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ORIGINAL ARTICLE

Exotic UV astronomy

Noah Brosch

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Abstract After considering a number of historical but somewhat "forgotten" UV astronomy experiments, I discuss a number of ways of non-conventional astronomy in the ultraviolet that, on first considerations, could be viable alternatives and valuable complements to classical space observations. These are (a) UV astronomy from the Antarctic or the Arctic regions that take advantage of the "ozone hole", (b) the use of high-altitude stratospheric balloon-borne telescopes, and (c) the operation of UV telescopes on the Moon. The advantages of these options are discussed and evaluated against the costs of each option and, one by one, are mostly rejected as not fully justifying the specific alternative. The possibility to achieve valuable (but limited) UV science, such as imaging at ∼2000 Å, using long-duration stratospheric balloons is described. The option of lunar UV observatories is retained to be implemented for the case of a UV interferometer, where the stability of the lunar regolith is seen as a significant advantage in comparison to free-flying interferometers. A location beyond the main asteroid belt, where the background due zodiacal light may be negligible, is advocated as an ideal location for a UV observatory in the Solar System.

Keywords Instrumentation: miscellaneous, balloons · Space vehicles: instruments · Ultraviolet: general

1 Introduction

As argued by Jeff Linsky in this volume, we seem to be approaching a "dark age" in the domain of ultraviolet (UV) astronomy, since the only instruments now operating are (a small fraction of) the HST that responds in the UV, the sky survey GALEX telescope, and the secondary instruments optical-UV monitor on XMM and UVOT on SWIFT. The foreseeable future heralds no major UV mission, with the exception of the WSO/UV. Modern UV astronomy requires space platforms, which tend to be very expensive, require long-range planning, and must compete for funding with other spectral domains.

Space observatories have become a regular tool of the astronomers and have greatly enhanced our possibility to study celestial objects. At this meeting, in the magnificent El Escorial setting, we have discussed very interesting missions that go way into the middle of the 21st century. These have usually been "regular" missions of free-flying spacecraft. In order to provide a better perspective of these missions it is useful first to consider some historical ones that were unusual in some aspects.

It is also possible that some promising alternatives, those explored by these unusual missions and others discussed below, could be significantly less expensive than space platforms but have escaped the attention of the scientific community and of the space agencies. These alternatives could consist of UV observatory locations different from the low or high Earth orbits, usually the choice for space ultraviolet observatories. For this reason it is worthwhile to re-examine these alternatives.

N. Brosch (✉)
The Wise Observatory and the School of Physics and Astronomy,
Beverly and Raymond Sackler Faculty of Exact Sciences,
Tel Aviv University, Tel Aviv 69978, Israel
e-mail: noah@wise.tau.ac.il

2 Historical heritage

A number of interesting missions of UV astronomy have been conducted in the past but have not been evaluated in connection with modern missions. The two highlighted here are the GLAZAR telescope on the Mir space station (part of the KVANT module), and the FAUST imager flown on the Space Shuttle. These two are emphasized here since they were conducted from manned space platforms as secondary experiments and received less attention than they merited.

The GLAZAR UV telescope was described by Tovmassian et al. (1988, 1990). GLAZAR was a 40-cm Ritchey-Chrétien telescope equipped with two field correcting lenses that provided a 1°.3 field of view. The detector was an MCP-based image intensifier with a CsI cathode responding primarily at ∼1600 Å coupled to a film transport mechanism. The film cassette could be changed from an airlock without requiring extravehicular activities. The telescope was mounted together with star trackers on a universal joint external to the KVANT module, which was part of the Mir space station complex. Field acquisition was done by manoeuvering the entire Mir complex while the tracking was done independently by the GLAZAR telescope. The final image resolution obtained by this instrument was about 10 arcsec.

A roll of film was sufficient for about 150 exposures, after which the cosmonauts changed the film cassette. The exposed film was subsequently returned to Earth for processing and measurement. The observations were performed exclusively during the orbital night, some 20–30 minutes long at the low Earth orbital altitude of the Mir station. The last published paper containing results derived from the GLAZAR telescope was by Tovmassian et al. (1993) and showed that the 1640 Å magnitude limit was actually 9^m for a four-minute exposure, using the monochromatic magnitude definition

$$m_\lambda = -2.5 \times \log(F_\lambda) - 21.175 \tag{1}$$

GLAZAR was therefore very limited in the type of astronomy it could offer, extending only slightly the information provided by the TD-1 satellite (Thompson et al. 1978).

The instrument was replaced in 1990 with the GLAZAR-2 telescope (Tovmassian et al. 1994), also mounted externally on the KVANT module. GLAZAR-2 eliminated the field corrector lenses, resulting in a calculated limiting magnitude of about 17.5 at 1640 Å, theoretically some four magnitudes fainter than the first GLAZAR. Unfortunately, this experiment was plagued with trouble since its beginnings. First, when trying to exchange the first film cassette, the handle of the airlock broke. This was fixed later, but in the meantime the camera was left in an improper position and became unusable. The collapse of the Soviet Union with its associated reduction in space research budgets implied that, unfortunately, this experiment could not be revived.

The FAUST experiment flew in March 1992 with the ATLAS-1 space shuttle mission. FAUST was a Wynne telescope (180-mm focal length at $f/1.12$) equipped with an MCP wedge-and-strip detector for wide-field photon-counting UV imaging. It collected 22 images of the sky, each 7°.6 in diameter, in a spectral band peaked at 1650 Å and extending from 1400 to 1800 Å, with full-width half-maximum point source images of 3.5 arcmin. The limiting magnitude of FAUST detections was approximately 10× fainter than that of the previous UV all-sky survey, TD-l, but FAUST covered only 4.4% of the sky. The catalog limit is approximately 10^{-14} erg/s/Å/cm^2 ($m_\lambda \le 13.8$), although it is not complete to this level, and it contains 4698 sources. The catalog was published by Bowyer et al. (1995). The instrument itself was described by Bowyer et al. (1993) and a first-cut at its results was presented by Sasseen et al. (1993).

Note that an earlier FAUST version operated on the Spacelab-1 station (Bixler et al. 1984). That version used an image intensifier coupled to film, but most exposures showed a high background level and not much science was accomplished.

The experiences of GLAZAR and FAUST, both UV imagers on manned low-Earth-orbit platforms, are not very encouraging. The immediate environment of a manned spacecraft or station is generally polluted by outgassing materials that contain significant organic contaminants. In the cold of space some of these condense onto the optics. Upon irradiation by solar UV photons during the orbital day, the organic materials dissociate and recombine sometimes into substances with a very high UV optical depth. The optical surfaces become effectively opaque to the radiation they are supposed to collect (Kinser et al. 1992). The Space Shuttle and other manned platforms on low Earth orbit suffer also from "Shuttle glow" (emission caused by the spacecraft surfaces interacting with the ambient tenuous atmosphere) and from a lack of stability; each time someone moves in the station or in the Shuttle a correction is imposed by the stabilization mechanism that causes telescope jitter and image smearing.

3 UV astronomy from the Antarctic

At first glance, the polar regions on Earth might provide a useful location for UV astronomy. The reason is a consequence of global warming and human pollution: the depletion of the ozone layer in the stratosphere, at altitudes of 15–35-km and peaks at 24-km. There is also tropospheric ozone, below 15-km, of which at least a part is the result of human activities. If compressed to ground-level 1 atm pressure, the total ozone content of the atmosphere would become only a

3-mm thick layer. Since ozone blocks the UV radiation and shields the life on Earth from harmful mutagenic photons, it is logical to expect that locations that are under a hole in the ozone layer might prove optimal for ground-based UV observatories.

The polar regions are harsh environments, though much easier for scientific investigations than space itself. Polar instrumentation requires specialized design for extreme-cold temperatures, but that is true also for space-based instruments. In contrast to space, heat dissipation is not a problem for such instrumentation, since cooling can be done to ambient air. In addition to operating at temperatures averaging −60°C during the winter, polar instruments must either prevent or withstand the formation and collection of ice on apertures, windows and moving parts. Above-ground installations must prevent their burial by drifting snow. Finally, these instruments must be well-tested so that they require negligible maintenance during the winter.

The Arctic environment is presumably less suited to astronomy than the Antarctic. The reasons are the higher level of atmospheric contaminants from trans-polar flights, and man-made pollutants such as industrial effluents from the countries in the northern hemisphere. Both factors influence the transparency of the air column above any possible observing site in the Arctic. Additionally, the Arctic region lacks high-altitude sites; this affects negatively any attempts at UV observations.

The Antarctic regions have attracted significant astronomical interest in the last decades, as witnessed by the intensive activity of the inter-divisional Working Group "Encouraging the International Development of Antarctic Astronomy" created by the IAU. Ashley et al. (2004) argued that the high Antarctic plateau contains the best astronomical observing sites on Earth and proposed the deployment there of a network of robotic telescopes. At present, there are two major contending primary locations for Antarctic astronomy: Dome A and Dome C.

Dome A, or Dome Argus, located at 80°22′S, 77°21′E, is on a 4-km high plateau located ∼1200-km inland. In the Antarctic summer (January) of 2005 a Chinese expedition arrived at Dome A and installed an automatic weather station. The coldest air temperature recorded by this station at Dome A during 2005 was −82.5°C. Astronomical site testing at Dome A was discussed by Lawrence et al. (2006).

Dome C, also known as Dome Circe or Dome Charlie, is located at 75° 06′.5S, 123° 23′.7E, at an altitude of 3.2-km above sea level 1,100-km inland from the French research station at Dumont D'Urville and within the polar vortex. In 1996, a French-Italian team established a summer camp at Dome C. The site hosts now an all-year manned facility, the Concordia Station, which became operational in 2005 and had a first winterover in February 2005 with a staff of 13. The very good seeing conditions at Dome C were described by Lawrence et al. (2004). The implications of the atmospheric conditions at Dome C for astronomy were discussed by Lawrence et al. (2007).

The advantages of both Dome A and Dome C from an astronomical point of view include very low infrared sky emission, a high percentage of cloud-free time, and a low aerosol and dust content of the atmosphere. In both locations there are no katabatic winds[1], typical for the coastal regions of Antarctica, because of their elevated locations and their high relative distances from the edges of the Antarctic Plateau. Dome C is located at the center of the austral auroral oval. The astronomical seeing was measured at Dome C and, while mediocre near the surface, the expectations are that at heights of a few tens of meters above the surface the seeing will be superior to that at any other astronomical observatory on Earth, including Cerro Paranal (Lawrence et al. 2004).

Our attention was drawn to an Antarctic possibility for ground-based UV astronomy by the oft-publicized "ozone hole" discovered by the British Antarctic Survey scientists Farman et al. (1985); the hole forms because chemical reactions on ice particles in polar stratospheric clouds (PSCs) in the cold Antarctic stratosphere, cause a massive, though localized and seasonal, increase in the amount of chlorine present in active, ozone-destroying forms. This process is localized into a relatively small region (the "hole") because the polar vortex formed over Antarctica is very tight.

The best-known images of the ozone hole are from the TOMS instrument that operated on the Nimbus-7 satellite. Since it is known that ozone (O_3) strongly absorbs the ultraviolet, we hoped that an Antarctic location might provide benefits in the transparency because of the O_3 destruction. This, even though the amount of dark hours in the Antarctic is smaller than at temperate latitudes.

The UV region is colloquially divided into a number of regions. UV radiation with a wavelength longer than 320 nm is called "UV-A"; it is not absorbed by O_3 thus might be observable from the ground. "UV-B" refers to radiation with a wavelength between 280 and 320 nm. These wavelengths are on the lower edge of O_3's UV absorption band, in the so-called "Huggins bands", and are absorbed. The absorption cross-section of O_3 increases by more than two orders of magnitude between 320 nm and the peak value at ∼250 nm. Depletion of the O_3 layer would primarily result in increased UV-B transmissivity.

The atmospheric transparency is governed by the radiative transfer equation, where the affecting factors are listed explicitly:

$$I_\lambda = I_0 \times \exp[-\tau_\lambda^R - \tau_\lambda^A - \tau_\lambda^{H_2O} - \tau_\lambda^{O_3} - \tau_\lambda^{Clouds}] \qquad (2)$$

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[1] A katabatic wind is a wind that blows down a topographic incline, such as from the mid-Antarctic plateu to the coast.

Antarctic locations have a much lower Rayleigh (R) optical depth than other sites since they are effectively at high altitudes. This is because the Earth's rotation flattens the atmosphere at the poles (a ∼400-m effect at the South Pole). The aerosol (A) and water optical depths are also significantly reduced. For the locations discussed here, the cloud optical depth is also very small and the ozone contribution could be crucial.

However, it seems that the ozone hole is not really a hole, i.e., a complete absence of overhead ozone covering a large sky fraction, but rather a mild reduction in the column density of ozone over the "hole" region. The reduction of ozone optical depth is only ∼30–50% at the hole maximum. Since the ozone absorbs the UV through its Huggins and Hartley bands, and the extension of visibility should come from the blue end of the atmospheric transmission into the ultraviolet, this modest reduction in ozone causes only a ∼50 Å shift in the blue end of the atmospheric transmission.

Moreover, studies of the ozone distribution showed that the low-ozone condition happens in both hemispheres during local spring; this implies that the winter dark time valuable for astronomy would not benefit much from a hole in the ozone layer.

Fig. 1 An Antarctic telescope, such as the AFOS (Antarctic Fibre Optic Spectrometer), has to operate high above the icy surface to prevent built-up of wind-blown snow and to reach atmospheric levels with excellent seeing (source: Dempsey et al. 2004)

The AFOS (Antarctic Fibre Optic Spectrometer, see Fig. 1) is a 30-cm Newtonian telescope which injects light through six 30-m long optical fibres onto a 240–800-nm spectrograph and onto a 1024 × 256 pixel CCD camera. AFOS was designed to probe the suitability of the atmosphere above the South Pole for astronomy in the UV and visible wavelength regions by observing bright, standard A and O-type stars (Dempsey et al. 2004). The observations were designed to probe the UV atmospheric cutoff wavelength, absorption due to oxygen and water, and the effect of auroral emissions on observations. Unfortunately, the results pertaining to the exact location of the UV cutoff and its seasonal changes are not readily available.

We must conclude that the Antarctic establishment of a major UV observing facility is probably not justified. It does make sense to initiate a program of studying the UV atmospheric transparency during the Antarctic night, perhaps at the higher location of Dome A, which would be relatively easy to justify given the modest expenses it would require and might extend the ground-based accessible window to ∼300 nm or slightly below.

4 Balloon UV astronomy

Since, as shown in the previous section, one of the culprits in limiting the capabilities of Earth-based UV observatories is the atmospheric absorption by O_3, one obvious solution is to lift the telescope above this layer without locating it completely out of the atmosphere.

Figure 2, from Wehr et al. (2002), shows observations by the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on ESA's ENVISAT satellite. The observations consist of spectrometry of setting stars that are occulted by the atmosphere. This allows the derivation of the vertical profiles of ozone and, for the purpose of this paper, it

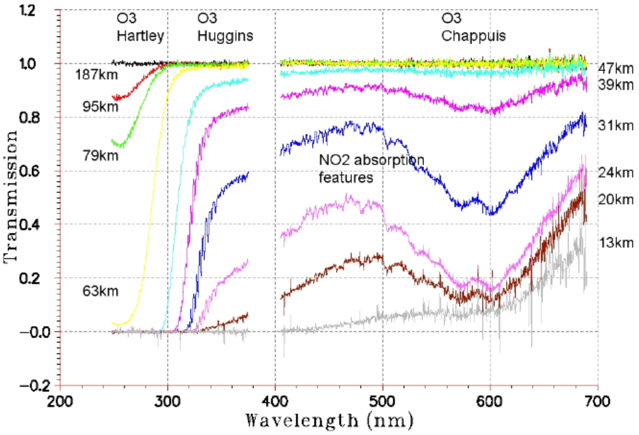

Fig. 2 Atmospheric transmission measured on May 6, 2002 by the GOMOS spectrometer on the ENVISAT spacecraft (source: Dempsey et al. 2004)

demonstrates the shift of the blue wing of the transmission with altitude. The figure shows that by lofting a telescope to 39-km would allow observations at 20% transmission or better down to 320-nm.

Historically, the Geneva observatory was the pioneer of UV astronomy ballooning by designing and building stabilized gondolas to carry telescopes to altitudes higher than 40-km. As far back as the early 1970s investigators there launched balloons to investigate the spectra of stars in the UV (Navach and Lehmann 1971; Navach et al. 1973). However, most of the scientific flights were done by a collaboration of French (Marseille, LAS) and Swiss (Geneva Observatory) teams.

The first flights were with the SCAP-2000 telescope, followed by the larger FOCA telescope. The last flights were with the 40-cm FOCA equipped with an image-intensifier based detector with electronic readout.

SCAP-2000 was described by Hugenin and Magnan (1978). The small telescope provided images in a band that was approximately Gaussian-shaped and was centered at 2015 Å with an FWHM of 188 Å that reached as faint as 13 mag. with 30 arcsec resolution. Results from SCAP-2000 flights pertaining to extragalactic astronomy were published by e.g., Courtes et al. (1981).

The FOCA system consisted of 40-cm aperture telescopes and was described by Milliard et al. (1991). Two versions were operated: FOCA-1000 ($f/2.6$) and FOCA-1500 ($f/3.8$), with the number denoting the focal length of the telescope. The systems provided a $2^\circ.3$-diameter field of view and 20 arcsec resolution, or $1^\circ.5$-diameter field of view with 12 arcsec resolution, respectively. The focal plane consisted of a MCP intensifier with a CsTe cathode recording the images on IIaO photographic film. The mirror coatings were optimized for high reflectivity in the 1800 to 2100 Å band, but the bandpass was effectively defined by the atmospheric extinction by molecular oxygen, and the resulting bandpass was centered at 2010 to 2030 Å. Results from the SCAP experiment related to extragalactic astronomy were reported by Blecha et al. (1990).

My impression is that the option of balloon-borne UV astronomy has not been sufficiently explored. It might be attractive, albeit limited in spectral range, because the cost of a balloon flight is orders of magnitude lower than that of a satellite. Moreover, while the SCAP and FOCA flights were generally of short, one-night duration, with take-off from France and recovery in Italy, it is now possible to perform very long duration flights using stratospheric balloons.

The Ultra Long Duration Balloons (ULDBs), developed by NASA Goddard's Wallops Flight Facility in the USA, can provide scientific measurements above 99% of the atmosphere. The balloons are designed for 100-day missions with floating altitudes close to 35-km, but might be adaptable to reach higher altitudes. Transported by stratospheric winds around the globe at an average speed of 30 m/s, such ULDBs circle the Earth in about two weeks. The balloons are 120 meters in diameter and can carry payloads up to 1500-kg. A ULDB is a super-pressure balloon made of a composite fabric (polyester + polyethylene film and fabric) filled with Helium and hermetically sealed. Meridional tendons provide additional rigidity to the envelope. The pressure inside the envelope is maintained above ambient at all times, to keep the balloon afloat at a constant altitude. During daytime, the internal pressure increases due to solar heating but the volume remains constant due to the envelope rigidity. At night the pressure drops due to infrared radiative cooling to space, but as long as the internal pressure remains above ambient, the balloon stays at the same altitude.

Balloons at temperate latitudes can operate during daytime to accumulate electrical energy using solar cells, then operate at night on battery power to provide UV observations. The data can be transmitted to a ground control station using geo-synchronous communication satellites in the same manner airborne telephony and internet access are now available to the general aviation. Alternatively, NASA developed 150 kbps data transmission capability for ULDBs using the TDRSS Multiple Access service. There appears to be no real "show-stopper" to implement a long-duration, high-altitude option for UV astronomy.

5 The Moon as a platform

A NASA web site is currently advertising the Moon as an ideal location for astronomical observatories:

> "*Why is the moon such a good place for astronomy? First of all, the moon has no atmosphere. The sky is perfectly black and the stars do not twinkle. Stars and galaxies can be observed at all wavelengths including x-ray, ultraviolet, visible, infrared, and radio. In contrast, the Earth's atmosphere absorbs light, causes distortion, and totally blocks the x-ray, ultraviolet and certain infrared and low frequency radio signals.*" (NASA Aerospace scholars 25 Oct 2006)

Is this correct? Are there any specific and definite advantages to lunar observatories in comparison with space-based ones?

Since the US presidential pronunciation of a return to the Moon, astronomers primarily in the US have considered what kind of benefits might the lunar surface offer to their discipline. While some advantages are obvious, such as radio astronomy from the lunar hemisphere facing away from the Earth so that a radio telescope there would be shielded from man-made emissions, there is no general consensus whether a lunar UV telescope would be a good step to take. This is still part of the scientific debate, since some propose

Fig. 3 The S201 experiment on the lunar surface, deployed in the shadow of the Lunar Excursion Module of the Apollo 16 mission (source: NASA)

building there giant telescopes based on the principles of liquid mirrors.

There are definite advantages to operations from the Moon, but these are similar to operations in deep space. The lack of an atmosphere mitigates extinction and refractive distortion. The possibility of radiative cooling of instruments is advantageous. The slow sidereal rate implies that tracking mechanisms can be simpler. The Moon can provide a large and stable platform for many telescopes. Finally, the US exploration initiative may offer on-site human maintenance. The low gravity can sometimes be a blessing, as will be seen below.

There are also lunar disadvantages in comparison to deep space, such as operations at L2. Bringing observatories to the moon requires a powered descent (higher launch mass, enhanced complexity). Dust and condensed gases may collect on optics or bearings, and on that I expand below. Bearings and drives are required for a lunar telescope, vs. gyros and/or reaction wheels on a spacecraft. The possible lunar atmosphere may prove problematic. Only half of the sky can be available at once to a lunar observatory located at one of the Moon's pole.

One should remember that UV astronomy HAS already been done from the Moon. The S201 experiment carried to the lunar surface by the Apollo 16 flight consisted of a 22-kg package with a 75-mm aperture magnetically-focused electronographic Schmidt camera with a field of view of 20 degrees and an angular resolution of $\sim$2 arcmin at the field center and $\sim$4 arcmin at the field edges (Carruthers 1973; Carruthers and Page 1984). The experiment used different exposure times for each observed field, from 1 minute up to 30 minutes, to circumvent the image spread from bright objects. The camera was deployed in the shadow of the LEM to mitigate straylight and was manually pointed to the targets.

The spectral response was set by the KBr cathode and by one of the two interchangeable correctors, one made of LiF and the other of CaF_2 with a thin coating of BaF_2 (to block Lyman α at the low temperatures expected on the Moon). Prior to taking off from the lunar surface, the electronographic film cassette was retrieved by the astronauts and returned to Earth. The film was digitized and measured, and the results, mainly referring to stars brighter than 10 mag, were published in a series of papers and NRL reports.

The backup S201 instrument was used, after minor modifications, on the Skylab space station to observe comet Kohoutek (Page 1974). This allowed the direct detection of the comet's Lyman α halo from two-band imaging, one including the line photons and the other blocking them. The observations were performed in conjunction with the UV spectrometer S019, an objective-prism spectrograph on Skylab.

A series of studies was conducted at the Marshall Space Flight Center between 1990 and 1993 to examine concepts of lunar telescopes. These ranged from a 16-m aperture Large Lunar Telescope, through a 4-m Lunar Cluster Telescope Experiment, to a 1-m Lunar Ultraviolet Telescope Experiment (LUTE). The latter was taken through a Phase A study in collaboration with Hugues Danbury Optical Systems, Inc., but had no follow-up. LUTE was seen at times as the precursor of a lunar-based UV interferometer that could offer unequalled angular resolution while relying on the stability of the lunar regolith. Recently, the idea of a large lunar telescope has been revived by Angel et al. (2006) but this might be adversely affected by the lunar environment itself.

5.1 Lunar dust and atmosphere

If the lunar surface contains large quantities of dust suspended above it, and if it has a very thin atmosphere, this could be very bad news for lunar telescopes and, in particular, for those planned to observe in the UV.

The tenuous lunar atmosphere contains ^{40}Ar, ^{4}He, O, CH_4, N_2, CO, and CO_2 that were detected in-situ by the Apollo astronauts. The total mass of the atmosphere is $\sim$100 tons, and it is naturally supplied at a rate of $\sim$10 gr sec^{-1} (Levine and Zawodni 2007). Most of the atmosphere might originate from outgassing of the lunar interior (Schultz et al. 2006). The lunar atmosphere is much denser during the lunar night (when it cools) than during daytime, and also its composition changes: Ar condenses at sunset and is only released in the morning; the small amount of CO_2 also freezes out at night. There is a strong tendency for the atmosphere to migrate across the terminator from the day to the night side.

The solar wind sweeps the lunar atmosphere into space, limiting its density to that of a collisionless gas (an exosphere). For a 1000× denser atmosphere, this process inverts itself and the atmosphere becomes stable for tens of millennia. The Apollo missions temporarily increased the lunar atmospheric density ten-fold by rocket exhaust (mostly CHONs). Each Apollo landing mission deposited significant amounts of rocket exhaust and spacecraft effluents into the thin lunar atmosphere (Vondrak 1974, 1988). Large-scale human activity on the Moon that would release rocket exhaust and human pollution gases, could push the total atmospheric mass over the limit and create a highly tenuous atmosphere that would be quasi-stable, threatening one of the most important asset that the Moon offers: sterility and almost atmosphereless nature (Levine and Zawodni 2007).

Reports of Apollo 15 and Apollo 17 astronauts, and Lunokhod-2 observations, suggest that the Moon also has a very high, thin dust atmosphere. Apollo 15 astronauts detected an excess of light while photographing the solar corona from lunar orbit, just after sunset. McCoy et al. (1975) claim this as evidence for a scattering source located a few kilometers above the lunar terminator.

While in orbit, the Apollo 17 astronaut Eugene Cernan observed light streamers just before sunrise, suggesting a scattering atmosphere extending beyond the 100-km altitude Apollo orbit (McCoy and Criswell 1974). Lastly, the Russian lander Lunokhod-2 detected an unusually bright sky background with a dependence on the zenith angle of the sun, once again suggesting a light-scattering atmospheric component (Severny et al. 1975). This report is similar to the finding from the analysis of the LMC observations performed with the S201 camera (Page and Carruthers 1978) and to reports from the Surveyor Moon lander vidicon observations of a horizon glow (Murphy and Vondrak 1993). These reports revealed an additional diffuse background whose intensity was related to the camera line-of-sight angle with the lunar horizon. This was attributed to scattering of sunlight by electrostatically-levitated dust suspended above the lunar surface.

The Apollo 17 astronaut Jack Schmidt suggested the following explanation for the Cernan report (quoted in Angel et al. 2006 and with my additions in square brackets):

> "*The 'streamers' we saw appeared to be related to the sun with the moon as an occulting disk of sorts. There is at least one paper on this. I do not believe that these extremely long streamers from the sun out into space were indicators of levitated lunar dust but rather of solar activity. There was some broad horizon glow just before sunrise that may have been caused by dust as seen through a very long path, however, in over 30 years, I understand from the Macdonald [McDonald?] Observatory people [that] the corner reflectors have shown no sign of dust accumulation on their cubes. Surveyor saw what some have interpreted as levitated dust at sunset and I think that is in their mission reports. Frankly, I don't think it will be a problem and if it is there may be an electrostatic countermeasure.*"

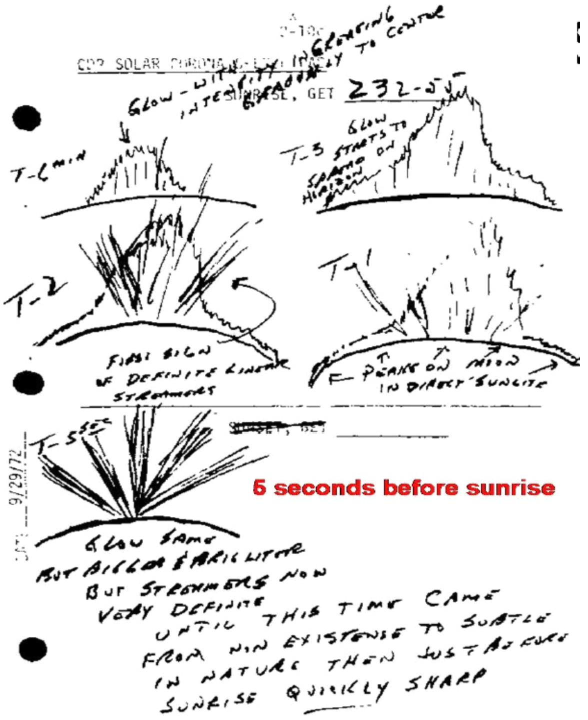

Fig. 4 A page off Eugene Cernan's Apollo 17 notebook: can this be taken as evidence for high-altitude lunar dust? (source: Stubbs et al. 2005)

These possible show-stoppers, high amounts of dust and a possible condensable atmosphere, argue in favor of an extensive site testing program for possible observing locations on the Moon that must take place before detailed studies of lunar telescopes are encouraged.

5.2 A lunar liquid-mirror telescope (LLMT) for the UV?

Angel et al. (2006) proposed to build a very large telescope on the Moon that would be dedicated to IR observations for cosmological purposes. They concluded from their preliminary analysis, in the framework of the Phase II study of a "Deep Field Infrared Observatory Near the Lunar Pole", that the presence of dust, either near the lunar surface or suspended at some altitude could be a serious, and perhaps decisive problem for a LLMT.

Primary mirrors made as a spinning dish of liquid in a gravity field represent a completely different technology from that of classical telescopes, with the potential to achieve very large size and high optical quality for an affordable system cost. Liquid mirrors take on a smooth and

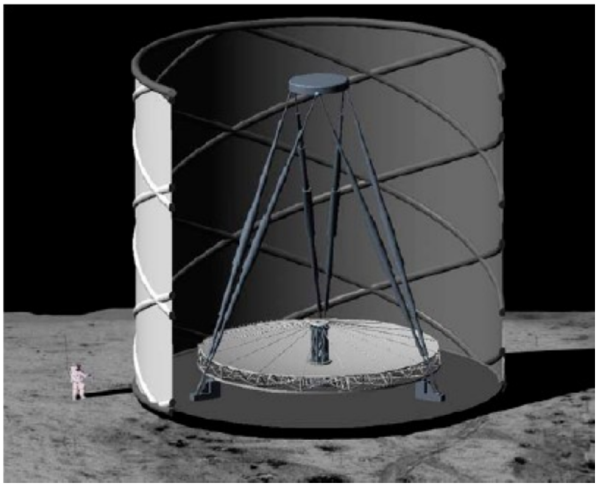

Fig. 5 A 20-m diameter liquid mirror lunar telescope proposed by Angel et al. (2006)

precise surface automatically, and when rotating in a gravitational field, assume the parabolic figure needed for a telescope primary. Mercury has been used on Earth to produce such inexpensive mirrors with excellent surface quality and the same technique should work on the $1/6g$ lunar surface.

Angel et al. (2006) conceived a 20–100-m survey telescope for the infrared that would operate at a lunar polar location. The dish of reflecting liquid would be levitated by a superconducting bearing (against an air bearing on Earth). The secondary mirror would be supported near the prime focus, some 25-m above the liquid mirror. The corrected field would be relayed to an instrument module below the mirror, which would be shielded from radiation by lunar soil, through a central hole in the bearing. The telescope would be surrounded by a cylindrical solar radiation shield made of very lightweight multi-layer insulation, feasible given the low gravity and absence of wind, but one would have to consider micro-meteorite penetration that would add to the straylight.

The ideal location for such a lunar LMT would be near one of the Moon's poles, in a well-shaded crater where the telescope would be in permanent shadow to reduce straylight, but close to a mountain peak in quasi-permanent sunshine where solar panels for power generation and communication antennas to an Earth control center could be erected. The closer the site would be to the pole, the stabler could be the thermal environment. For an IR telescope, as proposed by Angel et al. (2006), there is a need to avoid infrared radiation from Earth, but this is not a requirement for an UV telescope. On the other hand, the apparent diameter of the Earth in UV is much larger than in the IR, since the geocorona extends to ~80,000 km and it emits copious Lyman α photons. Good Earth avoidance of a lunar UV telescope is, therefore, a necessity.

The conclusion is that the Moon appears to be a less suitable and attractive location for UV astronomy than deep space far from the Earth, with the possible exception of a UV interferometer that could definitely benefit from a tectonically-stable location (once UV delay lines are developed).

6 Discussion and conclusions

I have shown here that the scientific community has experimented with a large variety of configurations to collect UV observations. The slim future, with only (part of) the HST, GALEX, FUSE, XMM's UV/OM and SWIFT's UVOT available to the community, should provoke creative thinking about future missions. This paper is a contribution in this direction.

The discussion above has shown that cost-saving measures, such as combining an observatory with a manned space mission, are probably not beneficiary to science. The community has probably missed an opportunity for limited UV science at low cost by using ULDBs; this can still be corrected, though it would never achieve the capabilities of deep space observatories. There seems to be no alternative to a space, free-flying, large UV telescope. Yet even here there are some locations that are better than others.

Is there an ideal location for a UV observatory? The identification of the best possible location for a UV telescope relies on one of the big advantages of the UV band in comparison with other spectral domains. O'Connell (1987) showed that the sky background in the UV, in low Earth orbit, is much fainter than that extrapolated into the UV from the optical domain. Even in the UV there are diffuse sources that increase the background. Within the Solar System, the most important background once a UV telescope is in deep space, far from the Earth and its geocorona, is the zodiacal light and, in the Earth-Moon system, the libration clouds of dust. The importance of properly accounting, if not of eliminating, such foregrounds when dealing with extragalactic observations, was stressed by Mattila (2006).

The UV background was discussed within the compilation of astronomical backgrounds of Leinert et al. (1998). The spectral distribution of this background component follows the solar spectrum, though it might be somewhat reddened. The zodiacal light contribution decreases strongly with heliocentric distance, as shown by Toller (1983) from Pioneer 10 observations. The conclusion is that if we are seeking the ultimate location of a UV observatory in the Solar System, this should be at least 3.3 a.u. from the Sun. For reasons of electrical power generation and communications capability, locations beyond the orbit of Jupiter or Saturn should probably be rejected.

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