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Naked-Eye Sunspots

Humans have been looking at the Sun for millennia. Nevertheless, on most occasions one only manages to be dazzled. But there are some situations in which the intensity of the light of the Sun diminishes and we can observe the solar disk with the naked eye. Some examples are the Sun observed through fog or during a dust-storm, or even the Sun observed through the smoke during a forest fire. On these occasions, we can see the solar disk without being dazzled. If there was a sunspot of great size just at that moment, then we might distinguish it inside the solar disk (see Figure 2.1).

There are several myths concerning the vision of spots or blemishes on the Sun in antiquity. For example, a supposed Aztec pre-Columbian myth has a god-Sun (creator of the world) with dirty marks on his face. This seems to be slightly more convincing than some supposed drawings of sunspots in Egyptian civilization. One can also mention a beautiful story from the area of the Zambesi in Africa that seems to be more credible. The Moon envies the Sun and throws mud at its face. Luckily, this does not happen very often since the Sun is vigilant. But every ten years approximately, the Sun loses concentration and gets dirtied by the mud (Brody, 2002).

Undoubtedly written observations are more trustworthy than myths and orally transmitted legends.[1] A 3000-year-old Babylonian tablet might contain a reference to observations of sunspots (Sayce, 1877). Surviving Late Babylonian astronomical diaries are very detailed (Sachs and Hunger, 1988), but a clear allusion to sunspots has not been found. It should be emphasized that: (1) no more than 5% of the original texts have survived and (2) systematic observations such as eclipses or planetary movements were recorded in abundance, but other sporadic events such as aurorae or meteors are very scarce. One can speculate that naked-eye sunspot observations in

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[1] Early writing systems are dated in the late 4th millennium BC. However, they were not a sudden invention and were based on previous traditions of symbol systems (Houston, 2004).

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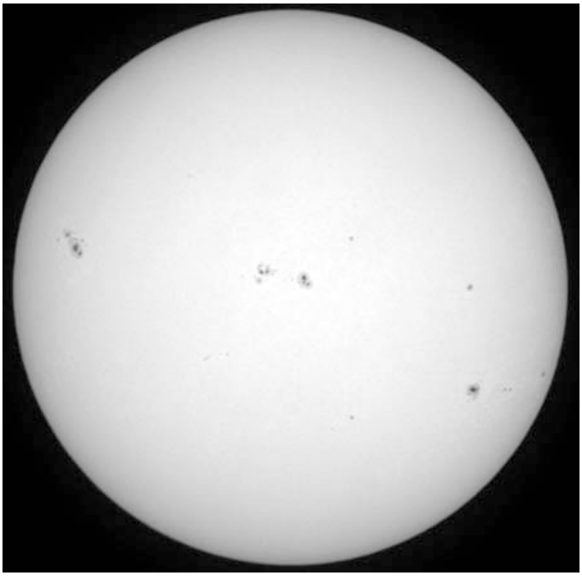

Fig. 2.1. Large sunspot groups in the solar disk on 27 October 2001 (courtesy of Catania Astrophysical Observatory). The amateur astronomer J. Ruiz saw, that day, four naked-eye sunspots using a filter.

China go back at least to the twelfth century BC (Hsü, 1972) and, probably, the classical Greeks also observed sunspots.

Bicknell (1968) has suggested that a naked-eye sunspot was observed by Anaxagoras of Clazomenai (500–428 BC) in 467 BC, but it is just a supposition. Sarton (1947) noted that there are no clear references to sunspots in classical literature. However, there are some texts that might suggest systematic solar observations for weather prediction. There are several references to possible naked-eye sunspot observations in the surviving fragments of *De Signis Tempestatum* ("On weather signs") by Theophrastus (371–287 BC). The work consists of several chapters describing signs of different weather meteors. Three fragments have references to possible sunspots (Hardy, 1991): (1) "If the Sun has a black mark when it rises, or if it rises out of clouds it is a sign of rain" (in the section "Signs of Rain"), (2) "If the Sun rises with a burning heat but does not shine brilliantly, it is a sign of wind. If the Sun has a hollow appearance, it is a sign of wind or rain... also black spots on the Sun or Moon indicate rain, red spots wind" (in the section "Signs of Wind") and (3) "If the Sun rises brilliantly but without scorching heat and without showing any special sign on his orb, it indicates fair weather" (in the section "Signs of Fair Weather"). We consulted the *Opera* of Theophrastus (Theophrasti Eresii, 1866), but an English translation of *De Signis Tempestatum* can be consulted (Theophrastus, 1916).

Nevertheless, Theophrastus might not be an "observer of sunspots" in the strict sense since he only expounded a simple rule of weather prediction using sunspots. Later, we can find other similar texts in Greek literature. Examples may be verses 822–824 of *Phaenomena* (Appearances) by Aratus (315–240 BC) or some verses of *Georgics* by Virgil (70–19 BC). Modern knowledge of major maxima and minima of solar activity (Usoskin et al., 2007) can help us. During the 4th century BC solar activity was low. Thus, it is improbable that Theophrastus's contemporaries saw naked-eye sunspots. However, solar activity during the 5th century BC was very high and it is quite probable that ancient Greeks observed sunspots (including Anaxagoras). Moreover, it is well known that the pre-Socratics were keen observers.

This chapter is devoted to naked-eye sunspot observations, and especially to their possible use for the reconstruction of solar activity during the last two millennia. Firstly, we will study the human eye as a detector of light. Secondly, we will study the criteria of visibility of sunspots. Then, we will be ready to present the historical observations that have survived and the modern programmes of observation carried out by amateur astronomers. Finally, we will show the interest of this kind of observation for the reconstruction of the history of the Sun during the last two millennia.

2.1 The Human Eye as a Detector of Light

In the context of this book, the human eye is the available detector. Therefore it is of interest to review its main properties. *Oculus hoc est fundamentum Opticum* by C. Scheiner (1619) is probably the first work about visual optics and anatomy. It includes detailed observations of the pupil during accommodation and of the refractive power of the lens and the aqueous and vitreous humour (Southall, 1922). He was impressed by the analogy between the eye and the camera obscura (Daxecker, 2004).

Sunlight enters the eye by passing through the cornea, where the image is focused. The brightness of the image is controlled by the varying diameter of the pupil, the aperture of the optical system. The average size of the exposed pupil varies throughout life, but averages between 6 and 7 millimetres. The iris regulates the amount of light passing through the pupil, acting like a camera shutter. As the amount of light entering the eye diminishes, the iris muscle pulls away from the centre, causing the pupil to dilate and allowing more light to pass. The image is given a fine focus by the *lens*. Finally the image falls on the retina, where the real power of the eye is located (Figure 2.2). At any given instant, the retina can resolve a contrast ratio of 100:1.

The retina is a thin layer composed of five types of cells lining the back of the eye. The cells are arranged in four layers. Using the outermost two, the retina can turn parts of itself on and off as it analyses the image. The photoreceptors are located behind. The ones that allow us to see colour are the cones, with their concentration moving outwards from an area of the retina called fovea centralis through the central part of the retina, called the *macula*. A few degrees from the fovea appear the rods, outnumbering

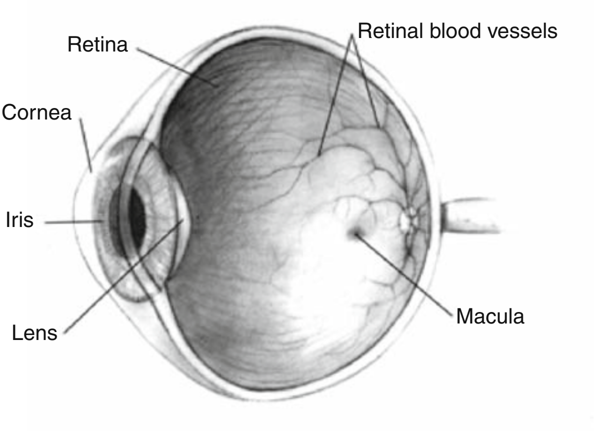

Fig. 2.2. Cross-section of the human eye.

the cones by 20 to 1, and acting as light collectors. These elements respond to light by generating electrical impulses that travel out of the eye through the optic nerve to the brain.

The sensitivity of the eye ranges over about 14 orders of magnitude from a minimum threshold to a light level that could possibly cause damage. The photopic (cone) threshold is almost four magnitudes above the minimum. The next two magnitudes are called the mesopic range and it is here that both rods and cones contribute to vision. The scotopic peak sensitivity (of rod cells) is at about 500 nm, while photopic sensitivity peaks at around 550 nm (Figure 2.3). Wavelengths shorter than 315 nm are absorbed by the cornea (causing injury) and do not reach the retina.

As in the case of telescopes, eyes are not perfect optical systems. So the relative intensity of the object is distributed across the retina as shown in

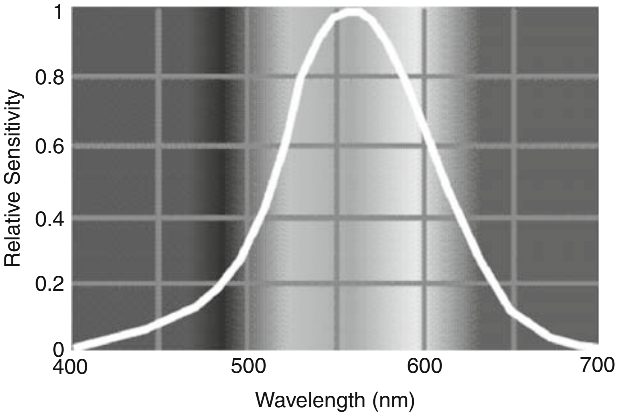

Fig. 2.3. Photopic sensitivity of the human eye.

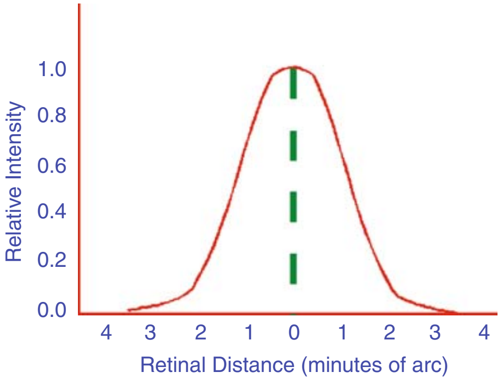

Fig. 2.4. The Point Spread Function of the retina of the eye.

Figure 2.4. At any given instant, the retina can resolve a contrast ratio of 100 to 1.

2.1.1 Solar Damage to the Eye

Solar retinopathy is a kind of damage to the eye's retina, particularly to the macula, induced by prolonged exposure to solar radiation. It usually occurs due to staring at the Sun or viewing a solar eclipse. The main damage to the eye is photochemical rather than thermal (Ham et al., 1976). Young people are much more likely to suffer damage than their elders, because the eye gradually becomes yellower with age, filtering out the harmful UV photons (Istock, 1985).

In a letter to British philosopher John Locke (1632–1704), Isaac Newton (1643–1727) describes the effects of looking at the reflection of the Sun in a mirror, while standing in a darkened room.[2] Westfall (1980) comments that "Newton left the sun alone after that". Newton's description of his symptoms

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[2] "The observation you mention [. . .] I once made upon my self with the hazzard of my eyes. The manner was this. I looked a very little while upon ye sun in a looking-glass with my right eye and then turned my eyes into a dark corner of my chamber and winked to observe the impression made by the circles of colours which encompassed it & how they decayed by degrees & at last vanished. This I repeated a second and a third time. At the third time when the phantasm of light & colours about it were almost vanished, intending my phansy upon them to see their last appearance I found to my amazemt that they began to return & by little & little to become as lively & vivid as when I had newly looked upon the sun. But when I ceased to intende my phansy upon them they vanished again. After this I found that as often as I went into the dark & intended my mind upon them as when a man looks earnestly to see any thing which is difficult to be seen, I could make the phantasm return without looking any more upon the sun. And the oftener I made it return, the more easily I could make it return again. And at length by repeating this without looking any more upon the sun I made such

closely agrees with a typical mild solar retinopathy characterized by a yellow foveolar dot and a central scotoma.[3] The damage was not evident immediately, but after several hours; the symptoms were most visible for a few days, and gradually subsided over a long time (several months), eventually disappearing entirely, or nearly so. Photophobia (in which the victim avoids the light) is also a common symptom.

2.2 Visibility Criteria

When is a sunspot visible by using an instrument? We are especially interested in the response when the instrument is only the human eye. Counting sunspots to establish the sunspot number is of great importance for astronomers, climatologists, and space engineers. Even at present, the sunspot counts are made using small telescopes. For this, several authors have calculated the conditions that must be fulfilled in order for a sunspot to be visible. In particular, their calculations serve to indicate when a sunspot can be visible to the naked eye.

The simplest visibility criteria are based on the spatial resolving power of optical instruments. Rayleigh's criterion establishes that the power of an optical system to distinguish two structures separated by an angular distance

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an impression on my eye that if I looked upon the clouds or a book or any bright object I saw upon it a round bright spot of light like the sun. And, which is still stranger, though I looked upon the sun with my right eye only & not with my left, yet my phansy began to make the impression upon my left eye as well as upon my right. For if I shut my right eye and looked upon a book or the clouds with my left eye I could see the spectrum of the sun almost as plain as with my right eye, if I did but intend my phansy a little while upon it. For at first if I shut my right eye and looked with my left, the spectrum of the Sun did not appear till I intended my phansy upon it; but by repeating this, appeared every time more easily. And now in a few hours time I had brought my eys to such a pass that I could look upon no bright object with either eye but I saw the sun before me, so that I durst neither write nor read but to recover the use of my eyes shut myself up in my chamber made dark for three days together & used all means to divert my imagination from the Sun. For if I thought upon him I presently saw his picture though I was in the dark. But by keeping in the dark and imploying my mind about other things I began in three or four days to have some use of my eyes again & by forbearing a few days longer to look upon bright objects recovered them pretty well, th not so well but that for some months after the spectrum of the sun began to return as often as I began to meditate upon the phaenomenon, even tho I lay in bed at midnight with my curtains drawn. But now I have been very well for many years, tho I am apt to think that if I durst venture my eyes I could still make the phantasm return by the power of my fansy." The quotation is taken from "The Correspondence of Isaac Newton" (Turnbull, 1961, pp. 153–154). The matter is discussed more briefly by R. Westfall (1980, pp. 93–94).

[3] An area of lost or depressed vision within the visual field, surrounded by an area of less depressed or of normal vision.

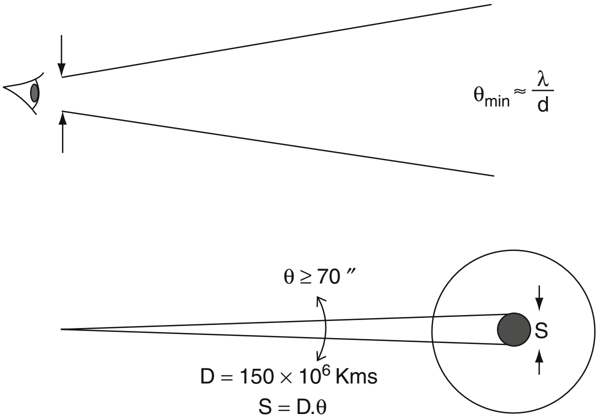

Fig. 2.5. The simplest visibility limit is based on the spatial resolving power of the human eye.

$\vartheta_{\min}$ can be expressed as

$$\vartheta_{\min} \approx (1.22\lambda)/\mathrm{d}$$

where λ is the light's wavelength and d is the diameter of the optical system (see Figure 2.5). The diameter of the pupil of our eyes changes between 1 and 5 mm, depending on the illumination conditions. We can assume a value of 1.5 mm for a diurnal observation and a value of 500 nm for the wavelength of the sunlight. Using these values, we obtain $\vartheta_{\min} \sim 70''$. Spots of this size are not too rare (3%) especially close to a maximum of the 11-year cycle of solar activity. It is obvious to think that a sunspot smaller than the value given for resolution of the human eye must be invisible. However, this logic is naive and contradicted by observation. For example, MacRobert (1989) observed sunspot groups with penumbral diameters from $22''$ to $26''$. It is important to note that since modern observers can use filters, the diameter of the pupil could be greater than 1.5 mm and, therefore, $\vartheta_{\min} < 70''$. The sunspot visibility problem should be approached as a problem of calculating contrast thresholds for the human eye (Schaefer, 1991). Schaefer (1993) developed a theoretical model of sunspot visibility that can be applied to naked-eye observation, direct vision through a telescope or pinhole camera, and telescope projection. In the following paragraphs, we shall show this theory applied to naked-eye sunspot visibility.

The threshold contrast ratio C_{th} is the lowest contrast (with respect to the photosphere) which makes a sunspot visible, and can only be established through physiological experimentation.[4] This threshold depends on the

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[4] In a general form, the contrast ratio is a measure of a display system defined as the ratio of the luminance of the brightest zone to that of the darkest zone that the system can produce.

background brightness, the size scale of the source, and the brightness distribution of the object. Blackwell (1946) presented half a million observations over eight orders of magnitude in brightness and nearly three orders of magnitude in size scale from 19 observers. This work is the definitive study on C_{th} from the physiological experimentation point of view.

Blackwell (1946) defined the critical visual angle θ_{cva} as the effective size over which the eye integrates, or the diameter of the effective pixel of vision. Using Blackwell's data, for diurnal vision one can write

$$\theta_{cva} = (40''/S)[10^{(B^{0.3}/60)}]$$

where B is the effective brightness in lamberts[5] of the photosphere as perceived by the eye and S is the Snellen ratio. This last parameter is a measure of the visual acuity of an observer compared with a standard observer.

We can write C_{th} as a function of B using Blackwell's data for B brighter than 0.001 lamberts using the equation

$$C_{th,B} = 0.0028 + [0.3 - 0.133\log(B)](\theta_{cva}/\zeta)^2 \tag{2.1}$$

where ζ is the angular diameter of the circular sources used by Blackwell.

There are two problems when we try to model sunspot visibility from Blackwell's work. First, sunspots do not have a simple shape (such as circular). Moreover, their shape is smeared out by diffraction and atmospheric seeing. Second, the experience of the observer is an important factor in the detection of sources with lower contrast. See, for example, Schaefer (1990) and Doggett and Schaefer (1994). The experience effect can be included in the model using

$$C_{th} = eC_{th,B} \tag{2.2}$$

where e is a factor based on the experience of the observer. We have e = 1 and e = 4 for experienced and novice observers, respectively.

The total solid angle covered by an idealized sunspot on the solar disk will be

$$\Omega_{sunspot} = \pi R^2_{sunspot}\cos\theta \tag{2.3}$$

where $R_{sunspot}$ is the angular size of the semimajor axis of the idealized sunspot and θ is its heliocentric angle. Moreover, the relation between the sunspot area and the solid angle of the sunspot can be written as

$$A_{sunspot} = (0.173\ \text{millionths per square arcsec})\Omega_{sunspot}/\cos\theta$$

The surface brightnesses for the photosphere, umbra, and penumbra can be calculated from the surface brightness of the centre of the Sun as viewed above the atmosphere (B_{centre}). This surface brightness is equal to 7.8×10^5

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[5] The lambert (symbol L) is a unit of luminance named after Johann Heinrich Lambert (1728–1777). It is equal to $10^4/\pi$ candela per square metre.

lamberts. These surface brightnesses depend on the heliocentric angle from the centre of the disk according to the equations

$$\mathrm{B_{photo}} = B_{centre}(0.41 + 0.59 cos\theta)$$

$$\mathrm{B_u} = B_{photo}(0.17 - 0.09 cos\theta)$$

and

$$\mathrm{B_p} = \mathrm{B_{photo}}(0.76 - 0.02\mathrm{cos}\theta)$$

using visual wavelengths of 5.5×10^{-5} cm (Allen, 1976). Moreover, the contrast ratios of the umbra and penumbra when compared to the background light of the photosphere will be $\mathrm{C_u} = 0.83 + 0.09 \cos\theta$ and $\mathrm{C_p} = 0.24 + 0.02 \cos\theta$. However, these values will vary from sunspot to sunspot. Thus, the result of the visibility model will be expressed with the contrast ratios as free parameters.

The sunspot images are smeared out by turbulence in the atmosphere. In addition, diffraction effects must be taken into account. Thus, we should calculate the two-dimensional convolution of the sunspot structure with smearing functions. However, this calculation is difficult and it is impossible to present the result in a simple and general form. Schaefer (1993) obtained the characteristic area of the convolution as an alternative. It can be proved that the second moment of a convolution of circularly symmetric normalized distributions is the sum of the second moments of the functions being convolved. For this reason, we must calculate the second moments of all the relevant functions.

The second moment of the normalized contrast ratio as viewed by the observer will have a different functional form for every observing method, and will be

$$\mu = \mu_{\mathrm{seeing}} + \mu_{\mathrm{diff}} + \mu_{\mathrm{aper}} + \mu_{\mathrm{sunspot}} \tag{2.4}$$

For the case of naked-eye observations, μ_{seeing}, μ_{diff}, and μ_{aper} can be neglected. For μ_{sunspot}, we can write:

$$\mu_{\mathrm{sunspot}} = (\mathrm{MR_{sunspot}})^2 \left(\frac{0.5[(\mathrm{C_u} - \mathrm{C_p})(\mathrm{A_u}/\mathrm{A_{sunspot}})^2 + \mathrm{C_p}]}{(\mathrm{C_u} - \mathrm{C_p}(\mathrm{A_u}/\mathrm{A_{sunspot}}) + \mathrm{C_p})}\right) \tag{2.5}$$

We can compare the visibilities of the observed light distribution with a uniform circular source. The second moment of a uniform circular source is $\mu_{\mathrm{circ}} = \zeta^2/8$ where ζ is the angular diameter. If we equate the second moments of the uniform circular source and the observed normalized brightness distribution, then the size scale of the equivalent normalized circular source will be

$$\zeta = (8\mu)^{0.5} \tag{2.6}$$

Then, we can write an equation for the contrast ratio for the sunspot as viewed by the observer:

$$\mathrm{C_{obs}} = (\mathrm{MR_{sunspot}}/\zeta)^2 \cos\theta[(\mathrm{C_u} - \mathrm{C_p})\mathrm{A_u}/\mathrm{A_{sunspot}} + \mathrm{C_p}] \tag{2.7}$$

Now, we should compare this contrast ratio against the threshold referenced in Equation (2.2). For naked-eye observations, only the sunspot size is relevant and from Equations (2.4), (2.5), and (2.6), we can write

$$\zeta = 1.74\mathrm{R}_{\mathrm{sunspot}} \tag{2.8}$$

According to our reasoning, the sunspot will be visible if $\mathrm{C}_{\mathrm{th}} < \mathrm{C}_{\mathrm{obs}}$. The limiting solid angle for a visible sunspot from Equations (2.1), (2.2), (2.3), (2.7), and (2.8) can be expressed as follows:

$$\Omega_{\mathrm{lim}} = \frac{\pi[0.3 - 0.133\log(\mathrm{B})]\theta_{\mathrm{cva}}^2}{[(\mathrm{C_u} - \mathrm{C_p})\mathrm{A_u}/\mathrm{A_{sunspot}} + \mathrm{C_p}]/\mathrm{e} - 0.0085/\cos\theta}$$

This general result shows that the visibility has a strong dependence on the observer and a weak dependence on the apparent brightness of the Sun and the position of the sunspot. We can estimate Ω_{lim} using some typical values. When a naked-eye sunspot is observed, the apparent brightness of the photosphere will depend on the observation conditions that can vary widely. However, typical values for B and θ_{cva} are 0.6 lambert and $42''\mathrm{S}^{-1}$, respectively. We can take $\mathrm{A_u}/\mathrm{A_{sunspot}}$ equal to 0.17 (see Chapter 1). In fact, larger sunspots are intrinsically darker than smaller ones (e.g. Collados et al., 1994). Using these values and for a sunspot located near the centre of the solar disk ($\theta \approx 0$), the limiting sunspot size is given by

$$\Omega_{\mathrm{lim}} = (35''\mathrm{S}^{-1})^2\mathrm{e}$$

If we assume typical values for $\mathrm{S} = 1.0$ and $\mathrm{e} = 1$ (for experienced observers), we have a reference value for Ω_{lim} equal to 1225 square arcsec. Schaefer (1993) compared his theoretical results with observations. However, he pointed out that the comparison of a single observation is dangerous. The model's limits are statistical in nature. Blackwell's results give the thresholds for the 50% detection level, and the theoretical model should be compared only against large data sets. Moreover, Schaefer made an observational test of his mathematical model. He observed naked-eye sunspots for 124 days (years 1990 and 1991). The observed solid angle subtended by a sunspots with 50% probability of detection was 2000 arcsec^2 and the theoretical values was $\Omega_{\mathrm{lim}} = 2500$ arcsec^2. Figure 2.6 shows the sunspot visibility fraction as a function of sunspot area, with the observed Ω_{lim} being where the probability of detecting a sunspot is 50%. The value of the model Ω_{lim} strongly depends on the adopted values of S and e. Comparison between the modeled and the observational values shows good agreement. The differences between the two quantities are comparable with the uncertainties in both the sunspot areas and the acuity of the observer.

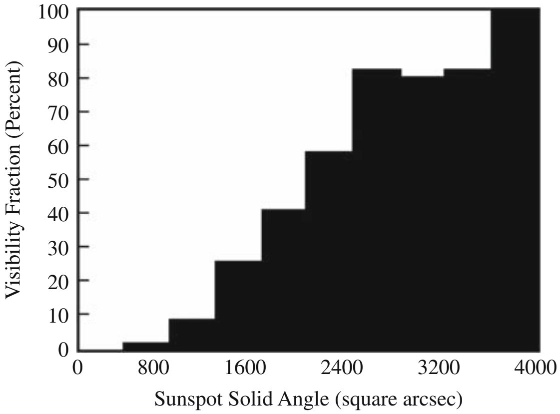

Fig. 2.6. Percentage of naked-eye sunspots visible as a function of sunspot area. Observations by Schaefer (1993) were made for 1990 and 1991. Figure adapted from Schaefer (1993).

2.3 Naked-eye Sunspot Observations

In this section, we will try to provide a general review of naked-eye sunspot records. The historical Oriental observations are the most complete set. However, a few examples of Arabic, European, Mayan, and Indian historical observations are available. Moreover, a considerable number of naked-eye observations were made during the telescopic epoch.

2.3.1 Historical Oriental Observations

The Sun was worshipped in ancient China, and there were daily sacrificial rites for welcoming and seeing off the Sun (Xu, 1990). Bone inscriptions of the Shang Dynasty (ca. 1500–1050 BC) are clear evidence for this. It is known that the ancient Chinese observed and recorded at least four solar phenomena, probably because Sun worship was the cause of spontaneous observations. They are (1) *Ri Hui* (the Sun was dark and gloomy), (2) *Ri Yun* (solar halo), (3) *Ri Zhi* (no definite translation), and (4) *Ri Shi* (solar eclipses). According to Xu (1990), the earliest sunspot observations should be identified by the expression *Ri Zhi* because sunspot is the most reasonable translation, although the words can be interpreted in different ways.

The great majority of the records of naked-eye sunspot observations (95% approximately) come from the East (especially China and Korea). The Oriental record covers a period of time four times longer than the period of telescopic observations. Unfortunately, only approximately 200 records survive. The records suggest the presence of the undecennial solar cycle, but only in the periods where a great density of observations exist (Yunnan Observatory, 1977; Ding et al., 1983; Wittmann and Xu, 1987).

There is information available about the astrological bases of this type of observations and about the differences of philosophy and religion that seem to explain the almost total absence of similar records from the Western world (Needham, 1959). In addition, one also knows how important are the effects of the persistent seasonal haze of the Asian continent on the Oriental record of naked-eye sunspots (Willis et al., 1980).

Nevertheless, our ability to interpret the record is determined by three factors: (1) the observational techniques used, (2) the frequency of the observations, and (3) the capacity of the record to reflect the state of solar activity during that epoch.

Of course, sunspots can be seen with the unaided eye if the sunlight is attenuated by haze, smoke, clouds, or similar, or when the Sun is near the horizon (sunrise and sunset) and the atmosphere becomes another natural filter. However, Needham (1959) has suggested that the Oriental astrologers may have used attenuating filters manufactured with rock-crystal or polished jade. Another possibility is solar observation by reflection on a pool of coloured liquid (Chu Wen-Hsin, 1934; Wang and Siscoe, 1980; Bo Shu-ren, 1983).

Chinese official histories and the systematic record of naked-eye sunspots in China started to be compiled in the Han dynasty (206 BC to AD 220). Moreover, there are numerous local topographies or histories called *Fang Zhi* (local gazettes) that formed an important supplement to the official histories. However, the *Fang Zhi* were ignored by the catalogue compilers until Xu and Jiang (1982).

In the mid-19th century, when Humboldt presented in his *Kosmos* Schwabe's discovery of the solar cycle, and solar studies were revitalized, several authors started to make compilations of naked-eye sunspot records. The most complete pioneering study was done by Kanda (1933), who compiled a catalogue of Far Eastern observations. There are more detailed works by the Yunnan Observatory (1977), Clark and Stephenson (1978) and Chen and Dai (1982). However, the two catalogues most used by the solar physics community are the works of Wittmann and Xu (1987) and Yau and Stephenson (1988). These two catalogues are very similar. There are a few differences in the translation of foreign languages. But the main difference is that Yau and Stephenson (1988) is restricted to records from East Asia extending down to as late as 1918. The most modern and detailed catalogue is the "*Catalog of Large Sunspots (165 BC–1992)*" by A. Wittmann which, although unpublished, can be consulted.[6]

The accounts of sunspots and a great number of astronomical observations such as eclipses, lunar and planetary movements, comets , and novae are mainly cited in astronomical treatises that form important sections of the official dynastic histories of China and Korea. The origin of this great interest in astronomical observation was astrological. An interesting aspect of this interest is that the terminology used in the reports remained almost unchanged

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[6] http://www.astro.physik.uni-goettingen.de/∼wittmann/.

over the last two millennia. With the aid of the catalogues, an overview can be given of the temporal coverage and geographical distribution of the records, and the most usual descriptions of sunspots (Stephenson, 1990).

There are very few reports before AD 300. The earliest reliable and well-dated report of an Oriental naked-eye sunspot dates from 165 BC. Until the year AD 1150, all the reports come from China except for one Japanese observation in AD 851. After that date, there are also reports from Korea but reports from China are more numerous. In AD 1276, 1593 and 1603, there are occasionally reports from Vietnam. Nevertheless, the number of sunspots recorded by ancient observers is very small in terms of modern sunspot observations (Mossman, 1989; Eddy et al., 1989).

With regard to the terms used by Oriental astronomers in their descriptions, there are two basic forms. The first is "Within the Sun there was a black spot" (*hei-tzu*) and the second is "Within the Sun there was a black vapour" (*hei-ch'i*). Occasionally, there are other descriptions using miscellaneous objects appearing within the Sun such as birds or stars. An important fact is that practically all the descriptions are written in Classical Chinese and there is no grammatical plural in this language. Thus, the best is to assume that all sunspot accounts refer to a single spot. Moreover, observations of double or multiple sunspots are recorded on several occasions. The earliest observation of two different spots in the Sun occurs in AD 355.

Stephenson (1990) summarized the time distribution of naked-eye sunspot records in Oriental sources in five characteristics (see Figure 2.7): (1) there are only sporadic reports before AD 1100, (2) the reports are relatively frequent in China and Korea during the 12th Century, (3) there are very few reports in the period AD 1200–1350, (4) there is a marked peak around AD 1370, and (5) there are relatively few reports of sunspots in China and Korea until AD 1600.

Figure 2.7 shows a record with poor uniformity. There are historical explanations for some of the gaps in this figure. For instance, the gap between approximately AD 600 and 800 is due to the sack of the T'ang Dynasty capital

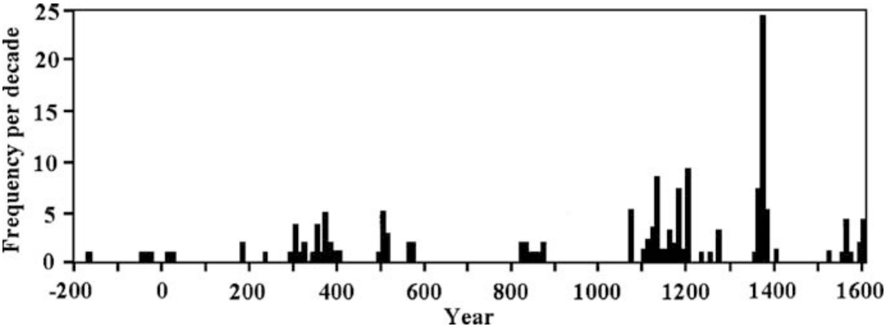

Fig. 2.7. Decadal distribution of naked-eye sunspots recorded in East Asia from 165 BC to AD 1610 (adapted from Yau, 1988).

of Ch'ang-an in AD 755. This situation meant that a large number of ancient records were destroyed. Important documentation was probably lost due to similar facts in other periods (as during the fall of a dynasty).

It is important to point out that sunspots were very often detected near the day of a new moon because at these periods observations were more frequent and intensive due to the determination of the new moon date. This kind of astronomical observation was important for calendar purposes (Wittmann and Xu, 1987).

Another important factor that can explain the poor uniformity of the record is astrology. Stephenson (1990) indicates that more than a half of all Chinese naked-eye sunspots during the pre-telescopic period were reported during the reigns of only six emperors. However, there were approximately 150 emperors during the period covered in Figure 2.7. Park (1977) cites another interesting fact from Korea: in February AD 1204, a sunspot was seen for three days but the Korean Royal astronomer tried to suppress the report. The cause was that he knew from Chinese history that it was a presage of the Emperor's death. Finally, the report was registered and the Korean king died a month later. Curiously, there are no reports of naked-eye sunspots in Korean historical sources during the next 54 years, although several observations were recorded in China! The conclusion is that the influence of astrology in the uniformity of the sunspot record is far from negligible.

Figure 2.8 is a plot of the decadal frequency of astronomical events of all kinds recorded in China from 200 BC to AD 1610. These astronomical observations may be comets, eclipses, lunar and planetary conjunctions, sightings of Venus in daylight, meteors, aurorae, etc.). The figure illustrates the great

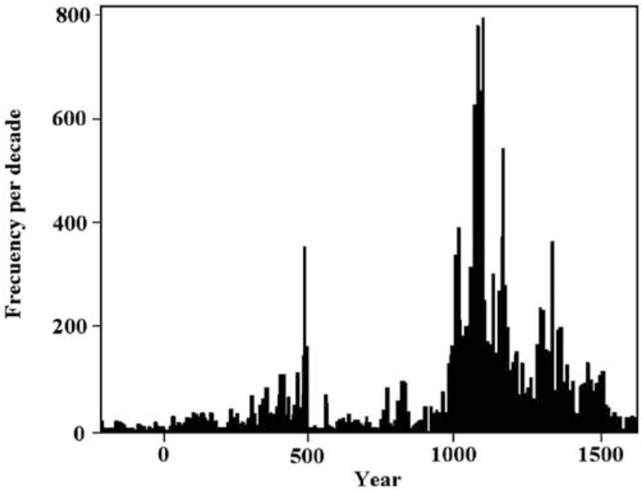

Fig. 2.8. Decadal distribution from 200 BC to AD 1610 of astronomical observation recorded in China (adapted from Yau, 1988).

variability in the number of astronomical phenomena recorded. According to Stephenson (1990), this complex variability must be largely of artificial origin.

Yau (1988) and Stephenson (1990) compared the variability of the naked-eye sunspot record with the variability of solar halos reported in East Asian sources. Although we know that the solar halo is an atmospheric phenomenon (Lynch and Livingston, 2001), it is recorded in the same sections of dynastic histories as sunspots ("solar changes" section). Figure 2.9 shows the decadal variability of solar halos recorded in Chinese sources during the period AD 1–1610. A great variability can be observed. Moreover, some of the main features of Figure 2.9 are similar to those of Figure 2.7. Peaks occurred approximately in AD 400, 1200 and 1400. This result suggests that the long-term variations observed in the sunspot record could be an artifact.

In 2004, a group of Korean solar physicists reviewed historical Korean sources looking for naked-eye sunspots and aurorae (Lee et al., 2004). They used the followings historical sources:

(1) *Koryo-Sa*: The Annals of the Koryo Dynasty (918–1391).
(2) *Choson Wangjo Sillok*: The Annals of the Choson Dynasty (1392–1910).
(3) *Jeungbo Munheon Bigo*: an encyclopaedia of 250 volumes, which was published in 1770 and revised later in 1908.
(4) *Daedong Yaseung*: unofficial historical book of 71 volumes, during the Choson Dynasty.

Table 2.1 presents the dates and descriptions of the naked-eye sunspots that they found. We have added some notes specifying the reference number in the Yau and Stephenson (1988) catalogue or the "new record" character. Lee et al. (2004) indicate that auroral sightings are recorded much more frequently than naked-eye sunspots (788 aurorae with respect to 60 sunspots). The sunspots observed in 1105, 1152, 1608 (17 May) and 1720 have not been included in previous works. Also, the sunspot on 16–19 March 1361 was

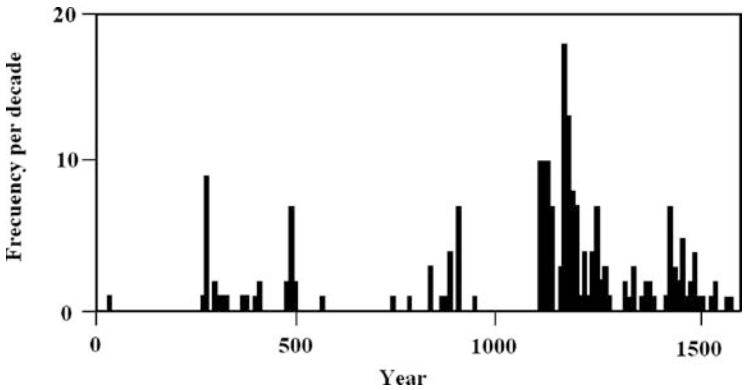

Fig. 2.9. Decadal distribution of solar halos recorded in China (adapted from Yau, 1988).

Table 2.1. Sunspot records compiled by Lee et al. (2004) using Korean historical sources

Year	Month	Day	Brief Description	Notes
1105	2	7	Black light	New record
1151	3	21	Black spot as large as hen's egg	Yau and Stephenson (1988) [79]
1151	3	31	Black spot as large as hen's egg	Yau and Stephenson (1988) [79]
1152	4	1	Black spot as large as hen's egg	New record
1160	9	29	Black spot	Yau and Stephenson (1988) [82]
1171	10	20	Black spot as large as peach	Yau and Stephenson (1988) [83]
1171	11	16	Black spot as large as peach	Yau and Stephenson (1988) [84]
1183	12	4–5	Black spot	Yau and Stephenson (1988) [85]
1185	2	11	Black spot as large as pear	Yau and Stephenson (1988) [86]
1185	3	27	Black spot as large as pear	Yau and Stephenson (1988) [88]
1185	4	18	Black spot	Yau and Stephenson (1988) [89]
1185	11	14	Black spot	Yau and Stephenson (1988) [90]
1200	9	19	Black spot as large as plum	Yau and Stephenson (1988) [93]
1201	4	6	Black spot as large as plum	Yau and Stephenson (1988) [96]
1202	8	23	Black spot as large as pear	Yau and Stephenson (1988) [97]
1204	2	3–5	Black spot as large as plum	Yau and Stephenson (1988) [99]
1258	9	15	Black spot as large as hen's egg	Yau and Stephenson (1988) [103]
1258	9	16	Black spot like a doll	Yau and Stephenson (1988) [103]
1278	8	31	Black spot as large as hen's egg	Yau and Stephenson (1988) [106]
1356	4	4–5	Black spot	Yau and Stephenson (1988) [107]
1361	3	16–19	Black spot	Yau and Stephenson (1988) [108]
1362	10	5	Black spot	Yau and Stephenson (1988) [109]
1371	1	2	Black spot	Yau and Stephenson (1988) [122]
1371	11	21	Black spot	Yau and Stephenson (1988) [125]
1372	5	8	Black spot	Yau and Stephenson (1988) [129]
1373	4	26-27	Black spot	Yau and Stephenson (1988) [132]
1373	10	23	Black spot	Yau and Stephenson (1988) [133]
1375	3	20–21	Black spot	Yau and Stephenson (1988) [136]
1381	3	23	Black spot	Yau and Stephenson (1988) [139]
1382	3	9–11	Black spot as large as hen's egg	Yau and Stephenson (1988) [140]
1387	4	15	Black spot	Yau and Stephenson (1988) [143]
1402	11	15	Black spot	Yau and Stephenson (1988) [144]
1520	3	9	Black gas	Yau and Stephenson (1988) [145]
1556	4	17	Black spot as large as hen's egg	Yau and Stephenson (1988) [146]
1603	4	16	Black spot like a coin	Yau and Stephenson (1988) [154/155]
1604	10	24	Black spot as large as bird's egg	Yau and Stephenson (1988) [156]
1604	10	25	Black spot as large as hen's egg	Yau and Stephenson (1988) [156]
1608	5	10	Black spot as large as pear	Yau and Stephenson (1988) [157]
1608	5	17	Black spot as large as pear	New record
1648	1	16	Black spot	Yau and Stephenson (1988) [183]
1660	5	22	Black gas	Xu (1983) gives a record from China
1720	5	8	Black gas	New record
1720	6	1	Black gas	Yau and Stephenson (1988) [194]
1726	10	21–22	Black gas	Yau and Stephenson (1988) [195]
1743	10	19–21	Black gas	Yau and Stephenson (1988) [197]

compiled by Yau and Stephenson (1988) (catalogue number 108) but only for day 16 and using a Chinese source. Only one naked-eye sunspot was recorded during the Maunder minimum in Korean sources according to the table. It was observed on 22 May 1660. This sunspot was also observed in China (see Xu, 1983). In Europe, Robert Boyle (1627–1691) saw this sunspot with a telescope on 25 May 1660 (Boyle, 1671).

2.3.2 Historical Occidental Observations

Though the majority of the observations contained in the catalogues come from the East, one can find some western observations (including observations from North-Africa, Europe, the Middle East, and Russia).

The most famous European observation of a naked-eye sunspot was related to the death of Charlemagne, King of the Franks and Emperor, by his secretary and adviser Einhard, who wrote *The Life of Charlemagne* (Einhard, 1880). He was not very careful dating the sunspot event. However, there is no doubt that a spot was seen on the Sun in 807 over eight days. In the *Annales Regni Francorum*, a Mercury transit observation appears during the days 17–24 March 807, but it is evidently a sunspot observation that confirms Einhard's account.

Another famous European observation was recorded by John of Worcester on December 8, 1128. He was not an Emperor, but he did make the earliest drawing of a sunspot (Figure 2.10). The text surrounding the drawing reads: *In the third year of Lothar, emperor of the Romans, in the twenty-eight year of the King Henry of the English, in the second year of the 470th Olympiad, seventh indiction, twenty-fifth moon on Saturday, 8 December there appeared from the morning right up to the evening two black spheres against the sun. The first was in the upper part and large, the second in the lower and small, and each was directly opposite the other as this diagram shows*

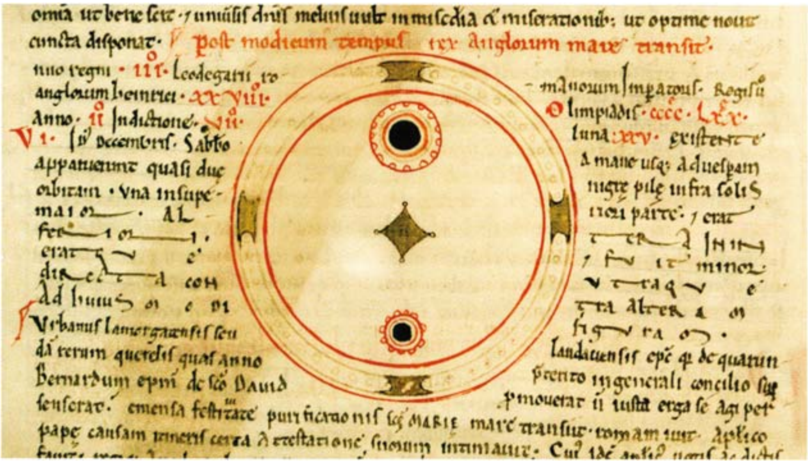

Fig. 2.10. The earliest sunspot drawing by John of Worcester (by permission of the President and Fellows of Corpus Christi College, Oxford, England, MS 157, Folio 380, lower half).

(Darlington and McGurk, 1995; McGurk, 1998). Curiously, the sunspots observed at Worcester were not observed elsewhere. However, this epoch coincides with a period of enhanced solar activity ("The Medieval Maximum") and Willis and Stephenson (2001) presented evidence of recurrent geomagnetic storms and associated aurora from AD 1127 to 1129.

Really remarkable in the sketch is the clear distinction between umbra and penumbra. Stephenson and Willis (1999) estimated that the two sunspots would have been within the latitude belt 25–35 degrees, in northern and southern latitude, with angular diameters of 2 and 3 arcmin, respectively, well within the resolution of the human eye.

Just eleven years later, a naked-eye sunspot was recorded in Bohemia. In the chronicle *Cosmae chronicon boemorum cum continuatoribus. Canonici Wissegradensis continuatio Cosmae*, the following description, dated in 1139, appears: *Fuerunt etiam nonulli, qui diceband se quasi fissuram in sole vidisse*[7] (Emler, 1874, p. 230). Chinese sources indicate a number of naked-eye sunspots during the interval 1136–1139. Křivský (1985) mentioned that a probable date for the sunspot observed in Bohemia is 24 July 1139, assuming 27 days for the Sun's rotation and relating this record with the Chinese observational dates.

Reports of Venus and Mercury transits stand out among the Occidental observations of naked-eye sunspots. Probably, the Aristotelian idea of a faultless Sun contributed to associating any sign or mark on the solar disk as a planetary transit, the only possible explanation for this phenomenon in the context of the astronomical knowledge of this epoch. Goldstein (1969) published the most complete study on mediaeval reports of planetary transits observed by Ibn Ishaq al-Kindi (800–873) also known as Alkindus, Ibn Seena (980–1037) or Avicenna, Ibn Rushd (1126–1198) or Averroes, and Ibn Bajja (1095–1138) or Avempace. Moreover, some transits are mentioned in non-astronomical texts. All these transit reports have to be identified as naked-eye sunspot observations.

In this context, it is interesting to note that Stephenson (1990) compared the list of computed dates for Venus transits (Meeus, 1958) with the dates of naked-eye sunspot reports compiled by Wittmann and Xu (1987) and Yau and Stephenson (1988), indicating that no coincidences or near coincidences of the records appear, and that Jeremiah Horrocks maintains his status of first observer of a transit of Venus in 1639 (see the second half of Chapter 5 for more details).

We have a description of the al-Kindi observation because Ibn al-Qifti wrote the event in his book *Ta'rikh al-hukama* (Ibn al-Qifti, 1903). He said that there appeared a black spot close to the middle of the Sun on 19 Rajab 225 (25 May 840), and al-Kindi mentioned that the spot lingered on the Sun for 91 days and that this spot was due to Venus occulting the Sun (Ibn al-Qifti, 1903, p. 156). This passage may also be found in Casiri (1760, pp. 422–423). It is

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[7] Some people said they had seen a fissure in the Sun.

evident that a Venus transit cannot last for 91 days. Moreover, astronomical calculation shows that Venus was near its greatest elongation on 25 May 840. Thus, al-Kindi saw a large sunspot.

Goldstein (1969) consulted an Arabic text identified as *Compendium of the Almagest* by Avicenna from the Bibliotheque National (Paris). Avicenna says that he observed Venus as a spot on the surface of the Sun but he does not mention the date of observation. Avicenna died in the year AD 1037. According to this date, the only Venus transit during Avicenna's life was on 24 May 1032. However, this transit was not visible in his geographical region.

The transit reported by Averroes is the most famous because it is cited by Copernicus (1543) in *De Revolutionibus*. Averroes reports that two black spots were seen on the Sun at the time of Ibn Mu'adh by Ibn Mu'adh's nephew. Moreover, Averroes says that he computed the positions of Venus and Mercury and both planets were in conjunction with the Sun. Averroes probably ignored the planetary latitudes in the calculation because transits of Mercury and Venus do not occur simultaneously. According to Goldstein (1969), a probable computation date is 15 May 1068.

The last transit reported in Goldstein (1969) is attributed to the Spanish philosopher Ibn Bajja (d. 1139), also known as Avempace. Unfortunately, no astronomical works by Avempace survive. However, the astronomer Qutb al-Din al-Shirazi (d. 1311) cites a Venus transit observed by Avempace: *At sunrise one day I was standing on the roof of my house, and I saw two spots on the surface of the Sun. I calculated the positions of Venus and Mercury at that time from the zij, and I found them both near the position of the Sun. Therefore I concluded that the two spots were Venus and Mercury* (Goldstein, 1969, p. 54, translated from British Museum Ms. Add. 7482, fol. 21b).

These notices on sunspot were written by Arabic astronomers and philosophers. However, it is possible to find notices on sunspots in Arabic historical books. Vaquero and Gallego (2002) presented an observation of a sunspot recorded in an Arabic source by Ibn Hayyan called *al-Muqtabis V*. The document narrates diverse facts during the epoch of the caliph an-Nasir from the year AD 912 to the year 942. There are modern translations in Arabic (Ibn Hayyan, 1979) and Spanish (Ibn Hayyan, 1981). The text describing the naked-eye sunspot observation is the following: *At the end of this year (327 h) a strange and unknown prodigy occurred in the solar disk, being covered by a patent spot, visible by eye, that removed part of its light and switched off its rays, situation that continued 7 complete days, 4 in Dhu-al-Hijjah*[8] *at the end of this year (October 14–17, AD 939) and 3 at the beginning of Muharram*[9] *following, at the beginning of the year 328 h (October 18–20, AD 939). At the end of the week that spot on the Sun disappeared, coming back its rays and light to the normal state after the 7 days, because of a copious rain fallen*

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[8] Twelfth and final month in the Islamic Calendar.

[9] First month of the Islamic Calendar.

down during the night of the Thursday before to the morning when it became resplendent (Vaquero & Gallego, 2002, pp. 207–208).

Other non-Oriental sunspot observations are available from medieval Russia (Dodd & Schaefer, 2002). The Sun appeared red and sunspots were visible due to the smoke caused by forest fires in the years 1365 and 1371. These accounts are described in the *Nikonovsly Chronicle* (Vol. II of the St. Petersburg series of Russian Chronicles published in 1897). Vyssotsky (1949) published an English version of the most interesting fragments from the astronomical point of view. The description of the two records is the following:

> "During this year (AD 1365) there was a sign in the sky. The Sun was like blood and there were dark spots on it, and haziness lasted for half of the year. The heat was very intense; the forest, the marshes and the earth itself burned, the rivers dried up, some water-covered lowlands dried up completely, and there was terror, dread and sorrow among men".
>
> "During this year (AD 1371) there was a sign on the Sun. There were dark spots on the Sun, as if nails were driven into it, and the murkiness was so great that it was impossible to see anything for more than seven feet. (...) Woods and forest were burning and the dry marshes began to burn, and the earth itself burned, and great fright and terror spread among men".

The number of naked-eye observations in Occidental sources increases during the early 17th century. Vaquero (2004) pointed out that a naked-eye sunspot was observed by Galileo. Probably, this is the first sunspot that was seen by naked-eye and by telescope at the same time. It is surprising that this case has been forgotten by the compilers of the naked-eye sunspot catalogues in spite of Galileo's fame. Galileo presented his sunspot telescopic observations in his work *Istoria e dimostrazioni intorno alle macchie solari* (1613). This work is organized in the form of letters from Galileo to Mark Welser (see Chapter 3). In the postscript, in the second letter to Mark Welser (Galileo, 1613, p. 56), one can read that on days 19, 20, and 21 August 1612 a naked-eye sunspot was seen by Galileo and other people.

Moreover, Galileo published in his *Istoria* the drawings of the solar disk observed by telescope (see the next chapter for more details). Figure 2.11 shows the solar disk (29 August 1612). One can see a large sunspot near the central meridian of the Sun. An approximate value of the area of this large sunspot from Galileo's sketch can be measured. Its area was some 2000 millionths of a solar hemisphere, large enough to be visible by naked-eye.

Another observation overlooked by the compilers of catalogues is the naked-eye sunspot observed by the poet and painter Raffael Gualterotti (1544–1639) on the day 25 September 1604. This observation is reported by him in his *Discorso sopra l'apparizione de la nuova stella* (1605) published in Florence: "The year 1604, the day 25 September, [...] I saw when the Sun was setting that a spot appeared on his body" (Gualterotti, 1605, p. 28).

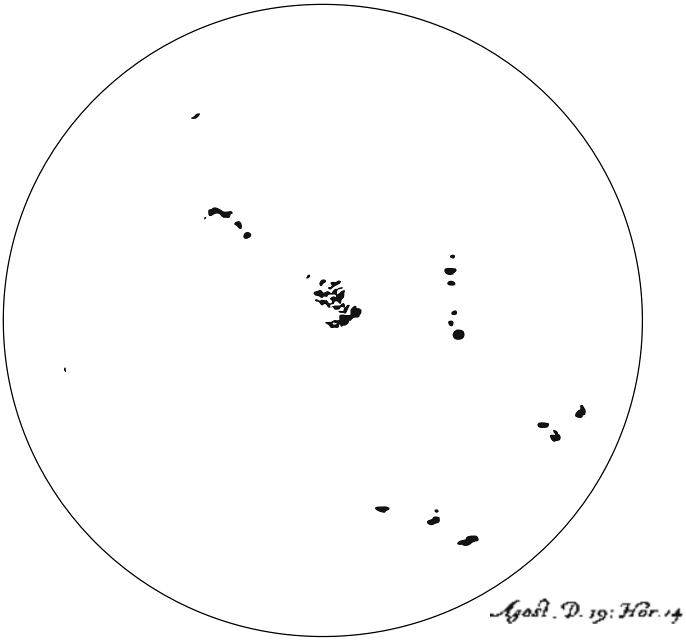

Fig. 2.11. Drawing of the solar disk showing naked-eye sunspots included in the *Istoria e dimostrazioni intorno alle macchie solari* (Galileo, 1613, p. 94). The original figure caption is "Disegni della Macchia grande Solare, veduta con la semplice vista dal Sig. Galilei, e similmente mostrata a molti; nelli giorni 19.20.21. d'Agosto 1612" [Drawing of the large sunspot seen by naked-eye by Galileo, and shown in the same way to everybody during the days 19, 20, and 21 August 1612].

Gualterotti explains that it cannot be Venus (during a transit) because that would have been much smaller and gives a tentative explanation for the observed sunspot. According to Gualterotti, the conjunction of Mars and Saturn attracted vapours and exhalations. Then these vapours were rarefied and taken to the Sun where they became sunspots. Moreover, Gualterotti described an aurora borealis during the same time. The Yau and Stephenson (1988) catalogue lists a naked-eye sunspot observed in Korea on the day 24 October 1604. It is probable that the sunspot observed in Korea is the same as that observed by Gualterotti but in the next solar rotation.

Other Occidental observations were made during ship voyages. Brody (2002) presents two nice examples. In 1590, the master of the ship *Richard of Arundel* registered: *On the 7 [December] at the going downe of the Sunne, we saw a great blacke spot on the Sunne, and on the 8 day, both at rising and setting, we saw the like, which spot to our seeming was about the size of a shilling* (Welsh, 1904, vol. 6, p. 450). Another spot was seen on the Sun, during setting, on the day 16 December. However, the bad weather did not allow other observations (Hosie, 1879; Schove, 1982). The second case from aboard ship is the crew of Henry Hudson's *Half Moon* that reported the Sun having a “slake”[10] in May 1609 when they were near to the Faroe Islands (Brody, 2002, p. 25).

As a final note, one can cite Sarton (1947) in which some possible Western observations of naked-eye sunspots are reviewed. He includes the sunspot observation by Guido Carrara and his son, Giovanni, in Bergamo about 1450. The latter described it in his *De constitutione mundi*: “At a certain time two drops of blood were seen on the Sun and the populace was terrified [...] However, my father, Guido of Carrara, whom I venture to describe as the outstanding figure of his age in every branch of letters, observed and compared the [position of] planets and found that Venus and Mercury were the cause” (Sarton, 1947, p. 70). However, the low solar activity during the 15th century is intriguing.

2.3.3 Mayan and Indian Observations

We can also find examples of observations (or possible observations) of naked-eye sunspots during the pre-telescopic epoch in other regions of the world such as Central America and India.

The city of Mayapan was the most important urban and military centre of the Yucatan Peninsula during the Mayan post-classic period (AD 1000–1519). In the middle of the 15th century Mayapan was destroyed as a result of a civil war. The Fresco Hall is situated at the southern end of the Central Plaza of Mayapan. It is a rectangular structure and the frescoes are still visible. Galindo Trejo and Allen (2005) suggested that descending personages depicted inside the sun-circles in the various panels of the mural might represent a Venus transit or sunspots. Mayan priests could have seen a naked-eye sunspot but it would have been interpreted as Venus inside the solar disk.

Another beautiful example comes from Varanasi, the paradigmatic holy city of Northern India where the Sun is honoured. Specific attributes of the Sun are represented by the *adityas*, the fourteen forms into which the Sun divided himself when he took residence in the city according to the Hindu tradition. The aditya shrines mark the sites of Sun temples destroyed during the Mughal occupation of the city after AD 1192. The *Kashi Khanda* is a fourteenth century Hindu text that contains the Varanasi spiritual traditions. This text describes the aditya temples and details about mytho-historical events related with *adityas*. Malville and Singh (1995) showed that some of those events seem to have involved astronomical phenomena. The presence of coiled and dark snakes on the Sun in a fascinating and complex story in the *Kashi Khanda* is almost certainly a reference to naked-eye sunspots probably dated during the Mediaeval Maximum of sunspot activity. Moreover, references to a “leprous” Sun may also have been related to this period of high sunspot activity.

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[10] Expression for mud or slime.

2.3.4 Naked-Eye Observations During the Telescopic Era

With the widespread use of the telescope, naked-eye sunspot observations turned into a mere curiosity for the majority of astronomers. In the European astronomy of the 18th and 19th century no systematic work exists on sunspots visible to the naked eye. Nevertheless, there were astronomers who observed them. We will discuss here two paradigmatic cases. W. Herschel (1738–1822) and E.W. Maunder (1851–1928) were two great astronomers who did major work concerning the Sun. Both observed sunspots without the aid of the telescope.

Herschel made important contributions to solar physics although he is famous for his discovery of the planet Uranus (see, for example, Hoskin, 1963). Herschel published three papers on the Sun, including observations, in the *Philosophical Transactions of the Royal Society of London* (Herschel 1795, 1801a,b). However, the bulk of Herschel's sunspot observations is in his unpublished notebooks. Hoyt and Schatten (1992a,b) transcribed and reproduced the fragment on solar observations of Herschel's notebooks. The original manuscripts are in Churchill College in Cambridge, England. In Herschel's notebooks, one can read that he observed naked-eye sunspots on two occasions:

> "April 19, 1779 ($2^{\mathrm{h}}\ 30'$) common time. There is a very large spot on the Sun visible to the naked-eye. By the telescope it appears to be divided into two. The length of the largest of them is by the micrometer 8.06". 7 ft. telescope."
> "September 2, 1792 ($9^{\mathrm{h}}\ 55'$) I saw two spots on the Sun with the naked-eye. In the 7 foot telescope, I found two cluster of spots besides many scattered ones; every one of them was certainly below the surface of the Sun."

Another paradigmatic case is Edward Walter Maunder, a pioneer in solar terrestrial physics and "discoverer" of the minimum of long-term solar activity during 1645–1715, which was posthumously named for him (Maunder, 1894). In his book *The Heavens and their Story* (1909) he relates his experience when he was fourteen years old: "*In February, 1866, as I was returning home from school one evening, I saw the Sun, low down in the West, shining red through the mist. The Sun was dim and red enough for me to look at him without blinking, and I saw plainly on him a round black spot*" (Maunder and Maunder, 1909, p. 103). Maunder saw other naked-eye sunspots sixteen years later. A very violent magnetic storm occurred on 17 November 1882. He wrote one day later: "*On November 18, 1882, Queen Victoria was holding a review in Hyde Park. The morning was somewhat foggy, and the Sun shone dull and red through the thick air, so that it was easy to look at him. On this occasion there was a great spot on the Sun; so big that it caught the attention of the soldiers* *who were marching across Blackheath [...]*" (Maunder and Maunder, 1909, p. 106).[11]

If one reads with attention the scientific literature of the 18th and 19th centuries, it is possible to find other observations. We shall present some examples.

The case of Richard Lewis is very interesting. He published a report on the aurora seen at Maryland in October 22, 1730 (Lewis, 1731). The report finished with a comment on naked-eye sunspot observation: "*Dr. Samuel Chew of Maidstone tells me, that he has for some Days past, at Morning and evening, observed several Spots, on the Sun, very plainly with the naked Eye, some of which seemed very large*". To the best our knowledge, this is the first account of naked-eye sunspots published from the American colonies.

Another interesting observation in America is due to John Winthrop (1714–1779), a contemporary and friend of Benjamin Franklin (1706–1790), in 1739. He was the most important American pioneer in mathematics and astronomy. Kilgour (1938) found some sunspot observations in Winthrop's unpublished manuscripts. The observations were made after the appearance of a great sunspot observed without the aid of the telescope:

> "1739 April 19th at Boston. Walking on the Common a little before sunset, the air being so hazy that I was able to look on the sun, I plainly saw with my naked eye a very large and remarkable spot. Its shape was oblong and the length of it was perpendicular to the horizon. I observed it several minutes till the sun was actually set. It was like wise seen by several persons in the company of Messrs. Skinner and Read. [...] I am since informed that several persons in the country saw them like wise with their naked eye, particularly some at Medford and the ferrymen at the Charlestown ferry" (cited by Kilgour, 1938, pp. 358–359).

Moreover, the following day, at night, a considerable aurora was seen by Winthrop, and he believes that there was some relation between large sunspots and aurorae (Kilgour, 1938; Eather, 1980), a suggestion usually first attributed to Mairan.

There are some observations published in periodical journals of the 19th century. There is no study that records systematically the information on naked-eye sunspots appearing in astronomical journals. However, there are very many records by (especially amateur) astronomers in this sense. We shall present three examples from *Monthly Notices of the Royal Astronomical Society*.

An extract of a letter written by A. Weld (1823–1890), Director of the Observatory at Stonyhurst College, was published. He says: "*On September 20, I observed a large spot on the sun with our equatoreal, and found that it consisted of several dark nuclei enveloped in one large penumbra*". Then, he

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[11] E.W. Maunder's name appears on the book, but he states in the preface that it was "almost wholly" the work of his wife Annie Maunder (1868–1947).

presented the results of his measurements: $2'41''.1$ for the greatest diameter of the sunspot, $1'7''.2$ for the greatest diameter of the nucleus, $2'14''.1$ for the equatorial diameter of the sunspot, $0'49''.2$ for the equatorial diameter of the nucleus and $2'14''.1$ for the meridian diameter of the sunspot. Weld (1848) finished by saying: "*The spot was distinctly visible to the naked eye before sunset*".

A very brief notice (eight lines only) was published recording the observation by Weld (1851) on the evening of 12 March 1851. The Sun was setting in the midst of a thick haze and Weld observed a sunspot with the naked eye. Another two persons saw it with facility. Weld observed the Sun the next day with a telescope and found a single large sunspot. According to Weld's comments, "Its greatest measured diameter parallel to the equator was $4^{s}.05$, that of the nucleus $1^{s}.60$, and its diameter measured along the meridian circle was $52''.53$". This observation is in accordance with the naked-eye sunspot recorded in the Oriental source "Ting-nan Hsien-chih 6" corresponding to number 203 in the Yau and Stephenson (1988) catalogue.

One more example could be the record by A.R. Hill published in 1870. He explains that the light of the Sun was "*obscured by a peculiar scud drifting over it, and giving the whole disk a reddish appearance, with the borders less luminous than the centre*" on Sunday, 22th May. He observed three large spots (Figure 2.12, left). The next day, the meteorological conditions were more advantageous for naked-eye observations. Hill saw four spots, but the fourth was only visible at the most advantageous intervals (Figure 2.12, right).

Another interesting case is the record of naked-eye sunspots by William Dawson. He was an active sunspot observer during the period 1867–1890. There are 1623 daily records by Dawson in the Hoyt and Schatten (1998) database. He published three papers with sunspot observations (Dawson, 1888, 1889, 1890). The first (Dawson, 1888) lists his sunspot observations made

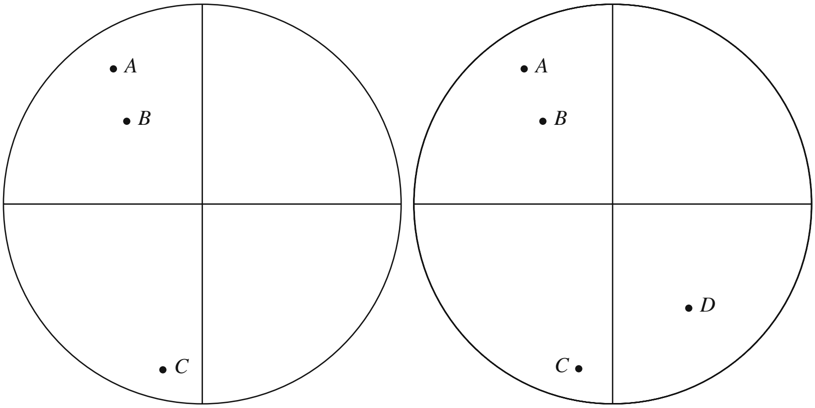

Fig. 2.12. Drawing by A. R. Hill (1870) showing the positions of naked-eye sunspots observed on 22 (left) and 23 (right) May 1870.

during 1884–1886 with a telescope with an aperture of 4.6 inches and about 70 inches focus made by A. Clark & Sons. The 100-power eyepiece was generally used. With respect to the naked-eye sunspot observation, he says: "*In 1871–78, I left off counting the spots on account of failing eyesight, simply noting the number of groups, large and small. Observations were much neglected in 1874–77. I estimate that I have seen about 40 different sun-spots with the naked eye—their diameters (umbrae) ranging from about 8,000 to 35,000 milles*". In this paper, Dawson mentions the naked-eye sunspot observed in the "notes" column. During the period covered in the paper (1884–1886), Dawson observed naked-eye sunspots on the following days: 6 Oct 1884; 3 Feb 1885; 9, 11, 19, and 22 June 1885; 7 and 24 July 1885; 11, 14, and 15 Sep 1885; and 15 Nov 1885. It is interesting to note that the sunspot observed on 7 July 1885 by Dawson could be the same sunspot reported in a Chinese source on 5 July (reference number 226 in the Yau and Stephenson (1988) catalogue).

Other naked-eye sunspot records appear when one is looking for other kinds of observation. Moore (2003) was intrigued to discover that T.W. Webb (1807–1885) observed a transit of Mercury on 9 November 1848. When he consulted Webb's notebooks in the Royal Astronomical Society library, he found a nice naked-eye sunspot observation by Revd Webb on 26 October 1852: "*...a large naked-eye sunspot on the disc of the Sun, dimmed by the morning fog of London about 10 am.*" (Moore, 2003, p. 306). A biography of T. Webb can be consulted (Robinson and Robinson, 2006).

2.3.5 Modern Observations

The low number of historical naked-eye observations could discourage potential modern observers. However, some amateur astronomers have been trying to see sunspots without the aid of a telescope for approximately the last 30 years.

One of the most famous observational campaigns was conducted by Mossman (1989), an experienced English amateur observer. He observed systematically the Sun using a dark filter or through clouds for thirteen months, near the maximum of the solar cycle number 22. Probably, the main conclusion of this campaign was that Mossman saw more sunspots in 13 months than are found in 18 centuries of pre-telescopic observations. Thus, it is clear that the sunspots that were recorded in historical sources are a very small fraction of those that could have been seen. Mossman (1989) showed that he could see features on the solar disk as small as 0.3 arcmin, distinguish roughly the shapes of sunspots, and identify as many as five separate sunspots in a day.

The longest series of naked-eye sunspot observations was made by Heath (1994). He observed naked-eye sunspots from 1959 to 1993 (35 years) during solar cycles 20–22 using a dark Sun filter with a Sun diagonal (Herschel Wedge), or No. 14 welder's glass. Figure 2.13 shows the results obtained by Heath. The total number of naked-eye sunspots observed during a year is well

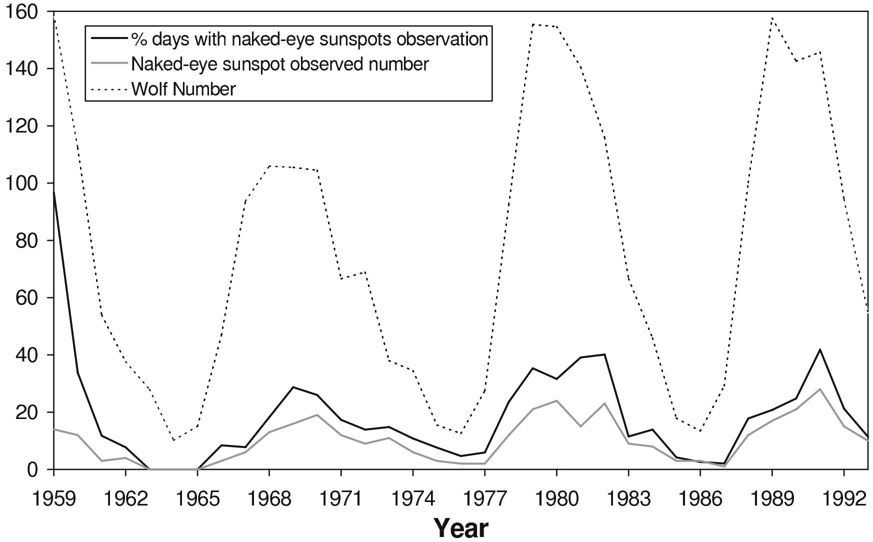

Fig. 2.13. Annual values of total number of naked-eye sunspots and percentage of days with at least one naked-eye sunspot observable during the period 1959–1993 by Alan W. Heath. The Wolf number is also included in the figure for comparisons.

correlated with the Wolf number (correlation coefficient r = 0.885) in spite of the possible influence of the days without observation. Similar behaviour corresponds to the percentage of days with at least one naked-eye sunspot observable on the solar disk (r = 0.778). During the period considered, a total of 357 naked-eye spots were recorded, which averages 10.2 per year. Heath's observations suggest that the peak of naked-eye sunspots occurs after the peak of the 11-year solar cycle.

P. Wade was other important modern naked-eye sunspot observer. From February 1980 to December 1992, he made 2876 systematic sightings (61% of the days in all the period). He noted the date and time and each report included details about the number and rough location of the sunspots and other points of interest. Figure 2.14 shows the annual mean daily frequency[12] (MDF) for his naked-eye sunspot observations. The 11-year cycle is clearly visible. The smallest sunspot reported by Wade (1994) was approximately 25 arc seconds in size (only 80 millionths of the solar hemisphere). A comparison between the naked-eye sunspot MDF and telescopic sunspot MDF shows the two quantities to be linearly related.

An interesting task carried out by Wade (1994) was recording the latitude of the naked-eye sunspots he observed. Wade used Stonyhurst disks to estimate the sunspot latitudes from 152 mm diameter images projected from a 73 mm refractor. According to his observations and measurements, the

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[12] Mean daily frequency is the average of the number of sunspot observed once per day during a month.

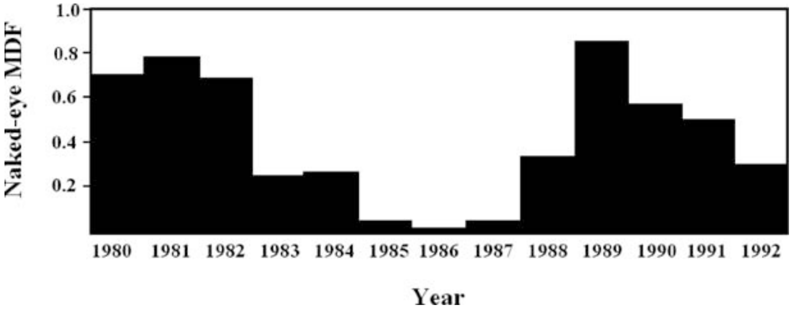

Fig. 2.14. Annual MDF for naked-eye sunspots observed by P. Wade during the period 1980–1992 (adapted from Wade, 1994).

distribution of the latitudes of naked-eye sunspots is similar to the latitude distribution for all sunspot groups observed telescopically. Thus, he concluded that naked-eye sunspots and the general sunspot population have the same main characteristics with respect to frequency and latitude distribution.

Keller and Friedli (1992) calculated an empirical visibility limit for naked-eye sunspot observations. Based on Keller's observations made during the period 1976–1986 (solar cycle number 21), they found basically that the number of naked-eye sunspots varies with solar cycle, that there is a linear relationship between naked-eye sunspot number and relative sunspot number, and that the visibility limit for naked-eye sunspots is 31 arcsec for the penumbral diameter of sunspots (for the acuity of Keller's eyes). They proposed a more general result using the data of an international network of naked-eye solar observers that was observing daily from 1984 to 1989. Keller and Friedli (1992) showed that an average observer is able to detect by naked eye a sunspot whose mean umbral and penumbral diameters are at least 15 and 41 arcsec when the spot is near the centre of the solar disk.

During recent years, a network of amateur astronomers has been observing the Sun without the aid of telescopes. Monthly naked-eye sunspot numbers recorded by the Spanish amateur astronomer Javier Ruiz ($\mathrm{R}_{\mathrm{naked-eye}}$) and sunspot numbers ($\mathrm{R}_{\mathrm{Z}}$) are plotted in Figure 2.15 from November 1998 (before the maximum of solar cycle 23) until December 2006. It is interesting that the Gnevyshev gap[13] between the principal and the secondary maxima of solar cycle 23 is more noticeable in the naked-eye series. The two data sets are closely related, as is illustrated in Figure 2.16 where the sunspot number is plotted against naked-eye sunspot number. The best-fit straight line, determined by the method of least squares, is also shown. This line is described by the equation

$$\mathrm{R}_{\mathrm{Z}} = (56 \pm 7)\mathrm{R}_{\mathrm{naked-eye}} + (46 \pm 5),$$

and the correlation coefficient is 0.625 (99.9% statistical significance).

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[13] The relative minimum between two consecutive peaks in a solar cycle is known as the Gnevyshev Gap (Gnevyshev, 1967, 1977; Kane, 2005).

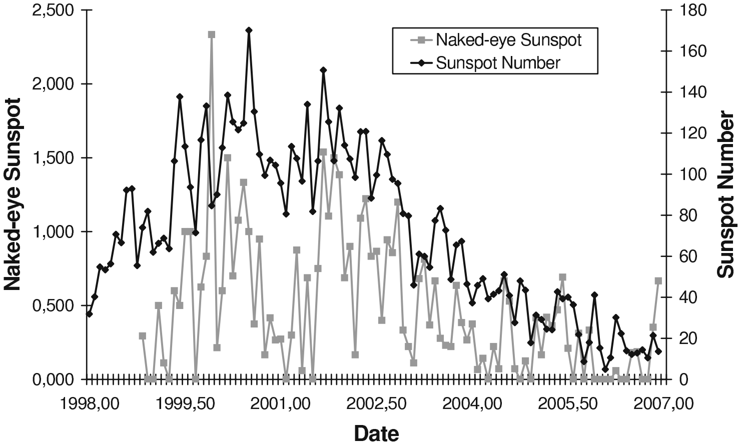

Fig. 2.15. Monthly International Sunspot Number and monthly average of naked-eye sunspots recorded by the Spanish amateur astronomer Javier Ruiz during 1998–2007. Data courtesy of J. Ruiz (available at http://www.astrocantabria.org/parhelio/).

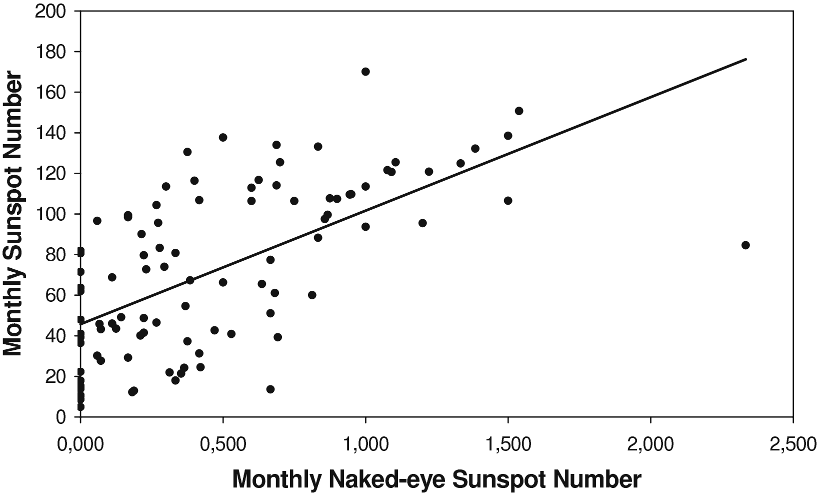

Fig. 2.16. The International Sunspot Number *versus* monthly average of naked-eye sunspots recorded by the Spanish amateur astronomer Javier Ruiz during 1998–2007. Data courtesy of J. Ruiz (available at http://www.astrocantabria.org/parhelio/).

2.4 Naked-Eye Sunspots and Temporal Evolution of Solar Activity

After this review of the historical and modern naked-eye sunspot observations, which showed the great differences between them, the key question is now: Can the historical naked-eye sunspot observations be used to study the Sun during the last two millennia? Usoskin and Kovaltsov (2004) indicate that the naked-eye sunspot record is not straightforward to interpret because: (1) the record is influenced by meteorological phenomena, (2) the record depends on the predominant traditions at the time, and (3) a direct comparison of Oriental naked-eye and European telescopic data shows important discrepancies. Usoskin and Kovaltsov (2004) conclude that the most reliable and useful proxy of long-term solar activity is formed by the data set on cosmogenic radionuclides produced by cosmic rays in the atmosphere of Earth (Stuiver and Quay, 1980; Beer et al., 1990; Bard et al., 1997; Beer, 2000; Solanki et al., 2004).

In the section 2.3.1 devoted to Oriental records, we saw some of the historical problems in interpreting the observations as a series that represents solar activity. The most important problems are the loss of information due to historical periods with political turbulence (such as the gaps existing between AD 600 and 800) and the role of certain political and sociological factors (such as astrology).

Another problem is the different type of documentation used. Hameed and Gong (1991) indicated that the series of the number of naked-eye sunspot observations correlates badly with ^{14}C from 1620. This is probably due to historical motives since during this epoch local historical sources were used. These sources show less reliability in the record of astronomical events. However, some naked-eye sunspots were recorded during the Maunder minimum (see, for example, Clark and Stephenson, 1980).

The influence of atmospheric conditions on the possibility of naked-eye sunspot observations is unquestionable. Willis et al. (1980) established that the dates of naked-eye sunspot sightings occur more frequently in late winter and spring. Figure 2.17 shows the number of unaided-eye sunspot sightings recorded in each month according to the Clark and Stephenson (1978) catalogue during the period from 28 BC to AD 1604. The dark part of the histogram shows the distribution of those dates specified without reservation and the grey part includes 12 uncertain dates. A marked spring maximum and a broad summer minimum are the main characteristics of the figure. The probability of obtaining the seasonal distribution shown in the dark part of the figure by chance is less than 1 in 25 000 using the chi-squared test. Of course, this probability is even smaller if one considers the whole histogram. It is possible to explain this seasonal distribution of naked-eye sunspot observations considering the general characteristics of East Asia's climate. The high number of observations in spring could be attributed to dust storms and sand storms originating over central China frequently during late winter and early

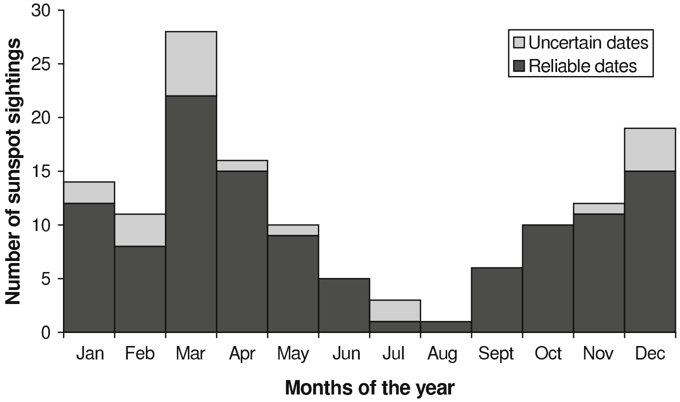

Fig. 2.17. Number of sunspots sightings recorded in each month by Clark and Stephenson (1978), from Willis et al. (1980).

spring. The summer minimum in the figure could be explained by the cloudiness and precipitation during the rainy season in East Asia. Willis et al. (1980) concluded that atmospheric conditions make a simple interpretation of Oriental naked-eye sunspot observations very difficult as a direct index of historical solar activity. In the same context, Hameed and Gong (1991) found a strong correlation between Oriental naked-eye reports and dust/rain events in China during the period 1621–1920.

Many naked-eye sunspot records mention reduction in sunlight intensity. This fact may be related to observation of the Sun very near the horizon or through fog, haze, or dust clouds. Moreover a similar effect could be the result of attenuation of sunlight by volcanic dust and aerosols in the stratosphere. Thus, it is reasonable to think that after a major volcanic eruption the probability of observing a naked-eye sunspot is greater, since the volcanic aerosol reduces the intensity of the sunlight, favouring the observation. Scuderi (1990) made a statistical analysis of Oriental naked-eye sunspot records including descriptions of “vapours” and related phenomena. This analysis shows that these records could be related to the atmospheric dust veil resulting from large volcanic eruptions.

Figure 2.18 shows a comparison between the 50-year moving average of annual naked-eye sunspots and Group Sunspot Numbers. It is evident that, quantitatively, the historical naked-eye observations must be interpreted with caution (Willis et al., 1996; Usoskin and Kovaltsov, 2004). Thus, a time series constructed using naked-eye sunspot observations cannot be presumed to represent the quantitative variation of long-term solar activity. Naked-eye observations cannot be interpreted quantitatively because only observed sunspots are reported and thus we cannot distinguish between no-spot and no-observation cases. Moreover, only some 67% of Oriental naked-eye observations have been confirmed by telescopic observations during the period 1874–1918 (Willis et al., 1996).

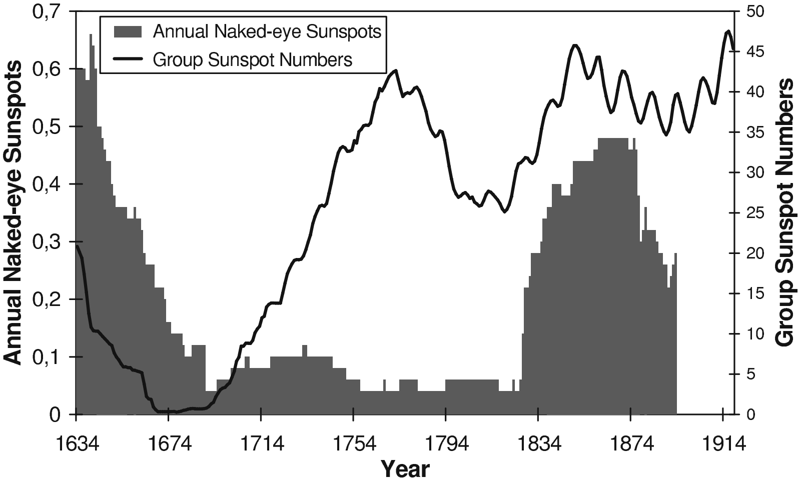

Fig. 2.18. 50-year moving average of annual naked-eye sunspots and Group Sunspot Numbers.

Another problem for the use of the data is that there is a marked upward trend in the annual number of events recorded in catalogues. This could reflect the greater difficulty of finding sunspot records as one goes back in time. Figure 2.19 shows how the secular number of naked-eye sunspots records, from Vaquero et al. (2002), varies from the 2nd century BC to the 19th century AD. The solid line is the best linear fit to the data indicating the increasing trend in the data. This upward trend is equal to 1.1 observed sunspots per century.

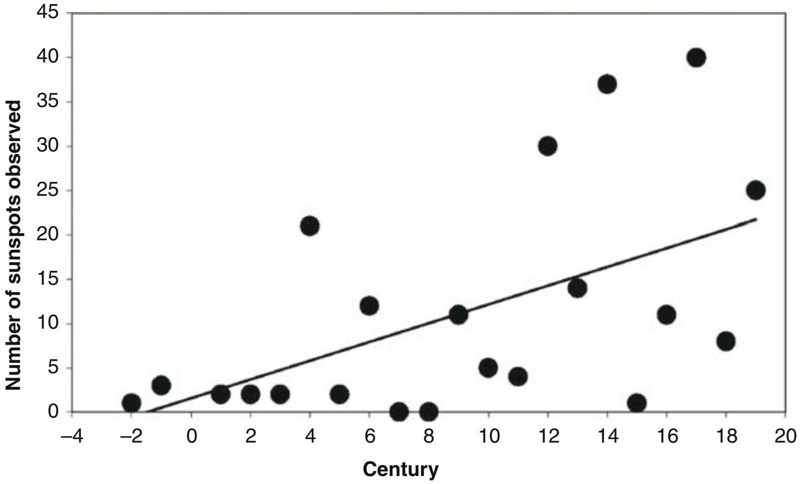

Fig. 2.19. Secular number of naked-eye sunspots recorded, from Vaquero et al. (2002). The line is the best linear fit to the data.

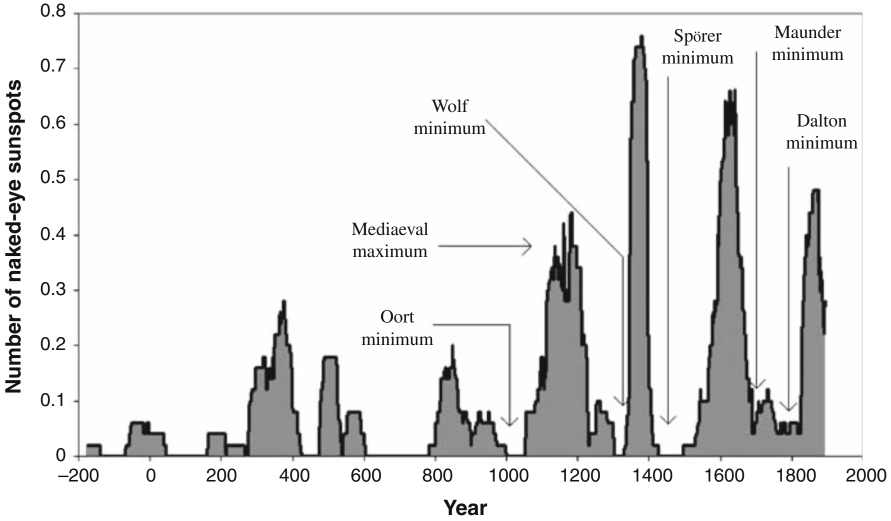

Fig. 2.20. 50-year moving average of the time series of naked-eye sunspots (adapted from Vaquero et al., 2002).

In spite of all the above arguments, one can plot Figure 2.20, constructed by calculating the 50-year moving average of the annual number of naked-eye sunspot observations recorded in the catalogues. The known minima of Oort, Wolf, Spörer, Maunder, and Dalton stand out sharply. The Maunder and minima are somewhat displaced from their original locations. The Mediaeval Maximum is centred on the first half of the 12th century and other maxima are around 1880, 1630, 1380, 880, 630, and 380. Thus, the most important episodes in the history of the Sun during the last millennium, and probably during the last 2000 years, appear qualitatively in the record of naked-eye sunspots. Though climatic, historical, and sociological factors clearly affect the information, these factors are so nonlinear and changeable on such diverse time-scales that the complete record reproduces the solar activity better that one might have expected.

2.4.1 Time Series with Naked-Eye Sunspot Observations

In spite of the evident problems that any time series obtained from the catalogues of naked-eye sunspot observations will contain, several authors have tried to use this information in studies of historical solar activity.

Probably, the most elaborate attempt to construct time series from the historical naked-eye sunspot observation reports was made by Nagovitsyn (2001). He tried to use the data of the Wittmann and Xu (1987) catalogue taking into account not only the mere facts of sunspot observations but also the qualitative description of each event. Thus, he obtained several different annual time series to characterize different aspects of the solar activity:

- Dichotomic series of uniform events (WX_0).
- Quantitative series of uniform events (WX_N).
- Quantitative series of mutually weighted events (WX_C).
- Duration of observations of individual events (WX_T).
- Hypothetical probabilistic parameter of the spatial organization of solar activity and time series of seasonal parameter (WX_Q).

The *dichotomic series of uniform events* (WX_0) was constructed using the value 1 for the cases of "at least one event during a year" and the value 0 for the "no event" case (see Figure 2.21).

Nagovitsyn analysed this series using the self-similarity function (binary statistics of events). This analysis revealed several harmonic components: (1) a 400-year cycle, which had previously been described by Link (1963), (2) a 260-year cycle, the most prominent peak in the amplitude spectrum, (3) a 200-year cycle, very close to the de Vries cycle (≈ 210 years), (4) 60, 90, and 130-year secular cycles, and (5) an 11-year cycle that can be resolved into a multiplet (peaks at 9.7, 10.6, and 11.2 years).

The *quantitative series of uniform events* (WX_N) is a sequence of the numbers of events recorded during each year. Numerous problems exist for the construction of this series such as events that could be the same, problems in the quality of the dates offered in the historical sources, etc. This index is less

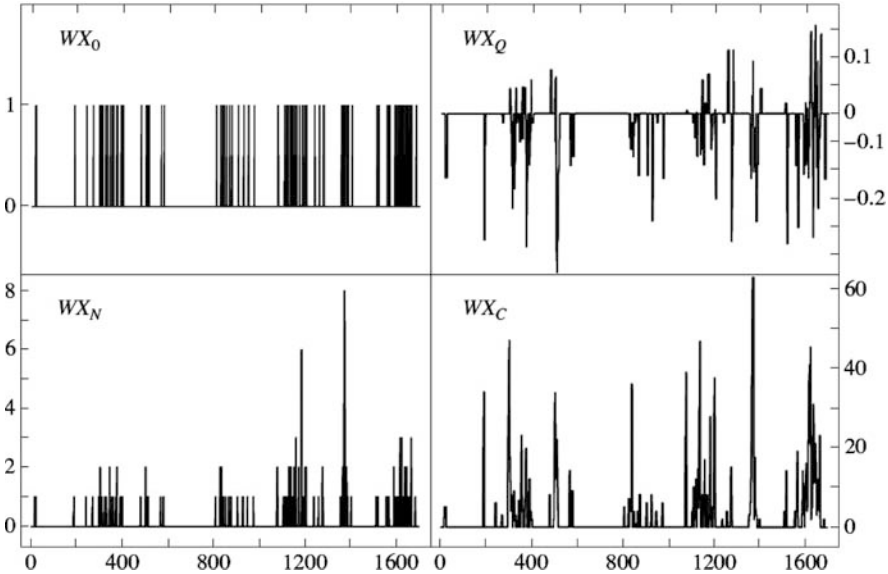

Fig. 2.21. Different time series constructed by Nagovitsyn (2001) based on the Wittmann and Xu (1987) catalogue.

robust than the previous one with respect to the typical problems of historical sources.

The *quantitative series of mutually weighted events* ($\mathrm{WX_C}$) can be constructed assigning to each particular observation a certain score. Thus, one can assume that the observer compares a particular spot with a familiar object according to the especially large size of the feature on the solar disk. The score depended on the characteristics of the report. For example, Nagovitsyn assigned score 10 to the features called "moles", score 15 to those called "spots" or "dots", and score 20 or 30 to events whose descriptions are followed by phrases similar to "as large as a plume" or "... peach" (20) and "melon" (30). Moreover, he took into account the duration of the event observation multiplying the initial score by a factor of 1.2, 1.5 or 2.0 if the event had been observed for 3–6, 7–13, or 14–20 days, respectively.

He also made a histogram of the *duration of observations of individual events* ($\mathrm{WX_T}$) supplementing the cases of events recorded directly for several days T by those where two adjacent events represented as independent catalogue entries (these are often records from different chronicles) are separated by less than 1.5 solar rotations (40 days).

The last time series constructed by him was the *hypothetical probabilistic parameter of the spatial organization of solar activity and time series of seasonal parameter* ($\mathrm{WX_Q}$). He assumes the following hypothesis: "Because of the viewing conditions due to the negative extremum of the Earth's heliographic latitude, a spot recorded in the Wittmann and Xu catalogue observed in the given year within the Gregorian March and seen just for one day is most likely to be located in the southern solar hemisphere. A similar spot observed in the Gregorian September is most likely to be located in the northern hemisphere". He estimates that the probability that an observed naked-eye sunspot is located in the northern hemisphere is equal to

$$\mathrm{p} = \frac{1}{\pi}(\arccos\frac{\mathrm{B_0}}{\mathrm{R_0}} - \frac{\mathrm{B_0}}{\mathrm{R_0}}\sqrt{\mathrm{R_0^2} - \mathrm{B_0^2}}) \qquad (2.9)$$

where $\mathrm{B_0}$ is the heliographic latitude of the Earth and $\mathrm{R_0}$ is the radius of a circle (concentric with the visible solar disk) equal to the mean limiting spot visibility radius. Since most of the naked-eye sunspot events were observed for one day only, $\mathrm{R_0}$ is equal approximately to 6° or 7°. Solar N-S asymmetry can be defined as

$$\mathrm{q} \equiv \frac{\mathrm{N} - \mathrm{S}}{\mathrm{N} + \mathrm{S}} = 2\mathrm{p} - 1$$

In Equation (2.9), Nagovitsyn (2001) used 7.5°. He used Equation (2.9) to compute p for various months and to infer the corresponding values of q, which he denoted as $\mathrm{WX_Q}$.

Other authors have used less ambitious and sophisticated indices of naked-eye sunspot records. However, the simplest indices are relatively easy to construct accurately and without ambiguities. Ding et al. (1983) found 11-year, 60-year, and ∼250-year periods in the time distribution of naked-eye sunspot records using auto-correlation analysis. Vaquero et al. (2002) constructed the series of the number of naked-eye sunspots from 165 BC to AD 1918. These data were analysed using the multi-taper method (MTM) (Thomson, 1982) and singular spectrum analysis (SSA) (Allen and Smith, 1996; Dettinger et al., 1995; Vautard et al., 1992). The most notable aspect of the MTM spectrum of the sunspot data from 165 BC to AD 1918 is the strong peak at around 250 years. It would be difficult for this period to show up in telescope-based sunspot series because of their relatively short length. There are also other peaks at 115, 85, and 60 years which could be related to the Gleissberg period. Other shorter-period cycles also appear, including the 11-year cycle.

Figure 2.22 shows a wavelet analysis of the annual number of naked-eye sunspots during the period AD 1–1918 (data from Vaquero et al., 2002). There are three intermittent periods in the long-term behaviour. A periodicity of 60 years is found around the early 6th, the 12th, and the 19th centuries. Other periodicities of 100 and 250 years are present in the last half of the record (1200–1918 and 800–1918, respectively). The main overall wavelet peak has a period of 241 years.

As a final comment, we can make a comparison between the solar activity reconstructed using cosmogenic radionuclides, the most reliable proxy to study the long-term behaviour of the Sun, and the series of naked-eye sunspot observations. Figure 2.23 shows the reconstruction of sunspot number made by Solanki et al. (2004) and a 50-year moving average of the annual number of

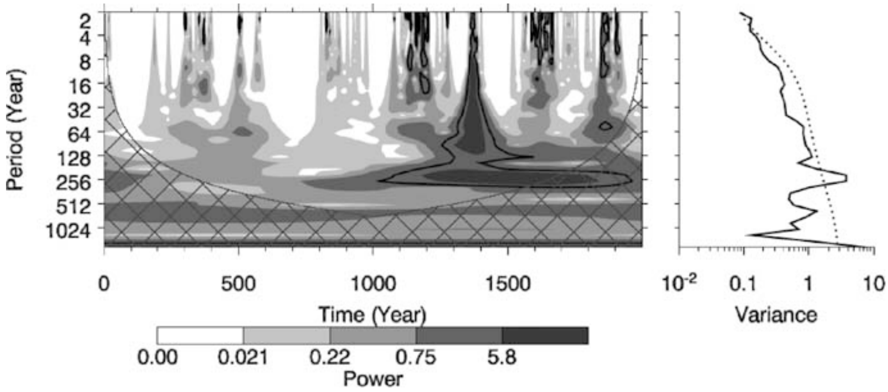

Fig. 2.22. (Left panel) The wavelet power spectrum of the annual number of naked-eye sunspot recorded during the period AD 1–1918 (from Vaquero et al., 2002). Contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. The black contour is the 1% significance level, using a red-noise background spectrum. (Right panel) Global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in the left panel.

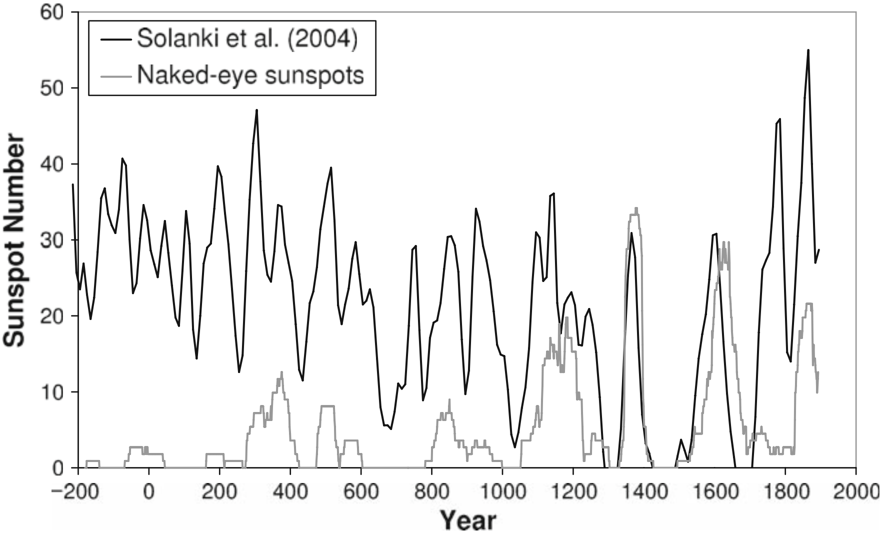

Fig. 2.23. Reconstruction of sunspot number by Solanki et al. (2004) (black line) and using the 50-year moving average of the annual number of naked-eye sunspots by Vaquero et al. (2002) (grey line). Data were provided by I.G. Usoskin.

naked-eye sunspot reconstructed by Vaquero et al. (2002) in arbitrary units. The naked-eye record is not useful for the study of long-term solar activity from 200 BC to AD 800 although some peaks of solar activity also appear in the naked-eye record. For the period 800–1600 approximately, the naked-eye sunspot record shows the most important periods of the solar activity although the amplitudes are variable. The two curves are quite similar during the period AD 1300–1600. Since the year 1600, the use of local sources in the Oriental record has made the correlation worse, and major differences can be observed during the period 1700–1825.

2.4.2 Solar Cycle and Giant Sunspots

Is there any relationship between giant sunspots (suspected as being observable with the naked-eye) and the 11-year solar cycle? Wittmann (1978) concluded that giant sunspots are reliable tracers of the maximum epoch. On some rare occasions, a large sunspot may appear in the time of a minimum, but the majority of giant sunspots appear concentrated around the maximum of the 11-year solar cycle. Figure 2.24 shows a bimodal distribution of large spots (area greater than 1500 millionths of solar hemisphere) with maxima at −1.4 and +0.6 years from the maximum epoch of the sunspot number. Clearly visible is the Gnevyshev gap (also recorded by modern observers of naked-eye sunspots) between the maxima at −1.4 and +0.6 years from epoch 0.

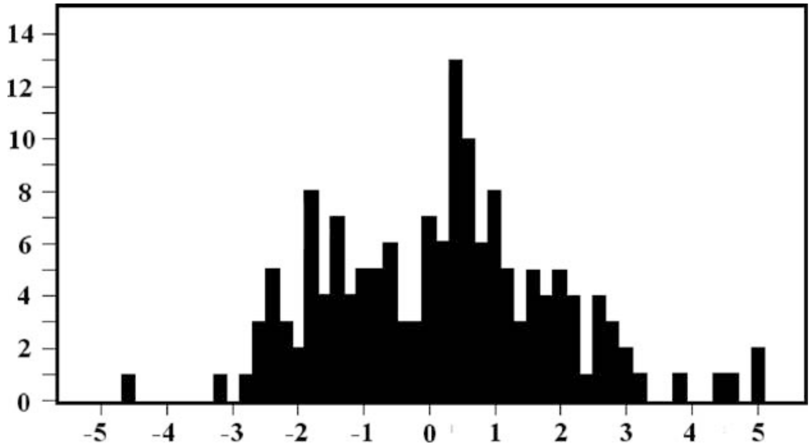

Fig. 2.24. Relative phase of occurrence for the 153 largest spots (areas>1500 millionths of a solar hemisphere) of the period 1872–1985.

Wittmann and Xu (1987) identified 44 maxima of 11-year solar cycles in their data on historical naked-eye sunspot observations. A fit of the whole sample with respect to Julian Day number gives

$$\mathrm{JD(Max.)} = (1722516 \pm 365) + (4060.1 \pm 2.5)\mathrm{N} \tag{2.10}$$

where N is an arbitrary cycle number. Wittmann and Xu (1987) chose N = 178 for the maximum of 1980–83. Also, Equation (2.10) can be written as

$$\mathrm{Year(Max.)} = (4.0 \pm 1.0) + (11.116 \pm 0.007)\mathrm{N} \tag{2.11}$$

if we neglect the differences between the Julian and the Gregorian calendars.

Wittmann and Xu (1987) computed the dates of maxima of the solar cycle using Equation (2.10) and plotted the relative phase for 235 historic sunspots as in Figure 2.24. This figure shows the distribution of historic naked-eye sunspots. A comparison between Figures 2.24 and 2.25 indicates that many historical records either do not represent genuine sunspots or are not representative of the maximum epoch of the solar cycle.

However, these authors went a step further because there are some reports with more reliable information than others. Thus, they selected the 360 most reliable giant spots for the period AD 299–1985. Figure 2.26 shows the distribution of these sunspots. They are concentrated around the epoch 0. With respect to Figure 2.24, the new data set partially fills the Gnevyshev gap. This may be proof that compact groups of small sunspot could also be observed with the naked eye.

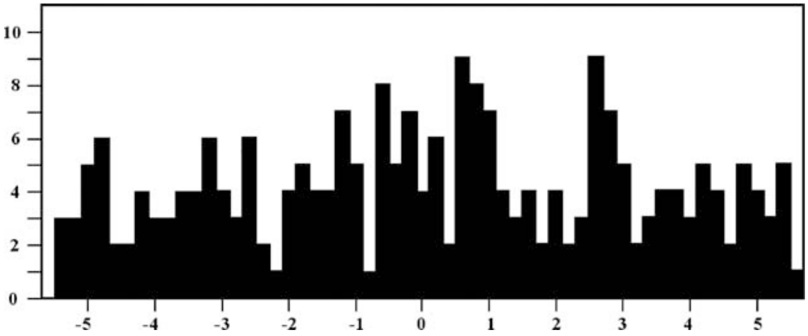

Fig. 2.25. Relative phase of occurrence for the 235 sunspots recorded by Wittmann and Xu (1987) in the period 165 BC–AD 1684.

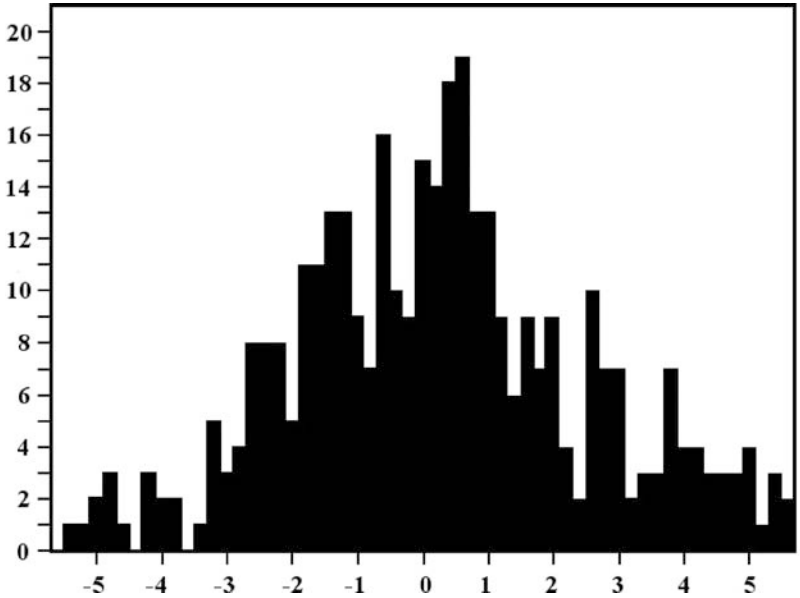

Fig. 2.26. Relative phase of occurrence for the 360 most reliable spots of the period AD 299–1985 (adapted from Wittmann and Xu, 1987).

2.4.3 High-Resolution Record

The most important advantage of the use of indices based on naked-eye observations is the high time resolution available. The majority of the observations are dated with a precision of days. The high resolution of these observations as compared with other proxies should be used coherently by space climate researchers.

A very nice example of the use of the high resolution of historical sunspot records is due to Willis et al. (2005). They have recently used a comprehensive collection of catalogues of ancient sunspot and auroral observations from East Asia to identify possible intense historical geomagnetic storms in the interval 210 BC–AD 1918. In previous work, Willis and Stephenson (2001) presented evidence for an intense geomagnetic storm in December AD 1128, using historical auroral and naked-eye sunspot observations in combination. On the one hand, the sunspot described in *The Chronicle of John of Worcester* was seen on 8 December 1128 (see Figure 2.10). And on the other, a red aurora was observed on the night of 13 December 1128 from Songdo, Korea. Moreover, there is additional evidence suggesting recurrent geomagnetic activity around this time. Several Oriental sunspot and auroral records occurred approximately in synodic-solar-rotation periods suggesting two series of recurrent geomagnetic storms.

Willis et al. (2005) compared the East Asian historical sunspot and auroral data-set looking for "approximate coincidences" between pairs of events. They formulated a selection criterion for the automatic identification of such geomagnetic storms. The assumption made in the work was the following: "an historical geomagnetic storm occurred if the time interval, T (measured in days), between the observation of a sunspot and the associated auroral display satisfies the following condition:

$$-8 \leq \mathrm{T} \leq +15$$

This selection criterion was chosen based on three specific assumptions about (1) the duration of sunspot visibility with the unaided eye, (2) the likely range of heliographic longitudes of an energetic solar feature, and (3) the likely range of transit times for ejected solar plasma. Table 2.2 lists the "approximate coincidences" between Oriental sunspot and auroral observations that were found.

Table 2.2. List of "approximate coincidences" between Oriental sunspot and auroral observations, derived from the sunspot and auroral databases by Willis et al. (2005). Dates before 5 October 1582 AD are in the Julian calendar; subsequent dates are in the Gregorian calendar

No.	Sunspot Observation	Auroral Observation
01	1–10 Mar 1137, China	4 Mar 1137, China
02	10, 11 Feb 1185, China & Korea	2 Feb 1185, Japan
03	27 Mar 1185, Korea	26 Mar 1185, Korea
04	3–12 Dec 1193, China	5 Dec 1193, China
05	3–12 Dec 1193, China	6 Dec 1193, China
06	19–31 Dec 1202, China	19 Dec 1202, Japan
07	21 Feb 1204, China	21 Feb 1204, Japan
08	21 Feb 1204, China	22 Feb 1204, Japan
09	21 Feb 1204, China	23 Feb 1204, Japan
10	28 Jan–3 Feb 1370, China	11 Feb 1370, Korea
11	21 Oct 1370, China	27 Oct 1370, Japan
12	17 Apr 1556, Korea	13 Apr 1556, Korea

Table 2.2. Cont.,

No.	Sunspot Observation	Auroral Observation
13	22 May 1618, China	17 May 1618, China
14	15–24 Oct 1620, China	19 Oct 1620, China
15	15–24 Oct 1620, China	20 Oct 1620, China
16	17–20 Mar 1624, China	21 Mar 1624, Korea
17	15, 16 Apr 1624, China	18 Apr 1624, Korea
18	15, 16 Apr 1624, China	19 Apr 1624, Korea
19	15, 16 Apr 1624, China	21 Apr 1624, Korea
20	2 Sep 1625, China	28 Aug 1625, Korea
21	2 Sep 1625, China	16 Sep 1625, Korea
22	29 Jun 1626, China	24 Jun 1626, Korea
23	29 Jun 1626, China	10 Jul 1626, Korea
24	9 Dec 1638, China	23 Dec 1638, China
25	16 Jan 1648, Korea	24 Jan 1648, China

Moreover, a set of appendices discusses the literary and scientific reliabilities of the East Asian sunspot and auroral records. The Scheiner telescopic sunspot drawings from *Rosa Ursina*, that will be reviewed in Chapter 3, were also used to assess the credibility of some of the later historical auroral accounts.

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