 1928, à $21^{h}15^{m}$.

1924 1926 1928

Changements survenus dans l'aspect des régions martiennes de Pandoræ Fretum et de Noachis depuis 1924.

Fig. 6.9 Mars. Drawings by E. M. Antoniadi

The Planet Mars According to Antoniadi (1930)

In 1930, the author made known the results of his research in an important monograph, *La Planète Mars* (*The Planet Mars*).

In this scholarly work, Antoniadi analyses all of the spots, patches and halftones observed upon the surface of Mars since the invention of the astronomical telescope. He described their changes with time. A general map in three sections and two for the polar regions completes the work (Fig. 6.10). The document defines the average appearance of the planets markings, their coordinates and the nomenclature.

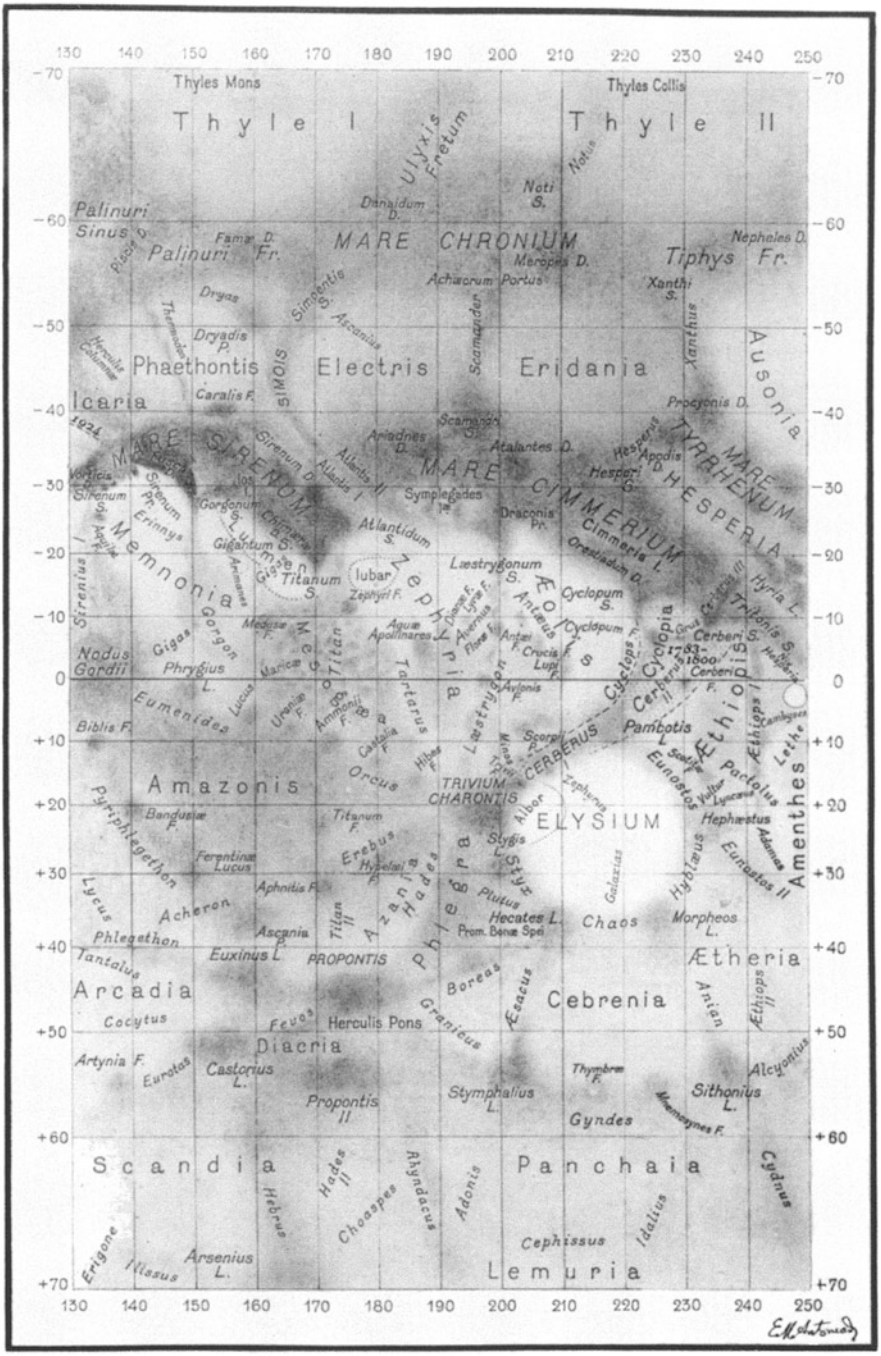
The planisphere would serve as a reference work for all the martian studies to come, right up to the time of the interplanetary probes. The work, written in the French language, escaped the attentions of engineers and investigators in charge of the first American survey mission to the planet Mars in 1965, whose base chart was would still be an ancient map of Lowell's showing canals. The monograph of Antoniadi would be translated into English towards the end of the 1970s, upon the initiative of the British astronomer Patrick Moore.

In his book, Antoniadi analyses the facts by the methods of the natural sciences. The properties of the planet are given in descriptive terms:

> The continental wastes of the planet occupy a surface area close to ten times larger to those of our Sahara with the deserts of Libya and Nubia. [32]
>
> I was able to prove by observation that there could not exist upon the planet any sea like our Mediterranean. [. . .] Mars is therefore in a state of desiccation incomparably more advanced than that of the Earth. [. . .] The low density must favour porosity and the gradual circulation of water towards the interior. But if not much water can be seen upon the surface, that does prevent it from being able to exist beneath the martian surface. [33]
>
> Upon Mars whitish clouds can also be observed, sometimes white, which seem to correspond to our mists, fogs or perhaps there again to our cirrus. [. . .] Indeed, like the snowy polar caps which make us see upon Mars the presence of water in a solid state, this element should also be found in a vaporised state, of which the condensation into droplets or needles of ice in all likelihood produce the white clouds. [34]
>
> The dark patches of Mars are stable in their general outlines, while subject in places to marked temporary changes in extent and intensity. [. . .] These changes are either secular or irregularly periodic in character and consist of a passing reduction in albedo or an invasion of dark or greenish matter of the lightly reddish and shaded regions in the neighbourhood of the large dark markings. [35]
>
> The great shaded extended regions of Mars behave as if they were covered with vegetation, which provides a high probability in favour of one form of life upon that world. [36]

The Planet Mercury (1927–1934)

Mercury is a difficult telescopic object. Antoniadi made use of the Grande Lunette to observe the planet principally from 1927 to 1929 [37]. He had to locate the planet in broad daylight, in order for it to be at a sufficiently high altitude above the horizon. Under these conditions, the Sun warms the ground, which is not favourable towards



RÉGION DES MARIA SIRENUM ET CIMMERIUM

Fig. 6.10 Mars. Section of the planisphere in four parts with nomenclature established by E. M. Antoniadi at the Grande Lunette of Meudon

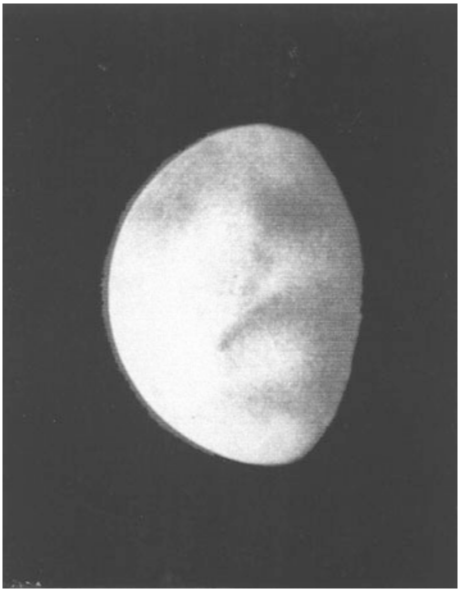


Fig. 6.11 Mercury, 1927 October 27. Great Meudon refractor. Drawing by E. M. Antoniadi

the quality of the telescopic images. Moreover, the objective illuminated by the Sun scatters light into the field of view and produces a milky background which reduces the contrast. Under the best conditions, this world in the refractor takes on the appearance drawn in Fig. 6.11. After Antoniadi: “The Meudon refractor shows upon Mercury spots the size of Sardinia [38].”

In the days of successive observations, Antoniadi recognised the similarity of the surface markings. He himself could exclude the possibility of a rapid rotation of the planet. From one observing campaign to another, the repetition of these similar aspects seemed to him compatible with a duration of rotation equal to the length of the planet’s annual revolution, in other words 87.97 days.

The Italian Giovanni Schiaparelli (1835–1910) and other astronomers had already attained similar results. Antoniadi compared the array of facts at his disposal: “There is a link between the very numerous mutual confirmations, absolutely independent, of the existence of spots seen upon Mercury by several excellent observers, and that always without any exception in the same positions, necessitates a uniform rotation of the planet equal to the duration of its revolution around the Sun [39].”

Under these conditions, only one hemisphere of the surface of the planet is illuminated by the Sun and the other half remains constantly in darkness. Antoniadi assembled his drawings to make a Mollweide projection map covering the sunlit hemisphere (Fig. 6.12). The map reveals itself to be very similar to that drawn by Schiaparelli in 1889.

Antoniadi then drew up a nomenclature for the regions and for the markings shown upon his map (Fig. 6.12). “I gave to the markings observed by me names inspired by Greco–Egyptian mythology of the great God Mercury, after the desert state and the enormous heat received by the planet [40].” The greyish stretches received the regional designation ‘Solitudo’ (‘S’ upon the map).

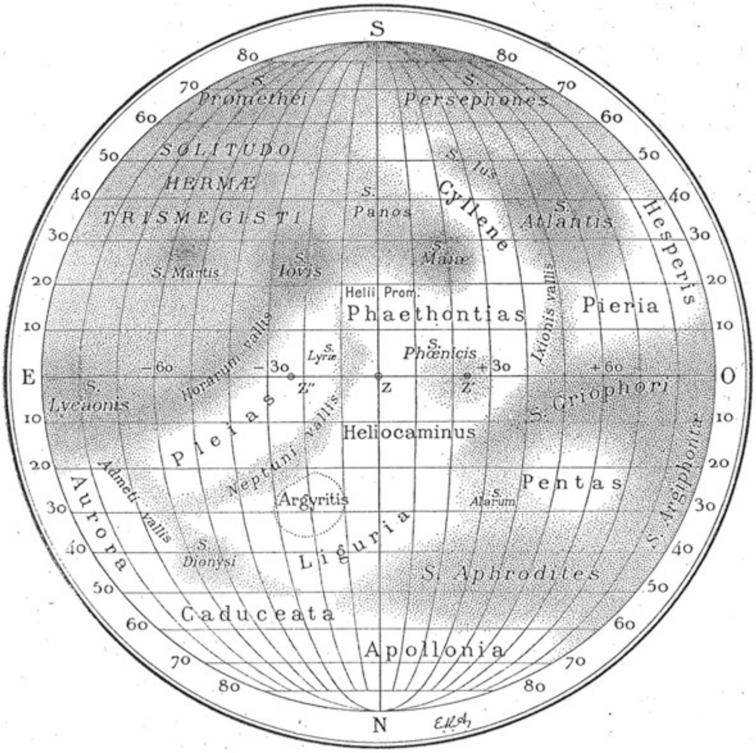


Fig. 6.12 Planisphere of Mercury, showing the 'sunward hemisphere' of the planet. After the observations made between 1924 and 1929 with the 83 cm Grande Lunette of Meudon

However, according to some observations, the regions figured upon the chart seemed absent, as though veiled. Antoniadi formed the impression of an atmosphere, upon Mercury, which carried dust clouds, capable of temporarily masking the configurations of the surface. He develops this conclusion in several papers in *l'Astronomie* [41] and in his summary work *The Planet Mercury and the rotation of the satellites* (*La Planète Mercure et la rotation des satellites*), published in 1934 [42].

In that book, and already in 1929 [43], Antoniadi puts forward a theoretical justification for the synchronism between the diurnal rotation and the orbital revolution. He compares the tidal forces exerted upon Mercury, the Moon and various satellites. The braking force is proportional to the inverse sixth power of the distance from the central body.

The work describes the physical conditions which seem to reign upon the planet. The surface of the planet is thought to be similar to that of the Moon. But the presence of the cloudy veils presupposes an atmosphere in order to carry them: "The most plausible hypothesis is that the veils are due to clouds of extremely fine dust, raised by the violence of the winds and aerial currents ascending above the vast empty regions which encompass the world [44].” “It is impossible for me to allow a significant density to the Mercurian air; this density seems to me only just enough to maintain in suspension the excessively fine dusts raised by the local winds [45].”

The thin atmosphere and the synchronous rotation imply special conditions: “Beneath the central regions of the hemisphere turned towards the radiant Sun, there must occur a continuous rarefaction of the overheated air which ascends in flowing out towards the terminator, going to raise the temperature of the unilluminated hemisphere, which, without that, would be close to absolute zero [. . .] and at the same time, cold air from that hemisphere is drawn closer to the Sun in a convergent manner towards the overheated, low pressure regions [46].”

However, these deductions about Mercury did not hold up to some new analyses. As soon as the work was published, that excellent planetary observer Georges Fournier threw into doubt the 88-day rotation period, which was not found in his personal, very numerous observations of Mercury, made between 1907 and 1927 at the astronomical stations of R. Jarry-Desloges.

Seven years after the publication of Antoniadi’s book, the planetary studies of Meudon would be resumed at the high mountain observatory of Pic du Midi, under much more favourable observing conditions [47]. From 1942 to 1950, Bernard Lyot, Henri Camichel and the present author would photograph the markings upon the surface of Mercury and would observe them with magnifications twice as high as those used at Meudon. Not a single mist or cloud would be discerned. Later, the length of the planet’s rotation would be found to be 58.6 days, or exactly 2/3 of the value of the planet’s year given by Antoniadi.

Guiseppe Colombo, in 1965, then other theorists in celestial mechanics would demonstrate that, because of the great eccentricity of the orbit of Mercury, the tidal theory yielded several solutions for the rotation period of the planet. To the classical result where the rotation equalled the period of revolution, 87.97 days, could be added a solution giving 2/3 of that value, namely 58.65 days. The same year, Gordon Pettengill and Robert Dyce, then others afterwards, came to establish, by sending radar echoes to the planet, a rotation period of 59 ± 3 days. Through confirmation by telescopic observations, the Pic du Midi astronomers were able to give an exact rotation period, namely 58.644 ± 0.009 days. A complete planisphere of the surface of Mercury would be established, covering all longitudes. The nomenclature of Antoniadi would be retained but redistributed to cover the whole surface of the world.

Jupiter, Saturn and Their Satellites (1924–1935)

With Jupiter, Antoniadi made use of the best observing conditions to make drawings of a rare quality (Fig. 6.13). Nine of them can be found in his publications, as well as drawings of particular features (Fig. 6.14). Following two communications to the French Academy of Sciences [48], their author published four accounts of his observations in *l’Astronomie* in 1929 [49].

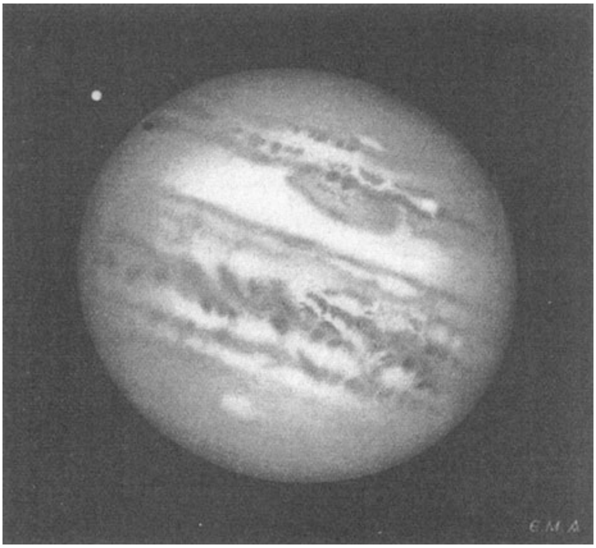


Fig. 6.13 Jupiter on 1927 September 28 at 21 h 22 m. Drawing by E.M. Antoniadi. 83 cm Grande Lunette of Meudon

The study remained morphological and descriptive. The evolution of the cloud structures was documented with reference to the oldest observations. Special attention was given to the changes in aspect of the formation known as the Great Red Spot.

Saturn was equally the attention of high quality drawings (Fig. 6.15). The temporary cloud formations, very rare, were observed (Fig. 6.16). Antoniadi published his results in 1930, in three very scholarly papers in *l'Astronomie* [50]. "The constant cataclysms of which Saturn's atmosphere was the theatre indicate, as with Jupiter, a considerable internal heat. [. . .] We only see, upon Saturn, that the vapours and gases

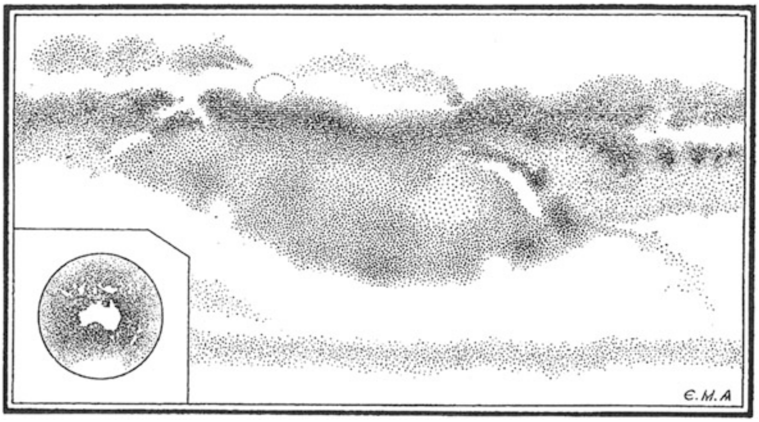


Fig. 6.14 The great red spot of Jupiter, 1927 October 6, 21 h 30 m, showing its irregular appearance and ragged edges. Observation in perfect seeing with a magnification of × 540 with the Grande Lunette

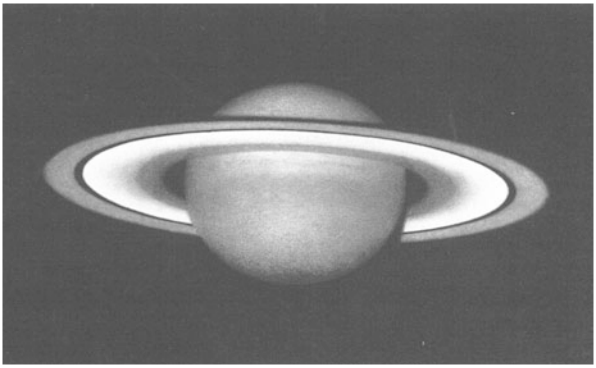


Fig. 6.15 Telescopic aspect of Saturn, 1924 June 2, 22 h 10 m. Drawing by E. M. Antoniadi

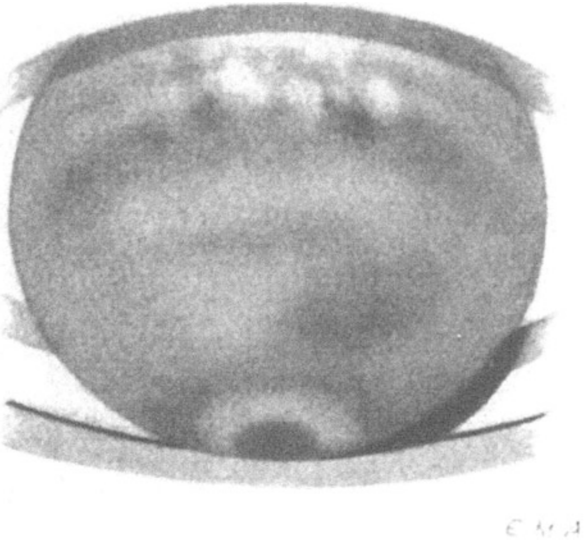


Fig. 6.16 Large irregular dark patch in the N. temperate regions of Saturn, 1927 July 18, 21 h 06 m. Drawing by E. M. Antoniadi

which come from the warm internal parts of the planet in order to cool themselves lose their energy in the upper regions of the atmosphere [51].”

The rings of Saturn were examined attentively [52]. But Antoniadi did not succeed in making out the numerous fine subdivisions which divide the rings, and he denied their existence. It would be necessary to wait for the instruments of Pic du Midi in order to establish their accurate descriptions, by Lyot, in 1945 [53].

On 1936 July 2, with Antoniadi, the Meudon astronomers Fernand Baldet, Henri Grenat and Henri Camichel were able to examine the rings of Saturn exactly edge-on, leaving only a very fine luminous thread [54].

Observations upon the planets Uranus and Venus gave rise to several scholarly summaries in *l’Astronomie* [55].

Io, Europa, Ganymede and Callisto, the four Galilean satellites of Jupiter, appear as very tiny bodies in astronomical telescopes. They were thus very poorly known.

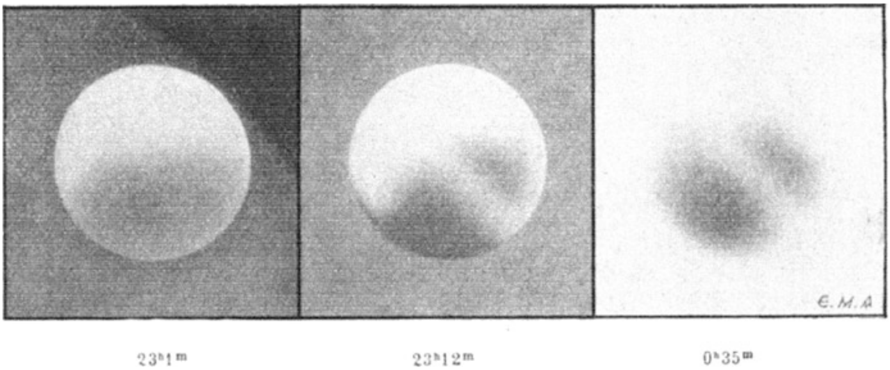


Fig. 6.17 Successive appearances of Ganymede entering into transit against Jupiter, and projected with its brown spots upon the background of the planet, 1927 August 29–30. Drawings by E. M. Antoniadi with the Grande Lunette of Meudon, magnification × 640

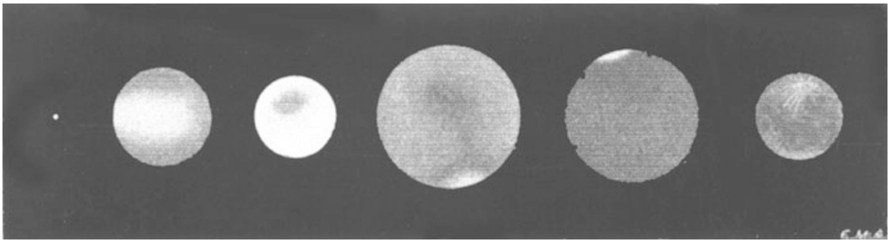


Fig. 6.18 Comparative sizes of the satellites of Jupiter and the Moon. From *left* to *right*: the 5th satellite, discovered by Barnard, Io, Europa, Ganymede, Callisto and the Moon

The Grande Lunette of Meudon reveals markings upon their tiny globes, essentially at the times when they are passing in front of Jupiter, when the bright background of the planet makes the perception of details easier (Fig. 6.17). Against the blackness of the night sky, Antoniadi was able only rarely to make out their faint patches with certainty [56].

Their dimensions, appearances and brightnesses of the four satellites were compared with each other and with the Moon (Fig. 6.18):

For the first satellite: “On every occasion when that satellite was observed in the great equatorial passing in front of the planet, it showed the two grey patches reported by Barnard, one towards each pole, separated by a lighter region. From this very remarkable invariability in aspect at inferior conjunction, we deduce a period of rotation equal to that of the revolution [57].”

For the second satellite Europa: “The yellowish surface of this satellite has an extraordinary brightness which approaches that of snow.”

For the third satellite Ganymede: “Our observations from Meudon have revealed the existence of two permanent brownish markings upon the third satellite passing in front of Jupiter. [. . .] These aspects clearly show that this body always shows the same face to the planet [58].”

About the fourth satellite, Callisto, whose albedo is 0.16, and much darker: “The albedo variations as it leaves the disk [of Jupiter] tends to indicate a rotation period different from its revolution period, unless they are due to an unlikely atmospheric cause [59].”

In 1941, planetary researches would be resumed at Pic du Midi under much more favourable skies. B. Lyot, H. Camichel and M. Gentili would regularly observe details upon each of the four satellites. A complete planisphere of the markings was drawn up for each of the satellites, After 1943, A. Dollfus and J. B. Murray would considerably improve these charts. Very fine measurements of their diameters would give the densities of these bodies with the precision necessary to understand their internal structures [60].

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Chapter 7
The Polarisation of Light (1924 to 1929)

The Technique of Polarimetry

In 1924, after the close of the work which had tied up the Grande Lunette while Antoniadi had restarted his visual planetary observations, Bernard Lyot (1897–1952) set out upon an innovative line of planetary research. He planned to analyse the polarisation of light coming from the planets.

By means of his originality, his ingenuity and his results, polarimetric analysis of planetary surfaces with the Grande Lunette would show itself to be a notable contribution to the astronomical knowledge of that time. The simultaneous use of the Grande Lunette by Eugène-Michael Antoniadi for visual observation and by Bernard Lyot for polarimetric analysis elevated French planetary astronomy to new heights, opening the way to the discipline which would later become planetary physics.

Polarimetric examination focuses upon the manner in which light vibrates, after having been returned by reflection upon a planetary body. The light which initially illuminates the planet is provided by the Sun, and is propagated by transverse vibrations in every direction, with the result that no particular direction is preferred to any other and there is an overall symmetry. But, after having returned from the planet, the perfect symmetry is not necessarily preserved. Certain vibrations are advantaged in the processes of reflection, with the result that a small proportion of the reflected light vibrates transversely in a privileged way. It is said that this light is *polarised.*

It is known that the proportion of polarised light depends upon the nature of the body upon which the light is reflected. A smooth and polished body produces a strong polarisation is certain directions, while a matt surface gives a much weaker effect, and with a different distribution. An absorbent material polarises much more strongly than a transparent one. Coarse sand will differ from a fine powder. Thus, from afar, one can distinguish the nature of the surface concerned.

Likewise, an ice crystal cloud produces a polarisation very different from a solid body. The particles of a fog give other effects, for which the diameters of the droplets are a determining factor.

In 1922, Lyot had designed a small instrument, the *fringe polarimeter*, which had a remarkable degree of precision. The instrument, built by the designer himself, can

A. Dollfus, *The Great Refractor of Meudon Observatory,*
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_7, © Springer Science+Business Media New York 2013

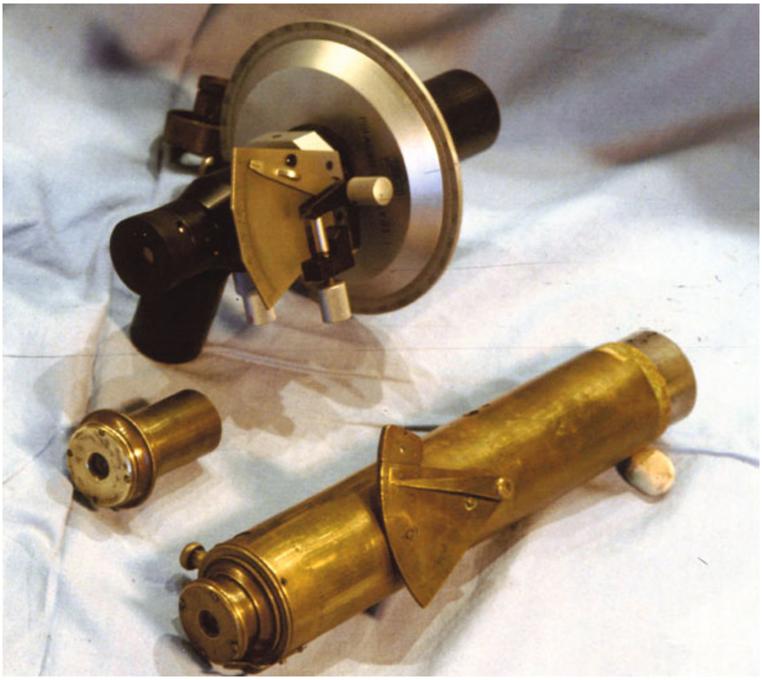

Fig. 7.1 Lyot's visual fringe polarimeter. In the foreground, the prototype of Lyot's apparatus together with its polariscopic eyepiece, used with the Grande Lunette by its creator from 1924 to 1928. In the background, the version of the instrument made by the société Jobin and Yvon, used with the Grande Lunette by J. Focas and A. Dollfus from 1965 to 1969, then by S. Ebisawa from 1973 to 1980

be seen in Fig. 7.1, alongside the commercial instrument of 40 years later with which different observatories were equipped.

Behind a refractor pointed at a planet, the apparatus produces jagged fringes covering the whole of the disk of the planet. The contrast of these fringes is all the more apparent than the planet's light, and is more strongly polarised. Following this optical device, a polarisation compensator is interposed, made from a thin slice of glass inclined at an angle in the field of view. The instrument produces a known polarisation which increases with increasing angle of inclination. A small lever allows the angle to be adjusted in order to produce the exact degree of compensation for the planetary polarisation being measured, demonstrated by the disappearance of the fringes.

To improve the sensitivity, Lyot added an auxiliary system of low contrast fringes produced by a second slice of inclined glass which could be in either of two positions. For one position, the fringes produced by the planet add to the contrast. For the other, the planetary fringes are overlapped and diminished in contrast. The exact compensation is apparent when the fringes are equal in both positions, a much more sensitive criterion than the disappearance of the fringes.

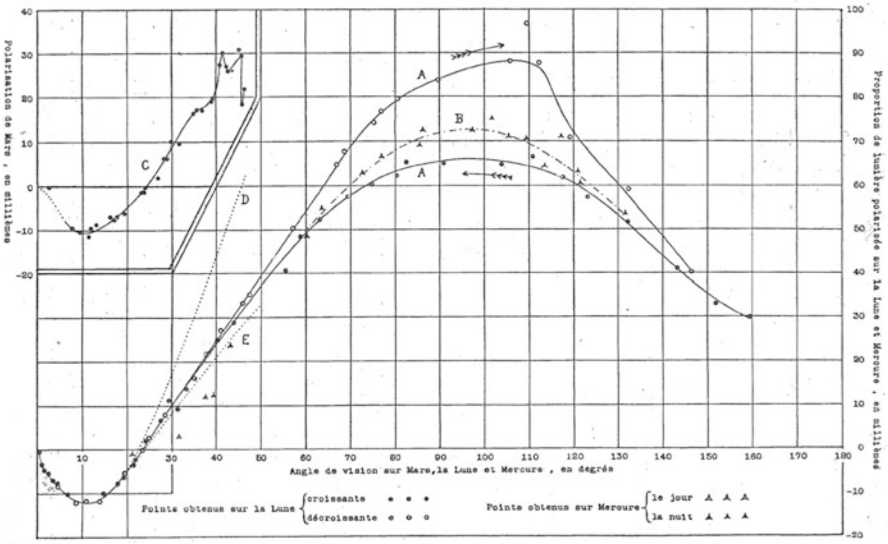

Fig. 7.2 Polarisation of the light of the Moon. Mercury and Mars. Horizontal axis: phase angle in degrees; vertical axis: the proportion of polarised light, in thousandths. Curve A: the Moon (whole-disk), for the waxing and waning phases. Curve B: Mercury (equatorial region). Curve C: Mars (disk centre)

With that instrument, the observer can determine very small degrees of polarisation, to the precision of one part in a thousand. A small refractor yields a polarisation value for the whole planetary disk. With the Grande Lunette of Meudon, the polarisation of different parts of the image can be determined.

From 1922 July, Lyot had determined the polarisation of the whole Moon, on numerous occasions and under all of its phases. He had established the relationship between the proportion of polarised light and the phase angle, producing the polarisation curve of Fig. 7.2. The comparative measurements carried out upon different types of surfaces had given a first important conclusion: “The Moon should be covered nearly completely by dusts having a composition similar to that of our terrestrial volcanic ashes [1].”

These first measures had been carried out with a small 175 mm refractor. Now Lyot was able to use the great 83 cm instrument of Meudon. He made measurements for the Moon and for the planets Mercury, Venus, Mars, Jupiter and Saturn and its rings. He could even analyse the polarisation in detail upon the different regions of the image seen with the instrument.

In 1929, after having announced his results in a series of notes to the French Academy of Sciences, Lyot summarised his researches in a unique Memoir which constituted his Doctoral Thesis [2].

The Polarisation of Mercury

The planet Mercury, like the Moon, offers the terrestrial observer a full range of phase angles, allowing the construction of a complete polarisation curve and for the precise characterisation of the nature of its surface.

For small phase angles, as with the large ones, Mercury is viewed in the sky at only a small separation from the Sun. One has to observe in full daylight, compensating for the polarisation of sunlight produced by the blue sky and guarding against light scattered by the telescope objective illuminated by the Sun. Lyot then used a small refractor, extended by a series of screens throwing their shadow upon the objective. Eleven observations of Mercury were thus made.

The determinations are represented by triangles in Fig. 7.2 and they define the curve labelled B, closely similar to the average curve of the Moon. "It is therefore very probable that the surface of Mercury has the same composition as that of the Moon [3]."

The discussion of the measurements brings another conclusion: "If the composition of the atmosphere of Mercury possesses a composition analogous to that of our air, its density cannot exceed 21 thousandths of that of the Earth's atmosphere [4]."

Antoniadi, we have seen, had reported observing clouds capable of masking certain regions of the planet Mercury. According to the polarimetry: "The regularity of the variations undergone by the polarisation of Mercury and the perfect similarity of these phenomenon with those of the Moon, tend to prove that no significant part of the surface of Mercury had been covered by clouds comparable with those of the Earth during the series of measures made upon that planet. [. . .] The presence of a very tiny and very transparent nebulosity, formed by droplets analogous to those of our clouds, is enough to sensibly deform the polarisation curve of Mercury [5]."

These precursory results have been greatly developed subsequently. In 1950, Audouin Dollfus would obtain at the Pic du Midi numerous polarisation measures covering different regions of the planetary surface. No trace of polarisation attributable to veils or clouds would be detected. From Meudon, the polarimetric measurements in five wavelengths of light would confirm the great similarity between the surfaces of Mercury and the Moon. They would fix the upper limit of a hypothetical Mercurian atmosphere at 10^{-4} bar [6].

The Polarisation of Mars

The planet Mars cannot be viewed from the Earth under a phase angle of less than 47°. Only the initial portion of the polarisation curve is accessible to telescopic observation.

In 1922, thirty two whole-disk observations with the small refractor had given Lyot the branch labelled curve C in Fig. 7.3. The measures from 1924–1925 and those from 1926 had given the same result. The comparison between that curve with

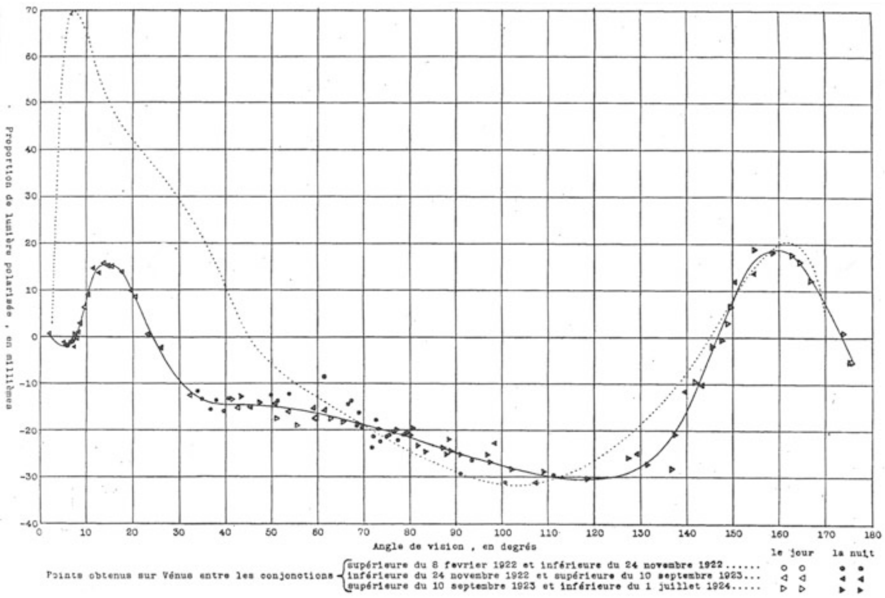

Fig. 7.3 Polarisation of the light of Venus (equatorial region), orange filter. Horizontal axis: phase angle, in degrees; vertical axis: the proportion of polarised light, in thousandths

that of the Moon showed that the polarisation of the Martian surface varied like that of our satellite [7].

With the Grande Lunette, the measures permitted examination of the polarisation of different regions of the planetary disk. Between 1924 April and 1926 December, forty-three observing sessions were carried out. Comparing the light regions, called ‘continents’, with the dark markings, designated ‘seas’: “Things happen as though there existed, upon the surface of the martian continents, a dust analogous to that which must cover the lands of the Moon. [. . .] The constitution of the seas is more difficult to assess. [. . .] Their polarisation differs little from the continents. Perhaps they possess a vegetation too sparse to hide the ground [8].”

In 1924 December, Lyot discovered a dust veil in the atmosphere of the planet: “On December 19, recommencing observations following several days of bad weather, I found Mars veiled by a thick cloud of a yellowish tint, making it difficult to distinguish the seas which were, in contrast, dark during the preceding observations. The polarisation only showed 9 thousandths (against 26 thousandths which is the norm under this phase angle). The thick veil persisted one month at all longitudes, while the polarisation increased slowly and irregularly. On January 18, I saw the reappearance of details again veiled by a thin cloud, while the polarisation suffered a slight decrease [9].”

The planet also revealed scattered white clouds, which, in contrast to the yellow dust clouds, showed strong polarisation: “The observations showed that the white areas have a different composition from the yellow clouds; they should float in the atmosphere of Mars at a greater height, since they remained visible during the great atmospheric disturbance [10].”

Polarimetric analysis again allows crystal clouds to be distinguished from a frost deposit on the surface: “Certain white areas apparent at the morning limb [. . .] could be composed of transparent particles, such as hoar frost, since, examined very obliquely they show, alike terrestrial snow, a very strong polarisation by refraction. Clouds do not give any polarisation under these conditions [11].”

All these results, completely new, would serve as the foundation for the very detailed polarimetric studies of Mars developed later, from the observatories of Meudon, Pic du Midi, Athens and Tokyo. They would result in numerous details concerning the physical properties of the surface of the planet, its atmosphere and its clouds [12].”

The Polarisation of Venus

Venus, like Mercury and the Moon, can be viewed from the Earth under all phase angles. In the course of eleven observing sessions, Lyot composed a complete polarisation curve, in orange light, for the equatorial regions (Fig. 7.3).

> Around greatest elongation, the measures were nearly always made at night, in preference with the Grande Lunette. To the contrary, when Venus was close to the Sun, I observed by day, with the small 175 mm refractor equipped with the apparatus designed to compensate for atmospheric polarisation. [13]

The large instrument lends itself to individual study of different regions of the crescent of Venus: “The polarisation was not, in general, quite uniform and its irregularities changed in the course of several days. [. . .] Under a phase angle of 89°, [. . .] the plane of polarisation turned towards the points of the cusps, in the inverse sense of the radius of the planet. [. . .] That deviation in the cusps was accompanied by alterations in the proportion of polarised light [14].”

The polarisation curve of Venus reveals itself to be totally different from those given by solid surfaces. Polarimetric analyses upon droplets, aerosols and colloidal solutions, conducted in the laboratory at Meudon allows the conclusion: “The polarisation of Venus appears to be essentially that of opaque clouds in whose highest strata will form very fine droplets, a little larger than 2 microns (2 μm) in diameter and whose [refractive] index will be in the region of that of water [15].”

Later, the polarimetric studies upon Venus taken up at Meudon and at the Pic du Midi since 1950, and then from the United States, would enable the extension of the measurements into the infrared and ultraviolet for nine different wavelengths [16]. The theory of Mie scattering, applied by J. Hansen and V. Hovenier, would reveal the nature of these clouds: spherical, transparent particles of 1.05 μm radius, of which the refractive index of 1.44 is compatible with droplets of sulphuric acid.

The Polarisation of Jupiter

To analyse Jupiter by polarimetry, Lyot made profitable use of the Grande Lunette on twenty-seven occasions, between 1924 and 1926. These sessions had been preceded by nineteen whole-disk determinations with the 175 mm refractor in 1922. Only the initial branch of the polarisation curve is accessible to observation. It is limited to phase angles less than 12° and deviates from those curves derived from solid surfaces.

The disk of Jupiter shows dark belts and light zones. The Grande Lunette allowed these regions to be analysed separately. Their polarisations, often identical, increased only slightly towards the east and west limbs: "The cloud belts are therefore not surrounded by a thick atmosphere."

On the contrary, in the polar regions, the polarisation was found to reach a maximum at the poles and to decrease steadily towards the equator. In moving away from the [planet's central] meridian, the polarisation remained radial with respect to the limb: "The curious polarisation which is shown by the polar regions agrees very well with the presence beneath the clouds of a thick or strongly diffusing atmosphere. The atmosphere will be progressively veiled towards the equator, and this will bring about the observed decrease in the polarisation [17]."

The Polarisation of Saturn and its Rings

The short portion of the polarisation curve accessible to observations departs from that of the Moon, of Venus and of Jupiter. To describe the polarisation upon the disk and the rings, Lyot made use of the Grande Lunette on thirty-five occasions, from 1924–1927.

> The polar regions of Saturn presented phenomena quite similar to those which I have described for Jupiter, but much less constant, their extent and intensity being subjected to parallel, very significant variations. [18]

The rings were first measured in their entirety, in the region of each of the two ansae (eighteen times in 1924 and 1925, using the Grande Lunette). Then, from 1925 May and until the end of 1927, separate measurements were made upon the exterior [A] and interior [B] rings.

> The curve of the interior ring is similar to that of a number of unpowdered minerals. [. . .] On the other hand this curve greatly differs from those of pulverised lavas and ashes. It therefore seems, in consequence, that the interior bright ring is not composed of fine powder, but rather of larger blocks. [19]

For the exterior ring, the polarisation revealed itself to be complex and variable. After having mentioned the effects of illumination of the rings by the globe of Saturn, or even the alignments of the blocks within the ring, Lyot had to conclude: "The exterior ring of Saturn thus seems to be the site of phenomena which remain very mysterious [20]."

Photometric analysis of the rings of Saturn would not be taken up again until 1950 by A. Dollfus with the instruments of Pic du Midi [21]. The interior ring would exhibit a radial and variable component of the polarisation, characteristic of temporary alignments of particles or the wakes of particles. The exterior ring would show local and variable concentrations of polarised light, suggesting active processes of accretion and of disintegration of conglomerates of particles, stretched out in filaments.

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Chapter 8
Stellar Explosions and High Magnifications (1935–1955)

Nova Herculis (1935–1936)

On 1934 December 13, at 4.30 am, the English amateur Prentice discovered from Stowmarket a star of magnitude 3.4 in the constellation of Hercules, previously invisible to the naked eye.

Henri Camichel (1907–2003), a young astronomer having begun his career at the Paris Observatory, had moved to Meudon in 1933 and was attached to the Solar Department. In 1935 January, while he was on holiday, a letter from Charles Bertaud (1904–1982), an equally young astronomer at Meudon, informed him of the discovery of Nova Herculis and hurried him to obtain spectra with the Grande Lunette.

Once back at Meudon, Camichel found the parts of an old spectrograph, dismounted and incomplete, dating from the time of Deslandres and designed for the Grande Lunette. He brought it into use.

The instrument allowed two optical combinations. The 55 cm focus collimator leads either to two flint glass prisms in a 60 cm chamber, or to three prisms in a 31 cm chamber, the latter giving less dispersion but higher resolution (Fig. 8.1).

Long duration exposures were necessary. To help obtain them, Camichel began by improving the conditions under which the great equatorial was used:

> At the beginning, the Park keepers were employed as assistants in the dome. One of them, with whom I had been on rather bad terms, was nevertheless quite happy to come to work for the modest supplement he earned. [1]

The long periods of successive photographic exposures, often more than an hour each, nevertheless gave such uncertain returns:

> I replaced the weights acting upon the Foucault regulator (which had to be wound up at the crank) by an electric motor. I had introduced a noisy system and an unlikely one for a good mechanic, which enabled the drive sector to be brought back into position by means of an electromagnet. [. . .] The hand controls had to be replaced by electric motors. [. . .] After all these improvements, I could arrive just a quarter of an hour before the observation and work without a single assistant. [2]

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_8,

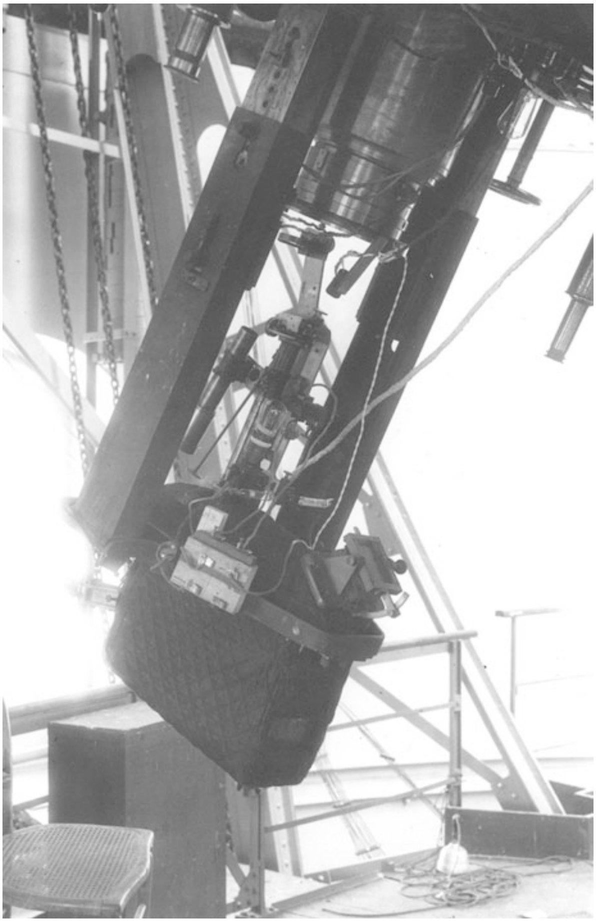

Fig. 8.1 Henri Camichel's spectrograph mounted upon the Grande Lunette in 1935

The first spectrum of Nova Herculis was obtained on 1935 March 7 with an exposure of a quarter of an hour, upon an Ilford hypersensitive panchromatic plate (Figs. 8.2 and 8.3). The magnitude was 4.1 and it remained at that value until March 30. Then, suddenly the brightness faded, making new spectra necessary.

Between March 7 and 30, eight favourable nights produced 32 spectra, some of which were exposed for up to nearly two hours. The exposures were generally made in two parts, with a short interruption for returning the telescope's toothed driving sector to its initial position and to adjust the settings. For a total of eight nights of observation, the total exposure time exceeded 22 hours.

Each spectrum covered the wavelength range 485 nm to 660 nm, with a dispersion much greater than the spectra of Deslandres. At the start of March, the spectra showed a background continuum with numerous emission lines, of which there were the red Hα and the blue Hβ of hydrogen, 12 lines of FeII, NII and OI and some unidentified groups of lines (Fig. 8.3). All the emission lines were broadened with two closely

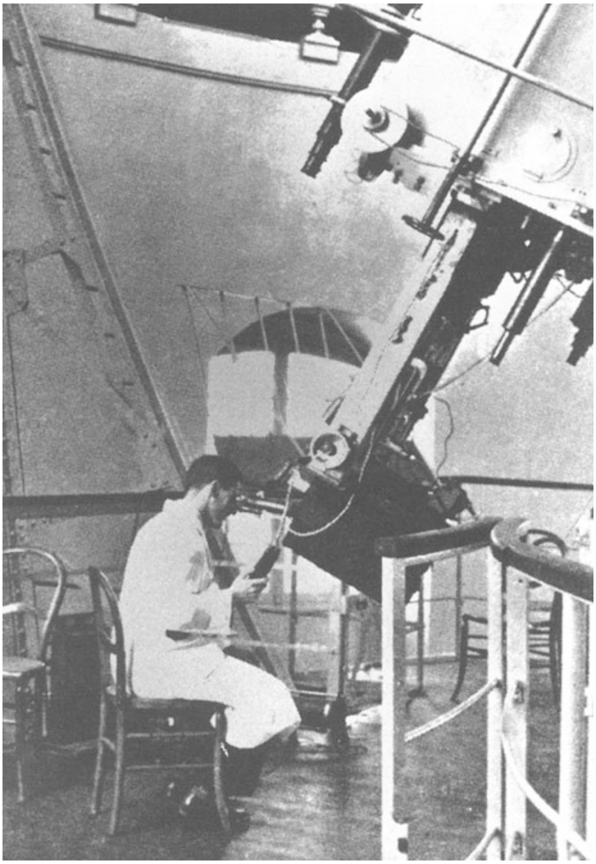

Fig. 8.2 Henri Camichel upon the platform of the Grande Lunette, collecting spectra of Nova Herculis in 1935

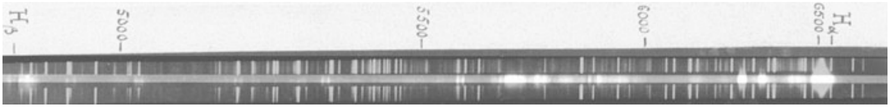

Fig. 8.3 Spectrum of Nova Herculis obtained by Henri Camichel in 1935 March. The spectrum of the star is framed on either side by comparison spectra. *Above*, wavelength in Angström units

equal maxima, symmetrical with respect to the normal position. Their separation corresponded to radial velocities from 590 to 870 km/sec.

After March 30, the star having become too faint, the spectrograph was dismounted to free up the telescope. On July 4, the Lick Observatory announced an astonishing result: the star looked double. Straight away the Meudon refractor was put to profitable use. On 1935 July 23 and 24, Fernand Baldet, with very considerable magnifications of 1,600 and 2,300, saw the star double. The two components had the same colour and were very close, separated by only 0.25 arcseconds. No trace of nebulosity could be suspected around the pair [3]. On August 6, Charles

Bertaud added confirmation. On October 12, Henri Camichel in his turn saw the star as double. In December it looked the same.

Meanwhile, at the end of April, the brightness, which had descended to magnitude 13, began to increase. Towards the end of August, the magnitude stabilised around 6.5. Spectra could be newly attempted. Between 1935 September 3 and 1936 June 15, Camichel made 20 spectra of the nova, amongst which were added control spectra of the star P Cygni. The duration of exposure was often around two hours, but nobody gave up. On March 17, a spectrum was exposed for four hours.

These new spectra demonstrated that the nova had reached a new phase in its evolution. The spectrum, indeed, had come to resemble that observed for the nebulae. From its initial state, it remained the Hα hydrogen line and the NII emission line at 575.5 nm. Now were added two green emission lines of wavelength 500.7 nm and 495.0 nm characteristic of nebulae. All these emissions remained broadened, doubled, and asymmetrical.

Even before the end of this considerable volume of observational work, Camichel presented his conclusions through Ernest Esclangon to the French Academy of Sciences at its meeting of 1936 January 27:

> One can account for the particulars of the spectra by supposing that the star, at the moment of its peak brightness, ejected gaseous masses which were illuminated according to the excitation mechanism for planetary nebulae [. . .] If the material was arranged in homogenous spherical layers, the emission lines must be symmetrically broadened with respect to their normal positions, and must have a constant intensity, which is not the case for Nova Herculis. One could explain the doubling of the emission lines in terms of two very large masses moving in opposite directions. That hypothesis seems to be confirmed by the fact that the star was seen to be double. [4]

Nova Lacertae (1936)

A little later, on 1936 June 18, came Nova Lacertae. Discovered at 11.00 UT by K. Gomi of Horonobe, Japan, the star was of magnitude 3.5 and its brightness increased rapidly.

Camichel immediately abandoned Nova Herculis, which was becoming very faint and whose last spectrum had been taken three days earlier. The first exposure upon Nova Lacertae, obtained on June 19 at 23.40 UT, gave the spectrum 36 hours after discovery. The brightness had already reached magnitude 2.0, nearly its maximum. The Hα line was in emission, bordered by a wide, intense absorption band, towards the violet end of the spectrum. The other lines were fine, and in absorption.

Then the brightness diminished rapidly. Spectra were taken up until July 9; the magnitude had already fallen to 6.0 and the star had become very faint. In all, 25 spectra were obtained, during 11 favourable nights. The first spectra were exposed for several minutes; the last ones, up to an hour and a half.

The absorption lines had disappeared. Nine emission lines had appeared, forming wide bands. From the last spectrum, the Nova was approaching the nebular phase. The greater part of the light emitted was in the Hydrogen alpha, while the continuum was no longer detectable: one could not yet see the green emission lines, characteristic of the nebulae.

Camichel's results were presented to the French Academy of Sciences on 1936 November 30 with the following conclusion: 'Nova Lacertae was clearly of a different type to that of N. Herculis; its light curve was of the rapid evolution type, its emission lines were broad and ill-defined, it showed the lines of interstellar sodium [5].

Upon the publication of this work in 1936 November, Camichel was appointed to the Pic du Midi Observatory to the post of physicist left vacant by the dramatic disappearance of Pierre Devaux by the shipwreck of the polar exploration vessel *Pourquoi Pas?* He left Meudon and hence the use of the Grande Lunette. His new research would concern the planets.

High Resolution Observations

From 1932 onwards, for stellar, cometary and planetary studies the Meudon Observatory had the use of a new astronomical installation known as the *table équatorial* (equatorial table), equipped with a 32 cm refractor, several photographic utensils and a spectrograph with a large objective prism. The instrument would be used essentially by Fernand Baldet and Charles Bertaud.

The Observatory also had the Eichens equatorial, housed in one of the two 7.5 m diameter domes in the region of the Park. The mounting carried a refractor and several spectrographs most notably used by Charles Bertaud. The other dome housed the large 1 m reflector of Janssen, then used by Bernard Lyot for the polarimetry of asteroids.

The main work was done with these instruments. But the Grande Lunette continued to offer, by means of its aperture and quality, a remarkably fine image quality. It allowed visual scrutiny with very high magnifications, each time it was necessary.

Thus we have seen above the practical value of the detection of the splitting of Nova Herculis on 1935 July 23 and 24. Here is another example, presented by Baldet to the French Academy of Sciences on 1930 June 16:

> I called attention to the exceptional interest which would be presented by telescopic observation of the nuclei of comets with large instruments, at high resolution, when one of these bodies came to approach the Earth sufficiently closely. The true solid nucleus which follows the Keplerian orbit and from which escapes the gases forming the comet, is indeed nearly always unobservable because it is mixed up with the luminous gases that surround it. [...] That nucleus too can be assigned a diameter from dozens, hundreds or even thousands of kilometres. [...] Now the new Comet Schwassmann-Wachmann (1930d) [...] passed by on 1930 May 30 at 0.0565 AU (8,450,000 km) from us, and I was able to observe it visually with the 0.83 m Grande Lunette of Meudon. [...] The gaseous head had the aspect of a diffuse nebulosity, slightly elliptical, 3–4 arcmin to 2–3 arcmin in size (1 arcmin = 2,460 km). [...] On several occasions, in better seeing, I nevertheless had the impression of a single stellar point, about 0.5 arcsec across, in the centre of the gaseous head. [...] Thus, in summary, the nucleus of Comet Schwassmann-Wachmann does not seem to have a diameter sensibly greater than 400 metres. [6]

The discovery of the very small dimension of cometary nuclei, of which we now know the importance, would be confirmed on 1936 August 3, again by the Grande Lunette, at the time of the passage of Comet Peltier (1936a), in close proximity to the Earth: “For a moment there could be seen a tiny stellar nucleus, pointlike, scintillating, at the limit of visibility. It was situated in the middle of a central gaseous condensation, circular and shaded off. [. . .] One might accept 11 for its magnitude [7].”

The refractor was also used to confirm the duplicity of stars reported as being double, but uncertainly so, with less powerful instruments. Baldet often noted the very favourable circumstances of the observations.

The ring system surrounding the planet Saturn is presented to the Earth under a varying inclination. The angle changes slowly, diminishing, becomes zero, then the rings progressively open out upon the opposite face. On 1936 June 29, the sheet of material was viewed precisely edge-on. The occasion is short-lived and occurs every 14 years. It allows an appreciation of the thickness of the rings, the flatness of their surfaces, and the condensations in their structures. Few good observations had been made in the past. From Meudon, during the night of 1936 July 1–2, very favourable sky conditions were encountered. The astronomers of the Observatory, Henri Camichel, Eugène-Michel Antoniadi and Henri Grenat (1900–1969) viewed the rings “reduced to an extremely fine line”, demonstrating the thinness of the ring-plane. The line “extended further to the west than to the east”, indicating a slight deviation in the flatness of the great disk of ring particles [8].”

Six months later, during the night of December 28–29, it was Sun’s turn to lie in the plane of the rings. The sheet of material was lit up like a thread. On December 19, again under nearly grazing illumination, Fernand Baldet was joined at the eyepiece by Charles Bertaud, Eugène-Michel Antoniadi and Marguerite d’Azambuja (1897–1985). The observers wrote: “Images exceptionally calm. Magnification 800. Rings dark grey, very narrow, very delicate in the ansae, without a trace of beads of light. All of us applied ourselves to looking for them under the same favourable conditions but without any success [9].”

Monitoring the Surface of Mars (1931–1942)

In his work *La Planète Mars* published in 1930 [10], Antoniadi had gathered the main part of his conclusions from his observations of Mars with the Grande Lunette. He had confronted those conclusions with the hypothesis of vegetation upon the planet’s surface, and could not exclude it. He had stated that the planet’s atmosphere, tenuous and transparent, had carried infrequent clouds, as well as raising dust clouds.

Subsequently, the planet would continue to be the object of a monitoring programme with the Grande Lunette, in order to document the changes taking place upon the surface as well as in its atmosphere. These observations, consigned to the Observatory logbooks, supplied the long-term database concerning the planet.

The approaches of Mars to the Earth happened close to once in every 26 months. That of 1931 January was not very favourable, the planet then exhibiting an apparent diameter not exceeding 14.4 arcseconds. The following approach, in 1933 March, was still more distant, the diameter not exceeding 13.9 arcseconds. The next one, in 1935 April, a little better, reached 15.1 arcseconds. Throughout these oppositions, Antoniadi and Baldet carried out a survey with the Grande Lunette and published their results in the magazine, *l'Astronomie* [11].

Then the approaches would become more favourable. In 1937, the diameter reached 18.4 arcseconds. Baldet followed the planet regularly. Between May 25 and Jul 4, 15 excellent drawings were made, with particular attention given to variations in colours.

A really favourable approach of the planet arose in 1939 July with a diameter of 24.1 arcseconds. But the declaration of War and the general mobilisation didn't allow use to be made of it. The following opposition, in 1941, was nearly as favourable, and the planet's diameter reached 22.8 arcseconds at the beginning of October. In spite of the limitations imposed by the War, Roger Servajean (1913–1986), a young astronomer at the Observatory, together with Baldet and Antoniadi managed to carry out a rigorous surveillance.

Twelve drawings were turned out first in the course of 11 nights with the 32 cm refractor of the *table équatorial*. Then the observations were transferred to the Grande Lunette. From September 3 till 1942 January 12, 14 favourable nights yielded 22 accurate drawings of the whole disk and of particular regions (Fig. 8.4). At the time of the final observations, Servajean noted a dust veil hiding part of the surface markings.

The observations would be analysed within the scope of the great campaign of planetary studies carried out since 1941 from the summit of the Pic du Midi Observatory, by Bernard Lyot and then his co-workers. Beneath the pure and stable skies of that altitude, planetary studies from the Pic du Midi would be carried out, with the help of the Meudon Grande Lunette, during the 32 years which would follow, up to the advent of spacecraft for planetary explorations [12].

The Grande Lunette During and After the War (1942–1945)

In observing book No. 4, under the date 1942 September 18, one can read, in Fernand Baldet's handwriting: "The DCA (Défense Contre Avion, or anti-aircraft battery) was set up around the Observatory and upon the main terrace. We dismounted the objective of the Grande Lunette with MM. Brébion (chief mechanic), Oberlin (assistant to Bernard Lyot), Chaudot, Monfort, Gaucher (technicians). Placed in its box and deposited in the safety of the cellars of the chateau."

Then in 1945, on December 28, peace having returned, with Baldet, Bertaud, Servajean and Oberlin (assistant to Lyot): "The 83 cm objective having been remounted, we tested the driving mechanism. The 120 volt electricity supply line is cut. The telescope is positioned manually. The instrument tracked very well during about half an hour. Observed the Orion nebula and θ Orionis."

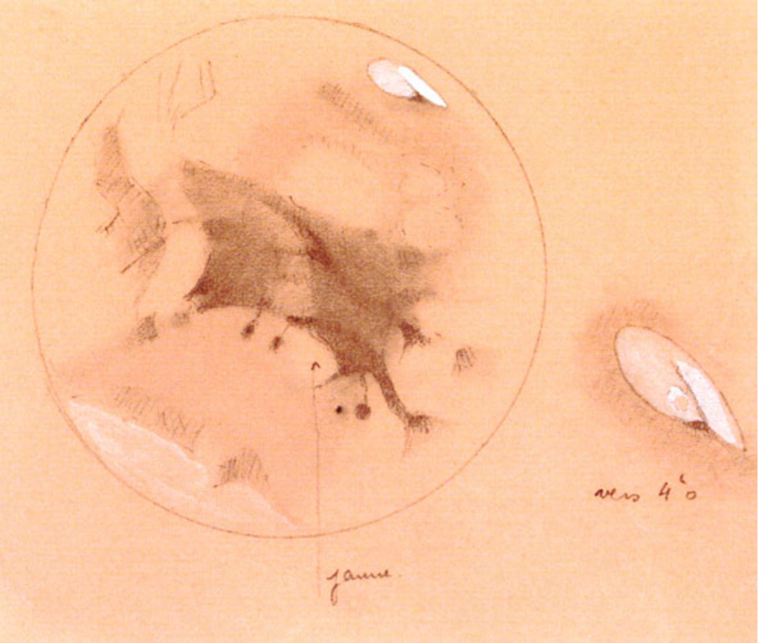

Fig. 8.4 The martian surface on 1941 September 24, between 01 h 20 m and 02 h 20 m. Drawing by Roger Servajean. The Grande Lunette was equipped with a × 460 eyepiece. "Around 2 h 15 m, I suddenly noticed in the Ganges or certainly upon its eastern border at Juventae Fons a black point without appreciable dimensions [. . . .]. M. Baldet saw it after several moments under unsteady seeing [. . . .]. M. Antoniadi saw it afterwards"

The first years after the War at Meudon necessitated a reorganisation, with the small means available. The Grande Lunette was not one of the priorities. In its existing condition it met various demands.

From 1946 to 1950, Bernard Lyot with Audouin Dollfus carried out some observations and test experiments, to accompany the developments in planetary physics at Pic du Midi. Madame Renée Herman (1908–1992), a spectroscopist who had entered the Observatory in 1946, replaced at the focus of the great refractor the spectrograph formerly used by Henri Camichel for the study of Novae Herculis and Lacertae.

Then, for the needs of stellar spectroscopy, new resources allowed the construction of a special 60 cm reflector with optics by Jean Texereau. The telescope would be brought into operation in the Park in 1950, under the dome of the old Eichens equatorial, and equipped by Madame Herman with two spectroscopes. The Grande Lunette would not be used again for spectroscopy.

Two astronomers from the British Astronomical Association, Patrick Moore and H. Percy Wilkins, preparing an Atlas of the Moon came to stay at Meudon in 1952 in order to check, upon the Moon with the Grande Lunette, some of their maps which would be published in their work entitled *The Moon* [13].

Fig. 8.5 The basket and telescope of the balloon of Audouin Dollfus, hanging from the moving platform in the dome of the Grande Lunette in 1956. The refracting telescope was adjusted under the basket and the take-off manoeuvre repeated by elevating the platform by electrical means. At the *bottom*, the British astronomers Donald Blackwell and David Dewhirst

In 1956, the equipment of the Grande Lunette's dome served an astronomical cause of another sort. Audouin Dollfus and two British astronomers, Donald Blackwell and David Dewhirst, in order to define the mode of transfer of heat across the solar photosphere, needed to make very high resolution photographs of the Sun's surface. They would take them at high altitude from a balloon. The moving floor of the great equatorial allowed the balloon's basket to be suspended in order to practise the tricky adjustment of the astronomical telescope beneath the cockpit (Fig. 8.5). The vertical movement of the platform, operated electrically, allowed the ground crew to repeat the delicate procedure for stowing the instrument beneath the basket at the moment of launch.

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Chapter 9
Double Stars and the Return to Planetary Studies (1956–1973)

Paul Muller and Double Stars

In 1956, as we have seen, Paul Muller, an astronomer from Strasbourg Observatory had been appointed to Meudon with the task of modifying the Grande Lunette for double star work, and to carry out the necessary changes. Paul Muller took up his post in April, removing the 83 cm objective lens in order for it to be examined by André Couder and Jean Texereau in the optical laboratory of Paris Observatory, and to improve the lens cell. He remounted the objective in 1957 March and carried out technical observations to define the improvements made to the telescope and dome.

These modifications consisted of the replacement of the mobile observing platform by a moving floor covering the entire surface of the dome. The huge space beneath the dome would be partitioned and fitted out with offices and laboratories. The works were completed in 1964 and observations restarted with the new layout at the end of the year [1].

It was known at the time that the modifications made to the building had the effect of improving the quality of the images in the refractor. According to Paul Muller: "The act of reducing the interior volume of the dome by a thickness of more than four metres in height, separated by a slab designed for good thermal insulation [. . . .] was a favourable factor. Not only was the volume of air which had to be exchanged with the exterior smaller (3500 m^3 instead of 4500 m^3), but the moving platform in the act of its motions worked like a broad vertical piston for hastening that [thermal] equilibrium [2]."

The mode of operation, for double stars, consisted in measuring the angular separation and the position angle of the two components. For pairs with obvious orbital motions, the accumulation of measurements yielded the elements of the orbit. This allowed the stellar masses to be deduced. The relationship between mass and luminosity is well known in stellar astrophysics.

Measurements upon double stars came within the scope of observatory programmes as long ago as the end of the 18th Century. In 1932, Aitken's catalogue already listed 17,180 double stars. Today the programme is coordinated worldwide by the International Astronomical Union.

A. Dollfus, *The Great Refractor of Meudon Observatory*,
Astrophysics and Space Science Library,
DOI 10.1007/978-1-4614-7288-9_9,

Practical determinations are generally made by filar micrometer. For very close doubles, Paul Muller preferred to employ the method of double image micrometry, a technique which he had refined [3].

The double image micrometer placed at the focus of the Grande Lunette allows the formation of two images of the star and the adjustment of the azimuth and the distance which separates them. When the star is double, the distance is adjusted in order to reproduce the separation of the components of the double star. The measurement is made by bringing between the double star and its replica some squares or some equidistant wires.

The method of double image micrometry does not require the precise pointing of the moving image of the star upon a thread. It is free from the movements, vibrations and oscillations of the telescope. It is perfectly adapted to the case of the Grande Lunette. According to Paul Muller: "After its return to service, in 1965, the 83 cm Meudon equatorial was used, for the first time in its existence, for the measurement of close double stars. After 30 years' experience of these observations, notably with the very fine instruments of Strasbourg (49 cm), the Pic (60 cm) and Lick (91 cm), I at once tackled the difficult objects, which could be measured nowhere else in Europe and in hardly any other places in the rest of the world [4]."

Under the finest observing conditions, Paul Muller recognised the duplicity of a pair at 0.15 arcseconds and an oval elongation at 0.12 arcseconds. The radius of the diffraction pattern, the theoretical limit, is 0.15 arcseconds.

During the following ten years, more than a thousand measurements of position angle and angular separation were accumulated with the Grande Lunette, in the course of 169 nights of observation. This considerable astrometric work would be concluded in 1974 with the appointment of Paul Muller to the Nice Observatory.

These measures would form the basis of three publications. The first reported upon 247 measures made upon 87 binaries. The second concerned 289 determinations for 113 binaries, and the third 451 observations upon 249 particularly close pairs [5].

At the end of these observing campaigns with the Grande Lunette, Paul Muller would make, in the last of his publications concerning Meudon, the following commentary: "It is at least uncommon to manoeuvre a double refractor of these dimensions, with all the stiffness of the original mechanism, between (latitude) $+60°$ and the pole, entirely by the power of one's arms; also the result should be judged in terms of the prolonged physical exertion which that presupposes, and that without doubt no-one after me will want to deploy [6]."

Jean Focas and Planetary Surfaces (1965–1969)

The instrument, back in service from the start of 1965, was also immediately used for new observations of planetary surfaces. Researches into the planets were then written into the programme run jointly by Meudon and the Pic du Midi for determining the properties of planetary bodies. The new attentions of planetary physics brought to bear telescopic scrutiny under high magnification, photography, photometry, polarimetry and micrometrical measurements [7].

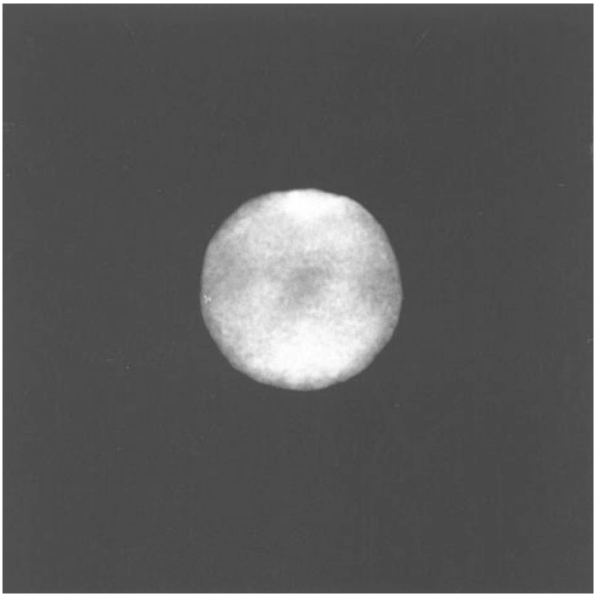

Fig. 9.1 Jupiter's satellite Ganymede, 1966 March 7 at 17 h 55 m with the Grande Lunette. The disk diameter subtends 1.2 arcseconds. The longitude of the centre of the disk equals 300°. Jean Focas used a magnification of 800×

The Pic du Midi excels at high angular resolution and photography. The reflecting telescopes of Meudon are suited to polarimetric studies. The Grande Lunette has the power of high magnification.

When, at Meudon, it came to happen that the images were perfectly stable, an infrequent circumstance nevertheless, the Grande Lunette with its 83 cm aperture could surpass in detail the 60 cm of Pic du Midi. Upon the high, isolated summit of the mountain, the instrument of the Pic, however, allowed more coherent studies.

Jean Focas (1909–1969), astronomer of the Athens Observatory, experimental researcher in planetary studies, had come to be living in France to add to his research work. He had earlier observing experience at Pic du Midi. Then, after the Grande Lunette was brought back into action in 1965, he was to use it for most of his studies of the planets.

From his first observations, Jean Focas remarked in his turn upon the salutary improvements made by Paul Muller upon the quality of telescopic images. The reduction in the volume of air beneath the dome around the instrument, as we have seen, and above all the reduction of the surface of the walls (of which the thermal inertia is great), more often than in the past yielded fine images in the field of the instrument.

Antoniadi, between 1909 and 1939, could but rarely glimpse the markings upon the surfaces of the small Galilean moons of Jupiter, essentially when they were projected in front of the planet's disk but almost never upon a black sky background. Nevertheless, J. Focas, A. Dollfus and later S. Ebisawa could often observe the details upon each of the four satellites (Fig. 9.1). To be able to see the smallest details of the image, the instrument required a magnification of 800×. In the refractor, the small

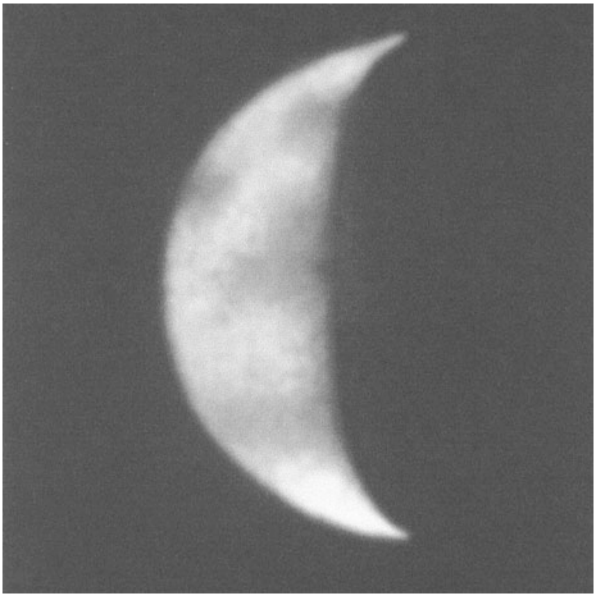

Fig. 9.2 Mercury, 1966 March 7, with the Grande Lunette. The phase angle was 105°. The diameter subtends 7.8 arcseconds. Jean Focas and Audouin Dollfus took turns at the eyepiece

disk of Ganymede is then seen with an apparent diameter half that of the Full Moon to the naked eye.

The observations upon the satellites with the Grande Lunette, in conjunction with those of Pic du Midi, would allow the construction in 1974 of planispheres showing the permanent markings upon each of these planetary-sized bodies, this being well before their study by spaceprobes [8].

New observations were practised upon the planet Mercury. For the purpose of drafting the planisphere of its markings, the observations of Pic du Midi still had some gaps. The region around the 300° meridian, poorly covered from the Pic, was seen through the Meudon refractor under excellent conditions (Fig. 9.2) [9].

Upon Jupiter, Focas made a routine surveillance of the state of its cloud systems in very considerable detail (Figs. 9.3 and 9.4).

The Appearance of Mars (1965 to 1967)

When, in 1965, the Grande Lunette was once more in a condition to allow a new study of the planet Mars, the nature of research was more specific. After the visual work of Antoniadi and the polarimetric work of Lyot in the years 1924 to 1930, interest focused upon characterising the life which might be possible on the surface of the planet. The observations made at Pic du Midi would go in this direction, and the Grande Lunette could thus support its work.

In 1965 April, the planet came close to the Earth, although it was a relatively distant opposition. The observing campaign had been put into operation at the

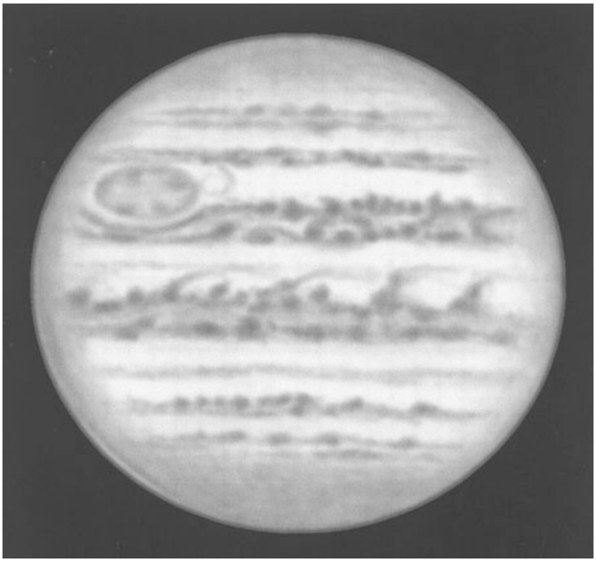

Fig. 9.3 Jupiter, 1966 March 6 at 18 h 13 m. Drawing by Jean Focas with the Grande Lunette of Meudon

Fig. 9.4 Mars, 1965 April 2 at 19 h 25 m. Drawing by Jean Focas with the Grande Lunette. The disk subtends 13 arcseconds. The magnification was 600×.

Pic du Midi since 1964 December by H. Camichel and A. Dollfus, while at Meudon J. Focas began his analyses with a small instrument. When the Grande Lunette became available, at the end of 1965 March, he undertook observations under high magnification.

An improved version of Lyot's visual fringe polarimeter (Fig. 7.1) was mounted upon the instrument. Determinations of the degree of polarised light relate to regions

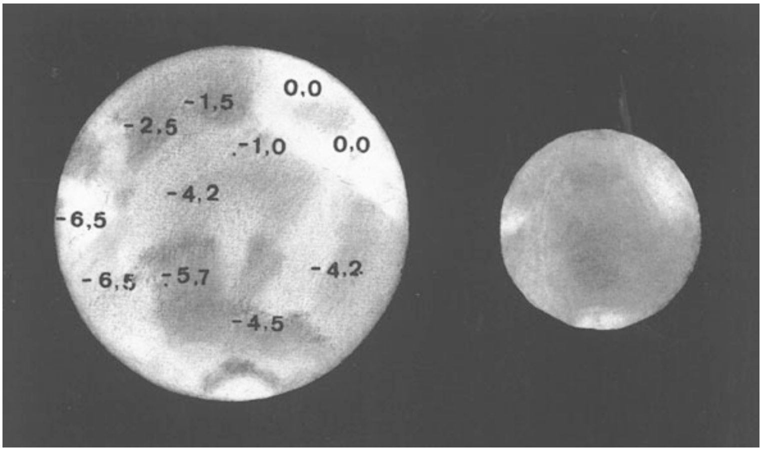

Fig. 9.5 Mars, 1965 March 31, at 20 h 10 m. Observations by J. Focas and A. Dollfus. At *left*, polarimeter readings are marked upon the disk. The degrees of linear polarisation are expressed in thousandths. The negative sign denotes that the direction of the polarisation is parallel to the Sun-planet-Earth plane. Under a phase angle of 17.5°, the lighter regions of the surface give − 4.2 thousandths. The dark markings are a little more strongly polarised. *Above* and to the *right*, a light region completely lacking in polarisation indicates a dust veil. In the *upper* part of the disk, the low polarisation values prove the presence of a residue of dust-clouds. To the *left*, all along the limb, the strong polarisation indicates a veil composed of small crystals. On the *right*, the appearance of the planet through a deep blue filter. The martian soil reflects very little in *blue light*; the aerosols show up strongly by contrast upon a *dark background*. The dust cloud at *top right*, the evening cloud at *left*, the small brilliant cloud by the limb at the equator and the north polar cap at the bottom of the image can be recognised

several hundred km in diameter upon the martian disk (Fig. 9.5). The degree of polarisation can reveal characteristics of the martian surface. Polarisation anomalies are detected and can be used to classify features as cloud formations, dust-veils or frost deposits upon the ground.

The polarimetric examinations were concluded by viewing through a deep blue filter. The surface becomes dark, and the thin white veils and clouds stand out in good contrast with the dark surface (Fig. 9.5, right).

In all, between 1965 January and July, Jean Focas made 19 visual and polarimetric analysis sessions with the Grande Lunette. Six further sessions were due to Audouin Dollfus, and five others were made jointly. A complete chart in the form of a Mercator projection was drawn up, showing the appearance of all the martian features during that period (Fig. 9.6). Different cloud formations were listed and dust clouds were discovered.

On 1965 July 15 the spaceprobe *Mariner 4* duly surveyed the planet, and the onboard camera for the first time photographed fine details upon the martian surface, along a 6,000 km band of terrain running across the planet's globe from the tropics up towards the south pole. On the preceding days, the target region was analysed at Meudon with the Grande Lunette.

Fig. 9.6 Average appearance of the surface of Mars between January and July 1965. Mercator projection map made by J. Focas according to his observations with the Grande Lunette of Meudon

The belt of terrain first to be photographed by the probe lay across the great ochre desert region known as Amazonis. In the refractor, the martian ground here showed its usual colour, denuded of dust veils or clouds in the planet's atmosphere. Through a blue filter, the dark ground revealed no trace of any atmospheric veil. Under the high phase angle of 39.6°, the polarimeter was rendered more sensitive to atmospheric impurities, and confirmed a very clear martian atmosphere. The spaceprobe photographs therefore showed the surface of Amazonis without the nuisance of any atmospheric interference.

Later, the target area of the probe duly reached the dark land of Mare Sirenum, and next the light region, Phaethontis. These high latitudes were in mid-winter. The eyepiece exhibited a whiteness, a brilliant cloud formation in blue light, the degree of polarisation of which reached a very high value characteristic of ice crystals. The images received from the probe, very washed out, can be explained by the presence of this winter cloud. The final image from the probe, almost uniformly blank, showed no more than the polar hood.

After having made a little more than one revolution around the Sun, the planet Mars returned to the proximity of the Earth in 1967, with an apparent diameter exceeding 15 arcseconds. The new observing campaign was conducted in collaboration with the Pic du Midi. Jean Focas worked entirely with the Grande Lunette.

From March 12 till June 14, Focas completed 32 visual observations. The smallest details were revealed upon the surface of the planet (Fig. 9.7). Eight large-scale drawings show the planet under a full range of longitudes. A complete planisphere was drawn up, in Lambert azimuthal projection in order to preserve the (telescopic) appearance of the polar regions (Fig. 9.8). The two charts in Figs. 9.6 and 9.8 document, by intercomparison, the changes in the configurations upon the planet's surface after one martian year.

Through polarimetric surveillance, Jean Focas noted the degree of polarisation upon different points of the planetary disk, for a total of about 200 determinations. Not a single exceptional cloud feature developed during the period concerned, but the morning and evening seasonal clouds were examined in detail. A cloud hood permanently covered the winter south polar regions.

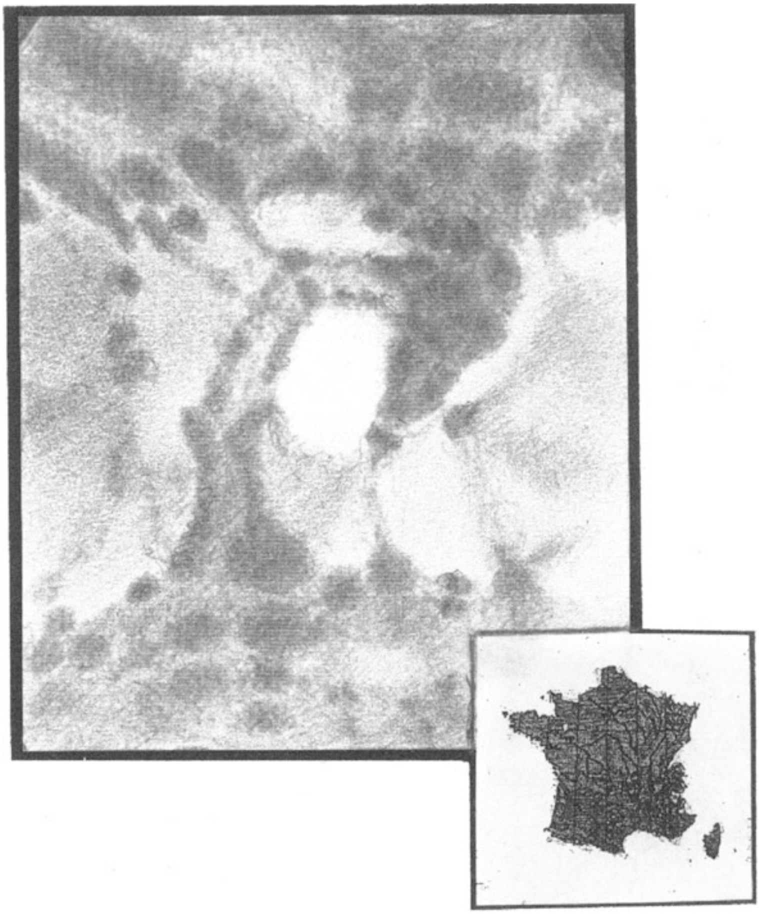

Fig. 9.7 The Syrtis Major region of Mars between April 29 and May 3, 1967. Grande Lunette; observations by Jean Focas

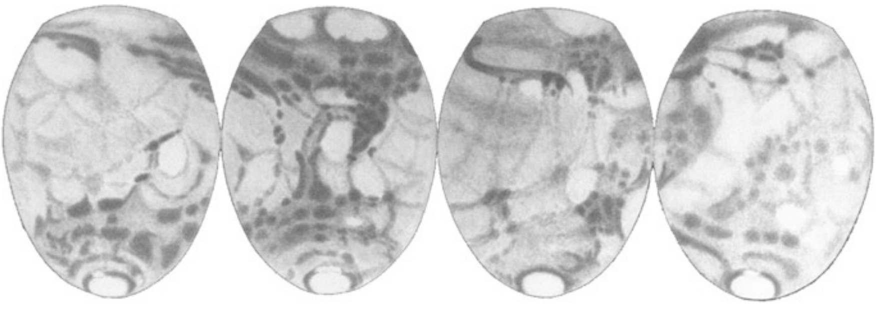

Fig. 9.8 Average appearance of the surface of Mars between April and June 1967. Grande Lunette; observations by Jean Focas. Lambert Azimuthal projection, preserving the telescopic representation of the north polar regions

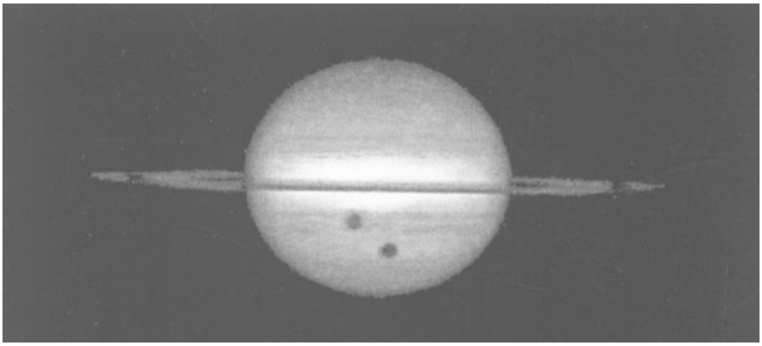

Fig. 9.9 The rings of Saturn observed under very oblique illumination, 1966 September 27 at 22 h 40 m. Grande Lunette of Meudon; drawing by G. de Mottoni and A. Dollfus. The satellite Titan, projected in front of the planet, much *darker* than the disk. Its shadow thrown upon the globe is perfectly *black*

Other Planetary Observations

In 1966, the rings of Saturn were viewed more and more obliquely and, on October 29 and then again on December 17, they were presented precisely edge-on. A little earlier, on 1966 June 15, the Sun had illuminated the precisely edge-on ring plane. These phenomena were examined at the time from Pic du Midi and Meudon [10]. With the Grande Lunette on September 25, Glauco de Mottoni (1901–1988) and Audouin Dollfus took advantage of a perfectly stable image (Fig. 9.9). The rings, very obliquely presented, were illuminated under a nearly grazing incident angle of only 1.5°.

> The image showed the satellite Titan and its shadow in front of the disk of Saturn. [. . .] The Earth was no more than −0.94° below the plane of the rings but they nevertheless remained visible, in projection in front of the disk. The corresponding dark line is underlined by a black thread which is the shadow of the rings projected upon the globe, whose apparent width was no more than 0.11”. [. . .] Cassini’s Division was seen upon both ansae, corresponding to the dark spot 0.55” long and 0.15” wide. Ring A was slightly darker than ring B. [11]

In 1971, a new 1 metre Cassegrain telescope was brought into operation in the observatory grounds, specially designed for planetary work and for polarimetry. Planetary researches were transferred to it, but the Grande Lunette remained the preferred instrument whenever a high magnification was required.

When, in 1973, a dust storm rose from the martian soil and spread to cover the entire surface of the planet, this rare phenomenon was studied in detail at the eyepiece of the Grande Lunette (Fig. 9.10). The suspended dust produced a change of colour that was immediately visible in the great instrument.

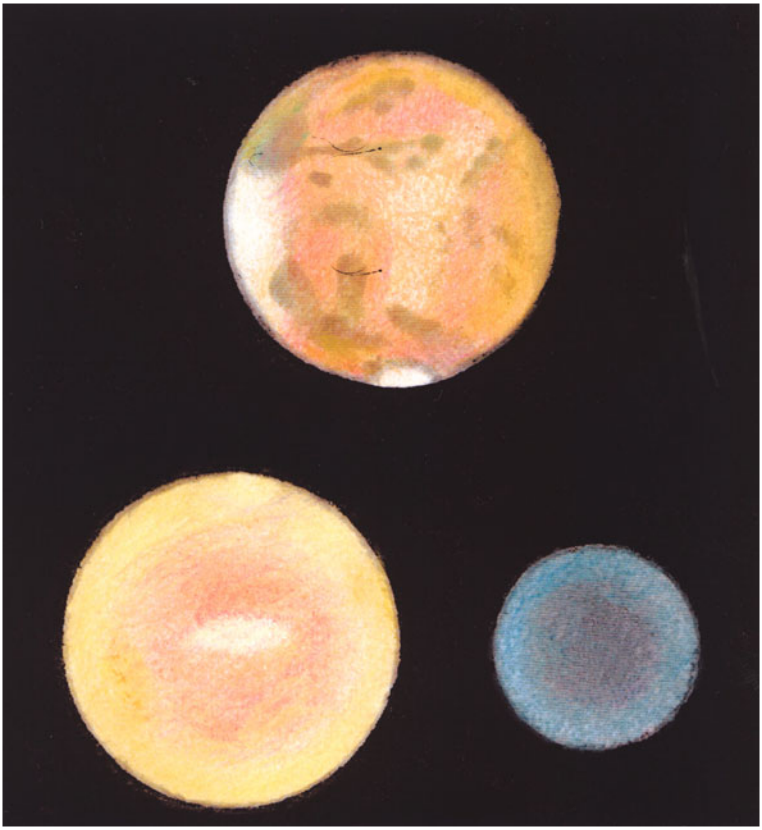

Fig. 9.10 Dust storm veiling the surface markings of Mars. Grande Lunette of Meudon; drawings by Audouin Dollfus. *Above*: Aspect of the planet on 1965 March 29. The martian sky is clear. Along the *left hand* limb an evening cloud can be seen. The north polar cap is visible at the *bottom* of the disk. Below *left*: The same martian longitude on 1973 October 25, obscured by a dust cloud. The surface is completely hidden. The colour, now lighter, borders upon citron *yellow*. A *white* cloud formation lies above the dust-veil close to the disk *centre*. The south polar cap is glimpsed at the *top* of the disk through the veil. *Lower right*: The same day, through a *blue* filter. The dust veil has produced a luminous areola all around the limb

Astrometry of Solar System Bodies

The planetary research programme developed jointly between Pic du Midi and Meudon between 1941 and 1973 demanded precise determination of the apparent dimensions of planetary bodies [12].

The double image method employed by Paul Muller for double stars lends itself for measuring planetary diameters with much greater precision than the classical determinations by bifilar micrometer. It needs a large aperture and excellent seeing conditions.

Fig. 9.11 Double image micrometers for the measurement of planetary bodies. *Front centre*: B. Lyot's apparatus for close double imaging, designed in 1941. *Rear right*: micrometer for wide double imaging of A. Dollfus, the prototype from 1952, and its accessory for photometry of planetary surfaces. *Rear left*: the Dollfus micrometer in its commercial version made by the firm of R. Danger

The asteroids Pallas, Juno and Vesta, measuring hundreds of kilometres in diameter subtend disks of only some tenths of an arcsecond. The measurements with the Grande Lunette made between 1967 and 1973 with the micrometer of Lyot (Fig. 9.11, centre), by J. Focas, P. Muller and A. Dollfus improved upon the rare filar micrometer determinations by E. E. Barnard and the interferometric measurements by M. Hamy going back to the 19th Century, the only ones available [13].

Jupiter, with an apparent diameter in the region of 40 arcseconds, necessitates a special type of micrometer (Fig. 9.11, in the background). This micrometer is capable of measuring to a precision of the order of one part in a thousand. At Pic du Midi the measurements by Focas and Dollfus, published in 1970 [14], had supplied equatorial and polar diameters of 70,850±100 km and 66,550±100 km, respectively. From Meudon, with the Grande Lunette, a series of measures at 5° intervals all around the disk in 1971 had yielded the form of the globe, whose ellipticity was found to be 0.061±0.001.

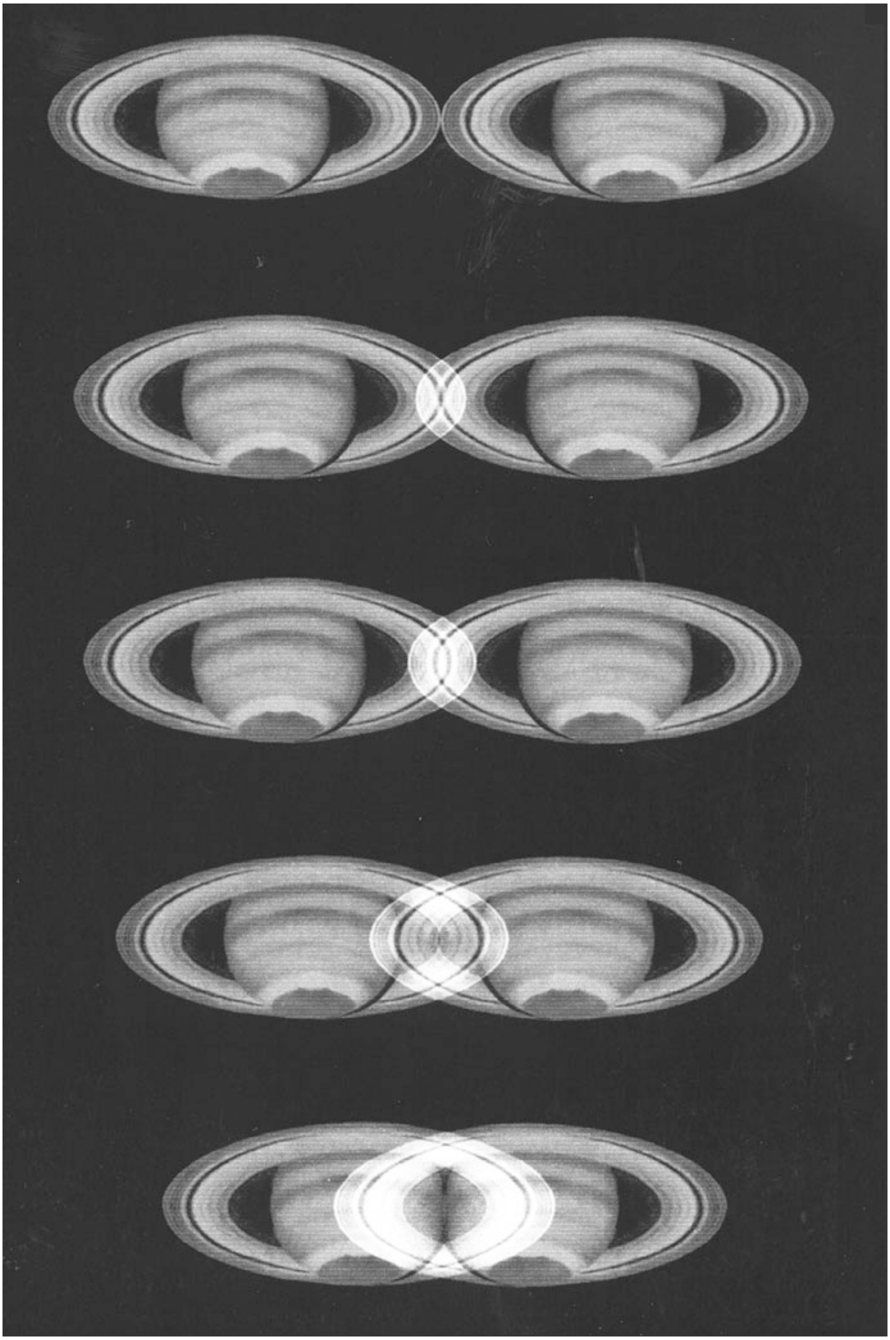

Fig. 9.12 Combining the double images with the Dollfus micrometer, for measuring the dimensions of the globe and rings of Saturn. *From top to bottom*: exterior diameter of ring A; average diameter of Cassini's Division; length of rings A and B; interior diameter of ring B; diameter of the globe

For Saturn, the measurements upon the globe and upon the major axis of the outer ring were completed by combinations of double images giving the radii of the different parts of the ring system (Fig. 9.12). The experimental work at Meudon would later yield very precise values from the Pic du Midi [15].

For the planet Mercury, the low quality diameter measurements available in 1953 left an error of 10 % in its density, insufficiently precise to understand its internal structure. During the transits of the planet in front of the solar disk, the circular black spot seen upon the luminous background of the photosphere allowed a precise measurement of the diameter. The transit of 1960 November 7, with the Grande Lunette, gave the most satisfactory value.

The objective of the Grande Lunette was diaphragmed down to 25 cm. The solar image 16 cm across formed at the prime focus caused a slight heating of the plate at the rear of the instrument. The turbulence and convection induced in the tube by the sunlight did not appreciably disturb the excellence of the image over one or two minutes. The objective was thus kept protected behind the dome, then unmasked in front of the slit by rotating the dome at the very moment of observation. Double-image measurements were carried out in less than a minute, after which the objective was newly covered for several minutes. Paul Muller, Charles Boyer and Audouin Dollfus took turns at each interval during the four-hour duration of the transit. Thirty-two determinations would yield the very precise value of 2,429±18 km for the radius of the planet. With the value of the mass given by Rabe, the mean density of the globe reached 5.45±0.14, implying a significant metallic core [16].

A little before that determination, then again later, radar echoes would give a radius of 2,439 km.

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Chapter 10
Final Scientific Services (1973–1990)

Shiro Ebisawa and the Atmosphere of Mars

Shiro Ebisawa from Japan has been a planetary observer since 1956. His observatory in Tokyo is equipped with a 49 cm reflecting telescope with polarimetric equipment. Nearly every year, since 1968, he has spent several weeks in France to take part in the observational programmes with the instruments at Meudon and at Pic du Midi. Between 1973 and 1989 the Grande Lunette was his main instrument.

With the Grande Lunette, Ebisawa followed the activity in the clouds of Jupiter. He made excellent drawings of its satellites. He confirmed from Meudon the numerous fine divisions in the rings of Saturn discovered at Pic du Midi. He had examined the rings since they were edge on in 1980.

Meanwhile Ebisawa's observations with the Grande Lunette mainly concerned the planet Mars (Fig. 10.1). Although Focas had concentrated his studies mainly upon the variable fine structure of the martian surface, Ebisawa studied the atmosphere of the planet, its mists, clouds, dust storms and its seasonal changes.

In 1980, Ebisawa examined the planet on five occasions with the Grande Lunette. During the 1984 apparition, between March 21 and May 1, he made drawings on 21 occasions, of which 11 were supplemented by polarimetric measurements. In 1986, the Grande Lunette yielded six excellent observations. The most favourable opposition of 1988 again provided him with nine observations and drawings as well as photographs.

With the great object-glass, the amount of light allowed a detailed inspection of the delicate nuances in colour which helped to identify white mists upon the ochre background of the planet. The Meudon observations were valuable in supplementing the numerous visual and polarimetric observations carried out in Tokyo.

Ebisawa showed the existence of a pre-polar hood which forms each martian year in the autumn at mid-latitudes (Fig. 10.2). This hood precedes the coalition of the clouds to form the polar hood under which the deposition of snow on the planet's surface forms the polar cap [1].

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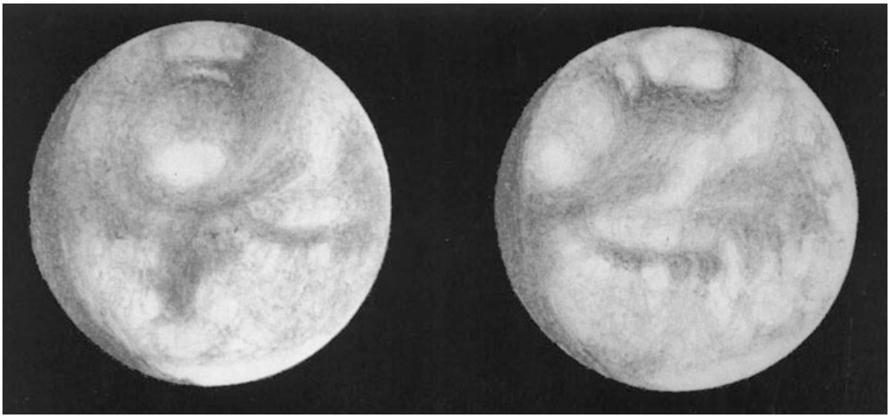

Fig. 10.1 Two aspects of Mars in 1988. Drawings by S. Ebisawa, Grande Lunette. *Left*, 1988 August 14 at 02 h 00 m with central meridian longitude 302°; *right*, 1988 August 8 at 01 h 30 m, CM longitude 351°

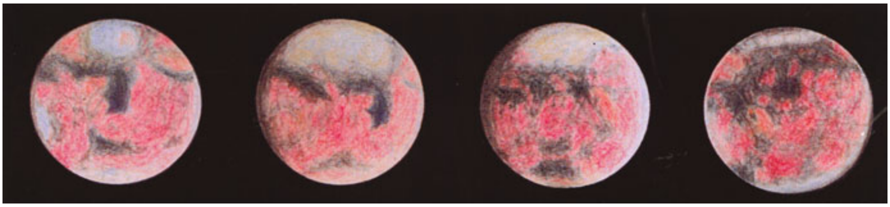

Fig. 10.2 Development of the precursor to the winter polar hood in the martian S. polar regions. Drawings by S. Ebisawa, Grande Lunette. From *left* to *right*, the first three drawings show the whiteness of the southern regions (*at the top*), during the progression of martian winter; 1984 March 23 (01 h 40 m), 1986 March 9 (04 h 20 m) and 1986 April 8 (04 h 50 m). The *right-hand drawing*, 1986 August 2, much later in the season, corresponds to southern spring. The polar region is free from clouds; the *white* surface polar cap is visible.

Mutual Phenomena of the Satellites of Jupter (1979)

Every six years, the planet Jupiter is seen from the Earth exactly in its equatorial plane. The four largest satellites, Io, Europa, Ganymede and Callisto are all in the same plane and appear to move back and forth in the line of sight. They can approach and occult one another, or throw shadows upon each other. Figure 10.3 illustrates some actual conjunctions, allowing their colours to be compared, as well as their brightness and the degree of contrast of the details upon their surfaces. The determination of the precise moments of the mutual events improves knowledge of their orbits.

The ancient theory of the movements of the satellites of Sampson dates from 1921. The Bureau des Longitudes works to keep it up to date. The adjustment of the numerical values can be improved by the precise timing of mutual phenomena.

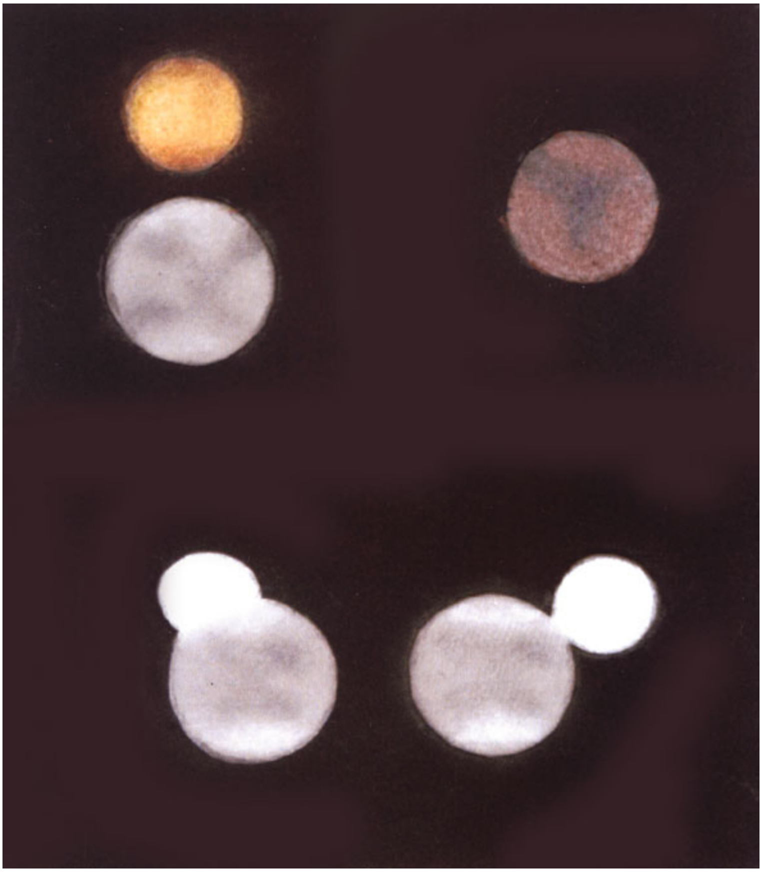

Fig. 10.3 The satellites of Jupiter. Observations by A. Dollfus with the Grande Lunette. *Top left*: Close conjunction of Io and Ganymede, 1973 October 21, 18 h 49 m 30 s. Io is *orange-yellow*, with dark blotches reaching the brightness of the lightest patches upon Ganymede. *Top right*: Callisto, 1977 January 31 at 19 h 20 m. The satellite is darker than Ganymede and exhibits a slightly brownish tint. *Below*: occultation of Europa by Ganymede, 1973 October 22: *left*, at 17 h 20 m 30 s; *right*, at 17 h 51 m 00 s. Ganymede is *grey*, scattered with spots. Europa is *white*, brighter than the lightest parts of Ganymede

After some trials during the favourable period of 1973, the Bureau des Longitudes decided to make plans for the following period, in 1979, in the form of an observing campaign designated PHEMU 79. It was coordinated between the French observatories by Jean-Eudes Arlot. The Grande Lunette of Meudon thereby contributed to the timing of two of the nine phenomena observed [2].

On 1979 June 16, the eclipse of Io by Ganymede was examined with the Grande Lunette by J.-E. Arlot, W. Thuillot, B. Morando and others. The observers estimated visually the brightness of the satellite Io on a scale with respect to the brightness of the other visible satellites. The analysis gave the instant of the mid-phenomenon: 20 h 24 m 06 s, or 20 h 24 m 16 s, depending upon the method of counting used.

The phenomenon of 1979 December 1 concerned the occultation of Europa by Io. The same observers found visually the mid-event time to be 04 h 23 m 24 s, or 04 h 23 m 57 s. A series of photographs obtained simultaneously with the 62 cm photographic objective gave 04 h 23 m 36 s ± 20 s.

In 1981, the new theory of the satellites of Jupiter by Sagnier would take account of the mutual perturbations of the satellites, the perturbations by the Sun, the effects of the polar flattening of the globe of Jupiter and resonances. The numerical adjustments made use of the results of the PHEMU campaign.

Comet P/Halley (1985–1986)

In 1985, the famous Comet Halley was approaching the Sun. Astronomers had already subjected comets to analysis by the tools of astrophysics. They had deduced that these bodies would be agglomerations of ice and dust. When these bodies approach the Sun, the warming effect vaporises the ice, liberating dust grains, which are ejected in a tumultuous manner. The dusts constitute a sort of nebulous region which surrounds the small central nucleus; repelled by radiation pressure, they are pushed further away to form the tail of the comet.

These conglomerates must initially have formed further out in space, from the earliest phases of the formation of the Solar System. They have been preserved by the coldness of interplanetary space. When they approach the Earth, they present themselves to us like relics, fossils of the material which constituted the Solar System at the time of its initial creation, when the scattered material began to gather together from the myriads of tiny pre-planetary bodies. Warmed up, the nuclei composed of primitive materials exude, under telescopic scrutiny, the gases and dusts of which they are composed.

At the Meudon Observatory, the researchers focused upon the physical state of the gases emitted by the comet's nucleus. Photopolarimetric observations made with the 1 m reflector at Meudon and the 1.52 m reflector of the European Southern Observatory (ESO) in Chile had for their goal the characterisation of certain properties of these grains of matter, such as their size, their texture and their reflective power. They would reveal the transformation in the state of the dusts after ejection and liberation into space, attributable to the vaporisation of the ices, to the destruction of aggregates, to the dispersion of grains, then by transport in the cometary head under the effect of radiation pressure.

An accompanying programme sought to understand the follow-up to the ejection of dust from the comet's head. The study of the puffs and jets in the surroundings of the head required a high magnification. The Grande Lunette was thus given over to a group of seven members of the Cometary Commission of the French Astronomical Society, coordinated by Annie-Chantal Levasseur Regours [3].

Between 1985 September and 1986 January, the observers took turns at the eyepiece of the Grande Lunette, in two groups run by Jean-Claude Thorel and by Serge Thébault. Twenty-eight drawings contributed to the record of details of the near-nuclear activity.

In October, the cometary envelope was noted as being weak and regular. It developed, and tiny jets appeared, different from night to night. Under an angular resolution of some hundreds of kilometres, certain of the jets remained perfectly filamentary. They could extend in length in the line of sight for tens of thousands of kilometres.

Other emissions, more diffuse in character, formed more persistent plumes.

The observations equally concerned the Comet P/Giacobini-Zinner. A number of drawings of Jupiter were also made.

Observations of Mars by Amateur Astronomers (1988 and 1990)

At the end of 1988, the planet Mars came close to the Earth, then subtending an apparent diameter of 24 arcseconds. The circumstances were the same as those of 1909, the year that revealed the planet to Antoniadi through the Grande Lunette and made him a militant campaigner against the existence of the martian canals, thus putting to an end to a notorious scientific error.

The success of the Comet Halley observing campaign conducted by amateurs prompted the use of the great instrument for other educational and cultural activities. It was possible to relive the epoch-making observations of Mars at the start of the 20th Century, at the time of the canal controversy, with the same instrument and under comparable conditions.

Eight observers of the French Astronomical Society had the full-time use of the great instrument from 1988 July till December, under the coordination of Daniel Crussaire [4]. Moreover, three overseas observers renowned for their planetary work were invited to participate: the Japanese Shiro Ebisawa already familiar with the Grande Lunette, the Englishman Richard McKim who a little later would become President of the British Astronomical Association, and the Italian Marco Falorni who also became President of the Unione Astrofili Italiani.

In the course of the one hundred and sixty nights allocated to the programme, very favourable atmospheric conditions offered more than one hundred clear nights, representing 60 % of those available. The observers were divided into two groups alternating with each other from night to night, with communal meetings beneath the dome with up to 11 observers. Various publications would later relate the ambiance and the results obtained [5].

Owing to the success of the operation, it was prolonged, though on a smaller scale, during the following opposition of Mars in 1990. Forty-five observations of the planet would again be made.

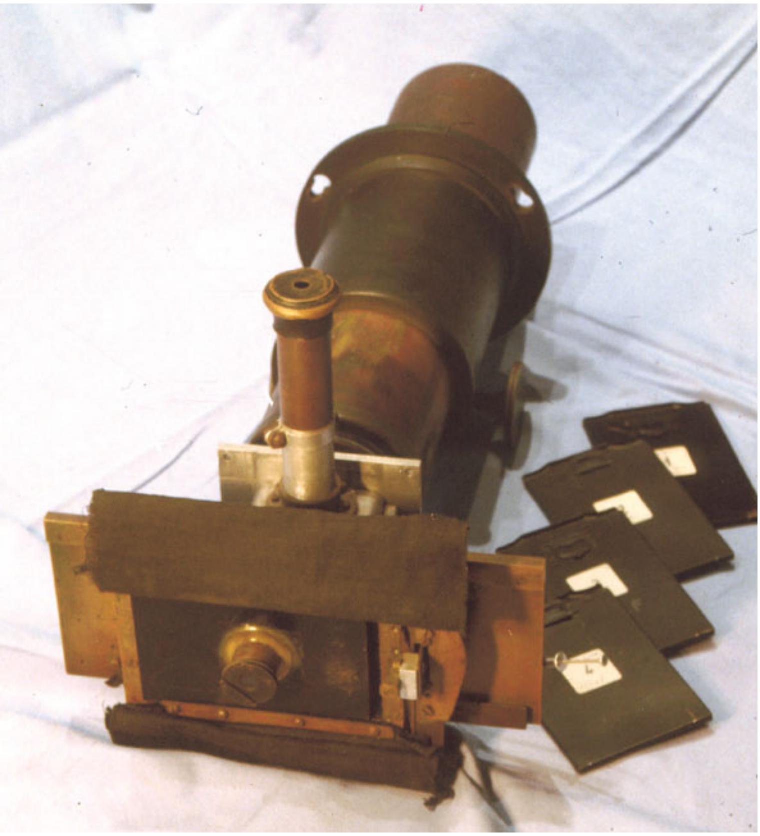

Fig. 10.4 Plate camera used for planetary photography by H. Camichel. Used at Pic du Midi since 1941 and with the Grande Lunette of Meudon by J. Focas from 1965 to 1968

Planetary Photography (1966–1990)

The oscillations of the great refractor make planetary photography difficult. One has to seize the moments of greatest amplitude, when for a fraction of a section the image of the planet is immobilised, before moving in the opposite direction. Light, rhythmic touches at the rear of the telescope tube help to damp out the vibrations, and sometimes to eliminate them for long moments. Multiple exposures allow for later selection of the best images.

In 1966, Focas had taken up planetary photography again, abandoned since 1909, by making use of the great visual 83 cm objective together with a plate camera (Fig. 10.4). His results mostly concerned Jupiter.

From the beginning of 1978, Ebisawa, Crussaire and other observers used the new film cameras, much easier to use than the plate cameras, allowing rapid and

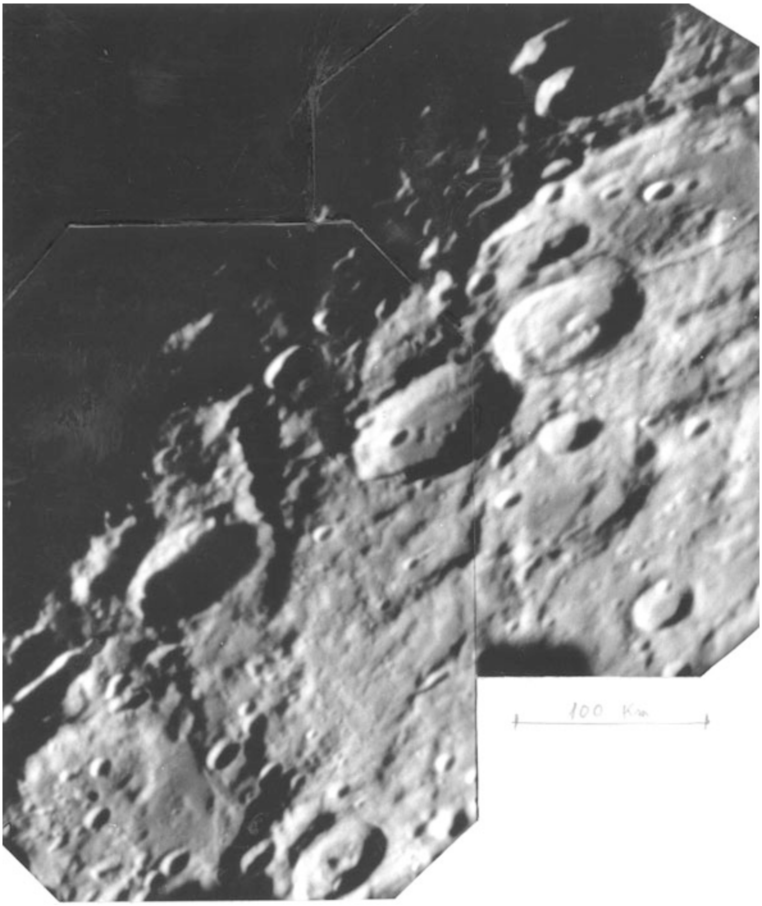

Fig. 10.5 The lunar surface on 1981 November 15. Photograph made by Daniel Crussaire with the 83 cm objective of the Grande Lunette. Janssen crater and environs

multiple exposures (Figs. 10.5 and 10.6). During the 1988 Mars observing campaign, numerous photographs of the planet were collected in that way (Fig. 10.7).

Nowadays, the numerous charge-coupled detectors, such as the CCD or the webcam, have deposed the photographic emulsion. The methods of digital image-processing, the taking rapid succession of images, the programmed selection of images and automatic centring give freedom from the oscillations of the Grande Lunette. Processing by multiple image stacking, unsharp masking, wavelets and other techniques brings out all the fine details of the telescopic image, which until then had only been available to the visual observer behind the eyepiece.

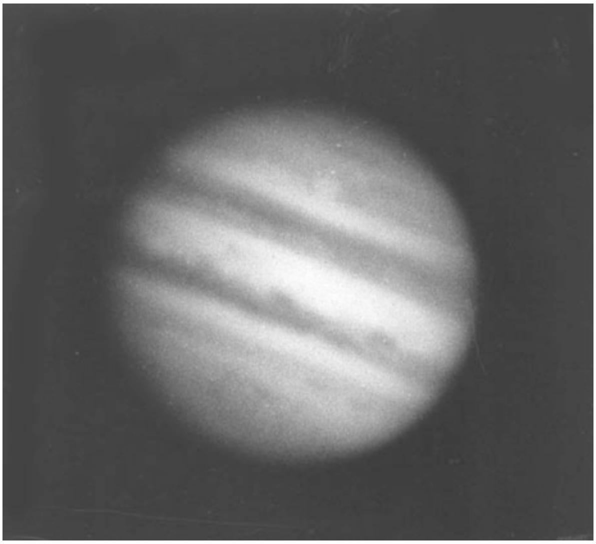

Fig. 10.6 Jupiter, 1986 July 20 at 02 h 14 m 20 s. Photograph made by Daniel Crussaire with the 83 cm objective of the Grande Lunette. TP 2415 film, exposure 1/4 s, no filter

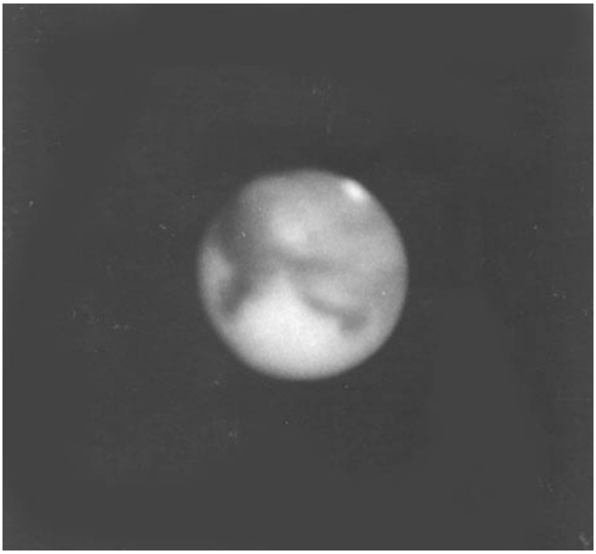

Fig. 10.7 Mars, 1988 September 20 at 01 h 12 m 35 s. Photograph made by Daniel Crussaire with the 83 cm objective of the Grande Lunette. TP 2415 film, exposure 1/8 s, W21 orange filter

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Chapter 1

Figures 1.1 and 1.6: Paris Observatory/J. Janssen, *Annales de l' Observatoire d'astronomie physique de Paris, sis à Meudon,* **1**, 1896.
Figures 1.2 and 1.5: Musée municipal d'histoire locale et d'archeologie de Denain/Plaquette des Anciens Etablissements Cail.
Figure 1.3: *Le Genie Civil*, 15 decembre 1892.
Figure 1.4: Paris Observatory/P. Muller.

Chapter 2

Figure 2.1: *l'Astronomie*, 1894 May, p. 25. Photograph from Paris Observatory.
Figure 2.2: *l'Astronomie*, 1894 May, p. 26. Photograph from Paris Observatory.
Figure 2.3: Club Bernard Lyot Société astronomique du Vésinet/Plaquette *La Verrerie au service de l'astronomie*, 1997.
Figure 2.4: Paris Observatory/F. Baldet, observational notebook no. 3.
Figures 2.5, 2.7 and 2.8: Paris Observatory/A. Dollfus.
Figure 2.6: *Je sais tout*, front cover, 1926 September. Photograph from Paris Observatory.

Chapter 3

Figures 3.1–3.3: Paris Observatory/A. Dollfus.
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Chapter 4

Figure 4.1: *Comptes rendus de l'Académie des Sciences*, **124**, 341–342 (1897). Paris Observatory photograph.
Figure 4.2: *l'Astronomie*, **13**, 364 (1899). Paris Observatory photograph.
Figure 4.3: *l'Astronomie*, **19**, 301–304 (1905). Paris Observatory photograph.
Figures 4.4–4.9 (left) and 4.10 (above): Paris Observatory photographs.
Figures 4.9 (right) and 4.10 (lower): A. Guillemin, *Les Nébuleuses, notions d'astronomie sidérale*, Paris, Hachette, 1880. Photograph by A. Dollfus.

Chapter 5

Figure 5.1: Branger/Roger-Viollet.
Figure 5.2: Paris Observatory photograph.
Figures 5.3–5.5: Paris Observatory/Grande Lunette observational notebook (4aGL).
Figure 5.6: Paris Observatory/A. Dollfus.
Figure 5.7: Paris Observatory.
Figure 5.8: *l'Astronomie*, **18**, 471 (1904). Paris Observatory photograph.

Chapitre 6

Figures 6.1, 6.5–6.7 and 6.10: E.-M. Antoniadi, *La Planète Mars*, Paris, Hermann, 1930. Paris Observatory photograph.
Figure 6.2: *Communications of the Lunar and Planetary Laboratory*, University of Arizona, Tucson, USA, **2**, no. 31 (1964). Reproduced with the permission of M.R. Calvert.
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Figure 6.8: *l'Astronomie*, **40**, 1926 August. Paris Observatory photograph.
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Figure 6.11: P. Humbert, *De Mercure à Pluton*, Albin Michel, Paris, 1937. Photograph by A. Dollfus.
Figure 6.12: *l'Astronomie*, **47**, 545 1933, Paris Observatory photograph.
Figure 6.13: *l'Astronomie*, **42**, 131 1928, Paris Observatory photograph.
Figure 6.14: *l'Astronomie*, **42**, 128 1928, Paris Observatory photograph.
Figure 6.15: *l'Astronomie*, **44**, 56 1930, Paris Observatory photograph.
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Figure 6.18: *l'Astronomie*, **43**, 389 1929, Paris Observatory photograph.

Chapter 7

Figure 7.1: Paris Observatory/A. Dollfus.
Figures 7.2–7.3: Paris Observatory/B. Lyot, "Recherches sur la polarisation de la lumière des planètes et de quelques substances terrestres", *Annales de l'Observatoire d'astronomie physique de Paris, sis à Meudo*n, **8**, part 1 (1929).

Chapter 8

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Chapter 9

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Figure 9.9: Paris Observatory photograph/A. Dollfus and G. de Mottoni.
Figures 9.10–9.12: Paris Observatory/A. Dollfus.

Chapter 10

Figures 10.1 and 10.2: S. Ebisawa.
Figures 10.3 and 10.4: Paris Observatory/A. Dollfus.
Figures 10.5–10.7: Paris Observatory/D. Crussaire.

Conclusion

After having climbed the spiral staircase that leads to the Grande Lunette, in the semi-darkness which prepares the eyes for the night, the curious nocturnal visitor comes out upon a small step in front of a closed door. He half opens it. A layer of cold air falls upon the visitor who senses an immense space, dark and icy. The slight hum of a motor adds to the mystery. Upward, a great indentation, a sort of wide slit, seems to glow with phosphorescence. It seems that it opens upon the night sky. Indeed, some stars can be made out there. Part of the long opening seems blotted out, occulted by a black mass. The end of the Grande Lunette!

The eye tries to follow what seems to be a long tube, which towards the lower end is lost in darkness. There, below, a tiny light seems to shine. It illuminates a bustling silhouette. As the visitor guesses, an astronomer is at work, in this sanctuary of science. It is best not to disturb him. Discreetly, the intruder closes the door and descends again, quietly. The vision will never be forgotten.

Later, the evening visitor, truly inspired by that strange discovery, will return to the scene to solve the mystery. It will be daylight. When the guide opens the door, at the top of the staircase, a flood of light strikes the face. The great tube, floodlit by projectors, seems colossal. The small step upon which our visitor finds himself somewhat overhangs the tremendous open space of the dome. The Grande Lunette is inclined, elevated upon one side, and descends towards the floor on the other, where one finds the observer. The vast floor below covers the whole circular surface. The guide explains that this floor is a mobile one, for elevating the astronomer to eyepiece level, whatever the direction of the star being viewed.

Plenty of other details will also be explained, before the group of visitors makes itself into a line to go round the instrument, from above, from the narrow gallery which runs all around the great circular wall, at the same level as the rim of the great hemispherical dome. After that plunging view, it will be time for the descent to the moving floor itself, to inspect the great metallic eye pointed upwards, like when working at its eyepiece.

That great refractor at Meudon is a symbol. It appeals to the popular imagination. The giant eye, it appears, can record; it can discover. The effect is powerful. The pupil of the human eye is two millimetres in diameter. Up above, the objective measures 80 centimetres across. The human eye has become 400 times bigger. The stars are

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closer in proportion. The brightness increases with surface area, as the square of the diameter. A simple calculation: in the eyepiece can be seen tiny stars of magnitude 18, nearly lost in the firmament. Running away from the retina, an immense but precise mechanism, rigid yet moving, weighty but delicate. Up there, a great lens, worth more than its weight in crystal. The Grande Lunette makes people dream.

From the first daring futuristic vision, then glorious recollection of the past, the Grande Lunette of Meudon has reigned throughout a Century of Astronomy. It has become legendary, an exceptional instrument symbolising a way of thinking and practising Astronomy.

For the giant eye of Meudon, the planets first stood out as special targets. At the eyepiece, capable observers competed to magnify, analyse, record and understand the events which unfolded upon these worlds. But comets would also approach the Earth, and would be seen closer than ever before. Stars would reveal their spectra at an epoch when spectroscopy was a new line of research. Stars would explode in the sky and the Grande Lunette would decompose their light.

After the Second World War, the great instrument was able to pick up new momentum. Double stars would move slowly in their orbits under the attentive gaze of the great lens. Planets would come back into the field of view. From them new knowledge would again shine, before spacecraft would change the way in which science was done.

The story is not over. The legend has become a symbol. Every visitor can reach the great instrument, in that great dome of the Observatory, and absorb its magic. In the building housing the instrument, finally reopen to the public, he will discover the great steps brought by the Observatory to knowledge, among the working instruments of a great research institution. He will be able to glimpse the new discoveries expected from a science which is always in motion.

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