PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Astronomical Determinations of the Solar Variability [and Discussion]

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Astronomical determinations of the solar variability

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Historical evidence of solar variability is based upon sunspot occurrence and rotation rates, and on observations of the Sun's radius. I present here the methods of observation used to this end, and assess their accuracy and limitations. I then discuss and interpret the periodicities I have found. The main conclusions are that, during the past three centuries solar variability has appeared in the form of recurrent expulsions of magnetic activity at the Sun's surface, accompanied by a modulation of its rotation and periodic changes in its radius. Periodicities of from 150 days up to as much as 80 years, including the well-known 11-year cycle, are present in the historical observations and contemporary observations. No exact theoretical model of the change in solar radiation output under the influence of periodic magnetic fields has yet been developed; but the presence of periodicities common to the Sun's activity and to the Earth's environment suggests a causal relation between solar variability and the meteorology of the Earth.

1. Introduction

Systematic observation of the Sun have been going on ever since Galileo first used the telescope for astronomy in 1611. Although two centuries went by before Schwabe, in 1837, formulated the concept of a regular 11-year cycle, observers had already noticed the variability of the Sun's activity (Picard 1671) as well as of its diameter (Lalande 1771) long before. The question of whether the observed variability was real or was only the result of systematic errors has raised passionate debates over all this time (Lalande 1771; Eddy & Boornazian 1979; Parkinson *et al.* 1980; Gilliland 1981), and remains controversial to our day. The grounds for uncertainty stem from the fact that comparing observations made with different techniques used by different observers is subject to criticism, except when observations overlap and can be calibrated (Ribes *et al.* 1987). The problem is even more difficult when dealing with historical observations obtained with optics that are no longer available. Assuming, however, that the periodicities are real, the question that comes immediately to mind is whether the sunspot cycle is a periodic oscillation of the entire Sun or rather the product of a turbulent dynamo in the convective zone alone. In the former case magnetic fields of alternate polarities are released from the solar interior by some unspecified processes and rise to the surface through a turbulent convective zone (Dicke 1978; Bracewell 1988). The phase of the cycle would somehow be locked, in spite of quite irregular cycles due to the turbulent convective zone. In the latter case, the dynamo is located within the convective zone, and is due to the interaction between the rotational and convective motions. Such a turbulent dynamo could not maintain its phase over a period of centuries.

The choice between these two alternatives is important because the timescales of the processes involved and the consequent effects on the solar envelope and on the Earth's environment are quite different. Very long records of solar activity (sunspots) and of its effect on the solar envelope (diameter, luminosity), are needed to answer this very fundamental question (D. O. Gough, this Symposium). As reviews are available on the subject of the astronomical means of detecting solar variability (Wittman & Débarbat 1990), I discuss them only briefly here, and emphasize instead the results obtained from homogeneous time series, so that the periodicities have some significance. Special attention is devoted to seventeenth-century observations of reduced magnetic activity (Maunder 1894) coincident with a severe cold on Earth, 'the Little Ice Age' (Le Roy Ladurie 1967). A connection between solar variability and the Earth's meteorology, if proved, would be of invaluable importance.

2. Historical methods for detecting solar variability

2.1 *Sunspot observations*

(i) *Sunspot occurrence*

Naked-eye observations of sunspots have been reported as far back as 2000 years ago. Because there is to be a paper on this subject (F. R. Stephenson, this Symposium), I concentrate here on telescopic observations. In the early seventeenth century, sunspots were observed on images projected by an objective lens of 2 cm aperture (an aperture ratio of 22). Larger, though strongly chromatic, lenses were available at the time; however, modest as they were, these primitive lenses enabled observers to detect most of the sunspots we moderns would have found with our powerful instruments. Only pores, about 10% of the total sunspot number, were out of reach. Furthermore, the number of observations made each year by our Paris counterparts during the second half of the seventeenth century was substantial (from 150 to 230 days) and, knowing that an average sunspot lasts almost as long as one 27-day rotation of the Sun, we may rest assured that our skilful observers did not miss many sunspots, and that their count provides a reliable index of the activity of the entire Sun. Their data are shown in figure 1.

The relative sunspot number is defined as $R = K(10g+s)$, where g is the number of sunspot groups present on the solar disk and s is the total number of sunspots for a given day. The parameter K is a scaling factor depending upon the observer, and is used to convert the scale to the original one established by Wolf (1856). The monthly sunspot counts are then smoothed by a six-month running mean to appear in figure 1. The activity index represented by the smoothed relative number is biased, as individual sunspots and pores are given greater comparative weight than clusters of spots. The physical reason of this is to emphasize the occurrence of magnetic fields rather than their size.

It is clear from figure 1 that the sunspot distribution is cyclic in time, although the periodicity is far from constant. Also, the peak of the sunspot number and the duration of the 11-year cycle both vary considerably from one cycle to the next, and the sunspot maxima are clearly modulated, with a periodicity of roughly 80 years. Finally, there is a period of 50 years or so when sunspot activity was practically non-existant, as the Astronomer Royal R. Maunder pointed out in 1894. A close inspection of the historical records of the seventeenth-century observations (Ribes *et al.* 1987) confirmed the existence of the magnetic anomaly of the Sun reported by the Paris observers (Picard 1671, among others). The 11-year signal as well as long-term modulation of the solar activity are clearly present in auroras (Gleissberg 1966; Schröder 1988) and other proxy records, showing that the cyclic character of solar activity is a fundamental feature of the Sun.

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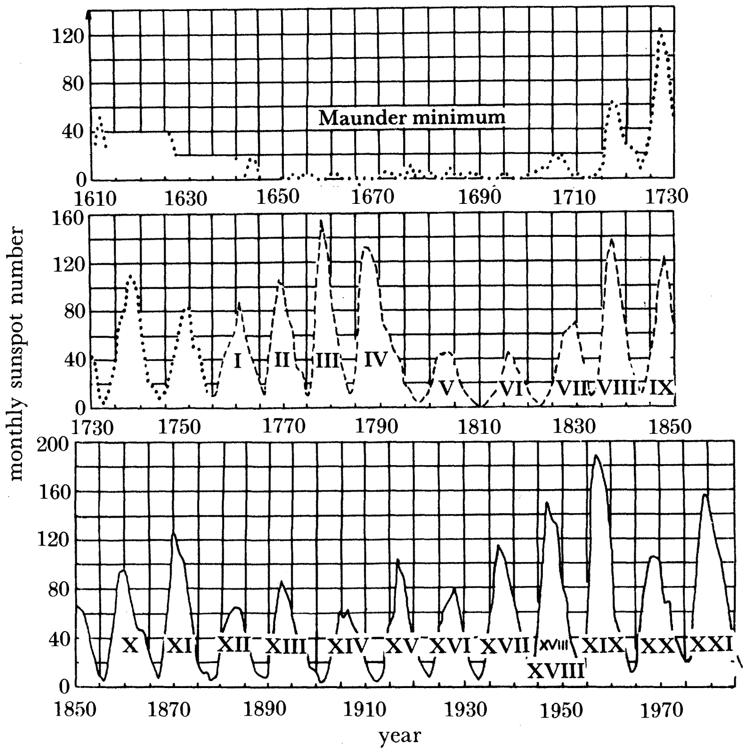

FIGURE 1. Monthly sunspot number against time, as determined by Wolf (1856) and pursued by the National Oceanic and Atmospheric Administration Space environment Services Center.

(ii) *Latitudinal distribution of sunspots*

Sunspots appear at preferential latitudes during the 11-year solar cycle. Classically, sunspot zones appear at the mid-latitudes (about $\pm 45°$) at the beginning of the cycle and this point of origin descends closer to the equator as the cycle goes on, following a 'butterfly wing pattern'. The amplitude of the sunspot maximum and the duration of the cycle are both related to the latitude where the activity starts: for low-activity cycles, for example, the activity starts closer to the equator. This was particularly clear during the Maunder Minimum, throughout which the meagre sunspot activity was concentrated at low latitudes (below 20°).

(iii) *Rotation of sunspots*

Sunspots have been used in measuring the rotation of the Sun. Apart from the well-known fact that the Sun's surface rotates differentially, with the equator rotating faster than the mid-latitudes, the rate of rotation varies from one cycle to the next and fluctuates through a given solar cycle. Again, I should stress that this phenomenon was particularly enhanced at the time of the Maunder Minimum (figure 2), when the whole surface seemed to rotate more slowly than now (Ribes *et al.* 1987). Early in the present century too, the rotation rate decreased by a few per cent (Balthasar *et al.* 1986), and this decrease corresponds to two cycles of low amplitude (cycles 12 and 13, see figure 1). The modulation of the rotation of the solar envelope results from recurrent emergences of magnetic activity.

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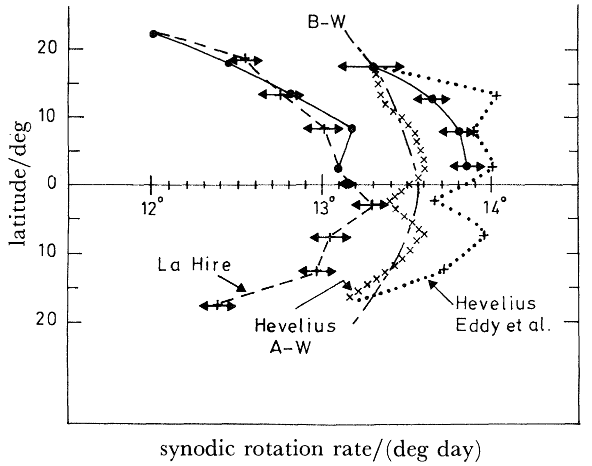

FIGURE 2. Rotation of sunspots against latitude from 1672 to 1719. The dashed line represents the modern rotation of sunspots (Balthasar & Wohl 1980). I have also plotted some controversial results of Hevelius drawings (1642–44) published by Eddy *et al.* (1976) and Abarbanell & Wohl (1981).

2.2. *Solar diameter measurements*

(i) *Filar micrometer method*

This method consists of measuring the linear breadth of the solar image as formed in the focal plane of a lens. The micrometer was invented by Gascoygne in 1640 and was considerably improved by Auzout (1729). It has given accurate readings of the Sun's edges. There are two problems connected with micrometer measurements: the first is determining the focal plane accurately, and the second is the calibration of the micrometer screw. Auzout claimed that an accuracy of ± 1 arcsec could be achieved by Picard when he measured the diameter of the Sun or any planet. There are two indications that such an accuracy was in fact achieved with Auzout's micrometer. First, Picard was able to detect a reduction of 0.5 arcsec in the equatorial diameter of Jupiter, when the planet was in quadrature with the Sun (Ribes *et al.* 1988*a*), the true effect being 0.4 arcsec. Secondly, the statistical error found for the 60 diameter observations performed by Picard each year does not exceed ± 1.5 arcsec (Ribes *et al.* 1987), despite the fact that day-observations may not be as accurate as those made at night since solar heating induces local atmospheric turbulence. However, if the amplitude of this statistical error contains a solar signal, then, Auzout's claim would be confirmed.

(ii) *Meridian timings*

The Sun's diameter can be estimated from records of the time it takes its image to travel through the meridian plane of a refractor (or reflector). In the seventeenth century, the pendulum clock was already very accurate (to within one or two seconds per day). The main limitation was the 'ear and eye' method of quantifying the timing. As the pendulum beat was one second, the uncertainty in each radius determination was about ± 3.5 arcsec. One immediately sees that a great many meridian timings must be made in a year to reduce the statistical noise just a little. A proper analysis of meridian timings should take into account a large number of effects carefully listed by Wittman & Débarbat (1990). For most meridian timings, the determination of the solar limb was, and often still is, visual; so one of the most serious errors affecting the measurements was the observer bias. According to Parkinson *et al.* (1980), the horizontal diameter can vary by as much as 2.3 arcsec among observers. For this reason, detecting periodicities on the basis of observations made by different people is questionable, unless the observations overlap significantly to permit scaling.

Another very serious error is the image blurring due to the Earth's atmosphere. This affects all Earth-based observations. The definition of the solar limb has been improved by photoelectric methods, which are, indeed more objective than the visual method. None the less, the time variation of the solar limb has not yet been properly modelled, so one should keep in mind that any periodicity that is found may be contaminated systematically or randomly by the observation method.

(iii) *Astrolabe*

This method consists of timing the edges of the solar limb, when the trajectory of the Sun crosses the almucantar defined by the instrument (Laclare *et al.* 1983). The Danjon-type astrolabe offers several advantages over meridian timings. The reference system (the mercury surface plane defining the horizon, and the time-stable prism angle defining the zenith distance) is not subject to the distortions that affect all transit methods. Nor is the method sensitive to errors in the refraction modelling, except if the reflection properties change during a given timing. On the other hand, the method is sensitive to the personal estimate of the coincidence of the two images, which explains why the diameter may vary from one observer to another. Also, in the same way as for the other methods (filar micrometer methods of meridian timings), there is the blurring due to atmospheric turbulence. In our day, an accuracy of ± 0.15 arcsec is possible on each radius determination (Laclare 1983).

(iv) *Solar eclipse timings*

Timing the duration of a solar eclipse is one very good way of measuring the solar diameter, as it avoids all of the usual atmospheric problems. To succeed in using it, however, we must know the surface topology of the moon around its entire limb; and this is not available, at least not with the accuracy needed. This is why timings made near border of totality are preferred: the contacts there correspond to the polar region of the Moon where the topology is better known. The accuracy of the solar radius obtained this way in the past could be of the order of ± 0.2 arcsec (Dunham *et al.* 1980). But unfortunately, solar eclipses are neither regular nor frequent and cannot provide any reliable short-term periodicities.

(v) *Timings of planet transits across the solar disk*

Somewhat like solar eclipse timings, the timing of the contacts of a planet with the solar limb can provide an estimate of the length of the cord joining the contact points, and hence of the solar diameter. However, contact determinations suffer from various difficulties and cannot be used to estimate of the solar diameter to within better than ± 0.5 arcsec (Parkinson *et al.* 1980; Shapiro 1980).

3. Periodicities present in the diameter series

As shown in the recent summary of historical observations published by Wittman & Débarbat (1990), the Sun's diameter exhibits a very large dispersion because all of the different techniques used. The fluctuations are much larger than those expected from real solar variability. As systematic errors are difficult to extract, the problem of absolute calibration is a very delicate one. So I consider only long series of observations made by a single observer using a given technique. This way, we can be sure that any periodicities we find from Fourier analysis will not be affected by personal bias or any systematic error of calibration.

Such long time series are available. For the seventeenth century, timings by P. La Hire (1718) using a $9\frac{1}{2}$ ft (*ca.* 3 m) quadrant, cover a large period during the Maunder Minimum and extend a little beyond it, when the solar activity has resumed (from 1705 onwards). Two independent time series (astrolabe observations at the Cerga observatory and meridian timings at the Belgrade observatory) covering the last solar cycle (1978–87) will enable us to detect periodicities of the present time and to compare them with the past Sun.

Finally, the eclipse and planet timings will be used to detect any possible changes in the Sun's diameter. The results are shown in figures 3 and 4.

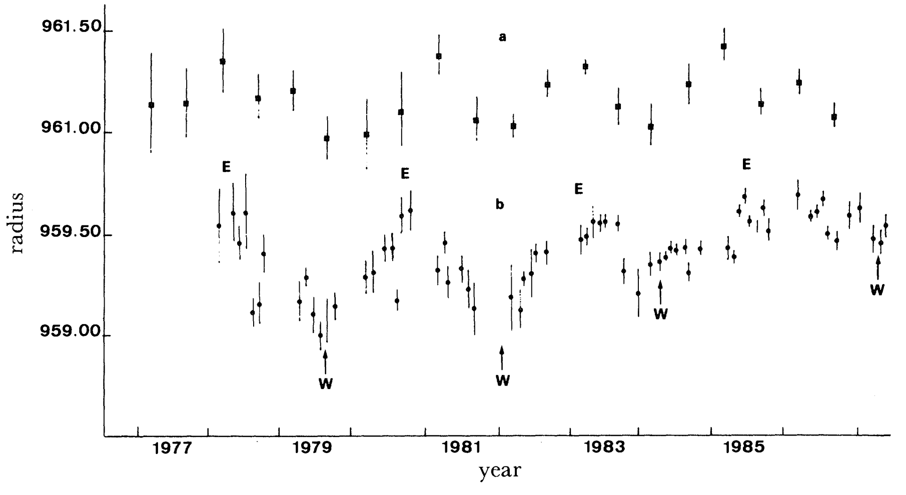

FIGURE 3. Diameter observations with the CERGA astrolabe against time provided by F. Laclare. The onset of the stratospheric winds at the 10 mbar† pressure (Naujokat 1986) are indicated by E (easterlies) and W (westerlies).

In the contemporary data, the remarkable result is a quasi-biennal oscillation of the solar diameter (figure 3). The fact this is present in two independent modern time series (Laclare 1987; Ribes *et al.* 1988*b*) shows that such a pseudo-periodic phenomenon is probably not the result of the technique used nor of the personal bias of the observer. A third independent time series of solar diameter has been obtained with an astrolabe (Leister, personal communication) and exhibits the 1000-day periodicity. As this series comes from the Southern Hemisphere (Abrahao de Moraes, in Brazil), no doubt that a comparative analysis will be of great importance for understanding the solar (or atmospheric) nature of the oscillation.

Other periodicities are present in these series, and are also found in the historical timings (figure 4). Their characteristics (amplitude) are somewhat different, which might be due to the secular variability of the Sun over the centuries. In particular, the amplitudes of the peaks present during the Maunder Minimum are much larger (by a factor of four to five) than those found in the modern time series. This can be understood as a superoscillation of the solar envelope, associated with the dearth of magnetic activity (Ribes *et al.* 1989).

† 1 mbar = 10^2 Pa.

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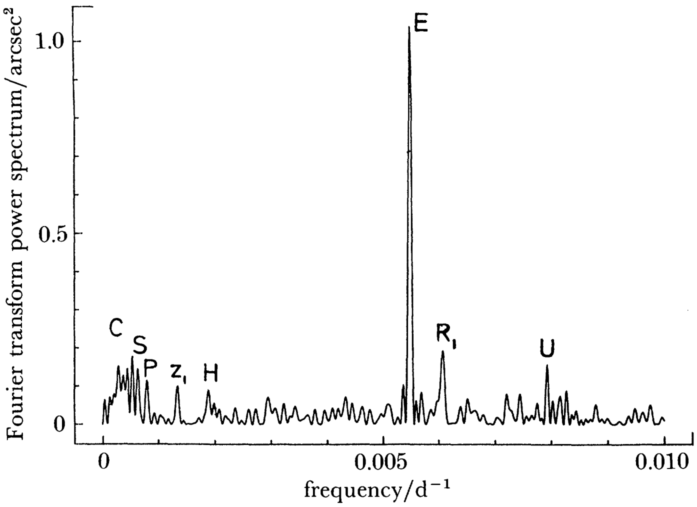

FIGURE 4. Fourier analysis (modulus) of the historical timings performed by P. La Hire from 1683 to 1718 against frequency. The most prominent features are the signature of the 11-year cycle (denoted as 'C') and the semi-annual signal indicating the change in the Sun's shape (denoted as 'E').

In the present day, there is also a particular difference between the characteristics of the quiet and active phases of the 11-year solar cycle: The apparent Sun looks smaller when its surface activity is large, and larger when its activity is reduced. The characteristics of the 11-year cycle during the seventeenth century are similar, and more pronounced at the time of the dearth. This supports the conclusion that the periodicities found originate from the Sun itself rather than from error or bias. The solar nature of the periodicities is further confirmed by the study of other solar and geomagnetic indicators (§4).

There are also a few singularities in both the modern and historical spectra which deserve some attention. The most striking feature is a line that rises far above the 15σ level in the Fourier analysis of historical time series (figure 4), but is weak in the Fourier analysis of modern time series. Before considering a solar origin for this semi-annual periodicity, one wonders whether some special meteorological conditions might be responsible for it. A seasonal nebulosity occurring in winter could change the apparent diameter and would yield an annual signal. A spurious effect of this kind has been investigated by Wittman (1980), and can be partly explained by a second-order effect of atmospheric refraction. After correction for the Wittman effect, the annual peak is eliminated but the diameter time series, still exhibits the 182.5-day peak. One remaining possibility is that the Sun is elliptical in shape, which would give rise to a semi-annual modulation of the horizontal radius, because the horizontal diameter approximates the equatorial diameter around the soltices. The observed diameter is smaller near the equinoxes and larger near solstices. To help settle this question, a simulation of solar oblateness has been performed: an ellipticity of 10^{-2} would be needed to explain the 182.5-day signal present in the historical time series (Ribes *et al.* 1989). This is three orders of magnitude larger than the oblateness expected from the dynamics of the interior. For the 182.5-day signal present in the modern timings of Belgrade, the ellipticity required is still 10 times larger than the assumed oblateness (10^{-5}). Alternatively, a recent study by Kuhn *et al.* (1988) has shown that the shape of the Sun is not at all regular: the Sun is hotter at latitudes of solar activity. As a consequence, the solar disk may be oblate with a solar-cycle-dependent bump at the active latitudes that moves toward the equator during the solar cycle. Such an effect could lead to a change of 10^{-4} in the diameter, which is precisely the value found in the Belgrade timings. Along this line of thought, the signal found in the historical timings can be explained by a drastic apparent oblateness due to the lack of surface activity at mid-latitudes. The resulting equatorial bulge would have reached about 3 arcsec on the diameter.

I should stress that my conclusion is completely independent of any calibration problems, as I have used data obtained by a single observer using the same equipment. However, it is interesting the compare this finding to other measurements performed at the time, and at the end of the Maunder Minimum. Picard, after measuring the horizontal diameter of the Sun, by the filar micrometer method, through the period from 1666 to 1673, came to the conclusion that the horizontal radius was about 965 arcsec. This is in agreement with timings performed by P. La Hire, whenever the solar surface was empty of sunspots. There is also the radius determination from the solar eclipse observed in 1715 by Halley, which gives a value of 960.11 arcsec (Dunham *et al.* 1980). Using the eclipse value of 1715 to calibrate the timings, a correction of 3 arcsec on the radius should be applied to the La Hire timings, reducing this highest record of the radius to 962 arcsec. Our conclusion remains unchallenged, i.e. that the Sun's apparent radius was larger in the deep of the Maunder Minimum (where practically no sunspots were seen) than it was at the end, when solar activity has resumed (from 1705 onwards). Although the change in the disk shape provides a plausible explanation of radius variability, one cannot exclude *a priori* a real radius change. An expansion of the solar envelope of about 3 arcsec on the diameter would be consistent with the cooling of the envelope and with a slowing down of the surface rotation.

4. Periodicities in atmospheric and climatic indicators

The variability of the Sun's diameter is interesting not only *per se*, for the understanding of the internal properties of the Sun. A variable Sun might also effect the Earth's environment, and hence the climatic conditions. Although the Sun–climate connection is the focus of this meeting and is approached from many angles, I simply report the apparent relation between the solar periodicities and those found in the Earth's stratospheric circulation. The most interesting feature might be the relation between the extrema of the solar diameter at the 1000-day period and the Earth's stratospheric winds (Ribes *et al.* 1988*b*): the diameter maxima coincide with the onset of the Easterlies, at 10 mbar pressure, while the diameter minima coincide with the onset of the Westerlies (figure 4). Although a causal relation still remains to be established, there is some indication that solar variability is the force sustaining this quasi-biennal oscillation of the stratosphere. The pseudo-periodic magnetic flux expulsion observed at the solar surface seems to induce a large-scale convective pattern, the azimuthal rolls. As a result, a modulation of the solar envelope would lead to concomitant variations of the radius and luminosity (Ribes & Laclare 1988). The observed changes of radius and luminosity are of the order of 10^{-4} over the 11-year cycle (Willson & Hudson 1988) and do not induce drastic changes in the climate. This is different for the Maunder Minimum, where the apparent ellipticity found was two orders of magnitude larger with a probable reduced luminosity of the order of 1 %.

Shorter solar periodicities are also present in various modern geomagnetic, atmospheric and meteorological records (Delache 1989). In particular, periods around 50–100 days in the solar diameter data correspond to analogous recurrent phenomena in the geomagnetic activity, the

Earth's rotation, the angular momentum of the Earth's atmosphere (Feyssel & Nitschelm 1985; Djurovič & Paquet 1987). It is not firmly established, however, that there is a causal relation between solar variability and the meteorological effects.

5. Tentative interpretation

Although the periodicities present in the diameter data seem to be real, it is still premature to conclude that they correspond to a real change of the solar radius. An alternative could be a change in the thermal structure of the Sun, under the action of the magnetic fields as suggested by Kuhn *et al.* (1988). As the limb brightness changes with latitude and is time dependent over a large range of scales (from days to the 11-year cycle), these changes can induce peaks in the diameter data of power spectra. The limb brightness contributes about several tenths of an arcsecond to the radius, which is the order of magnitude of the radius changes found in the modern time series (Delache *et al.* 1985; Ribes *et al.* 1988*b*).

There are some theoretical arguments indicating that magnetic fields located within the convective zone could not produce detectable radius changes, thus lending support to the thermal structure as the main cause of the apparent radius changes. On the other hand, the numerical simulations predict some significant radius change if the magnetic fields are concentrated beneath the convective zone (Dappen 1983). The crucial point, then, is the location of the dynamo (within or below the convective zone). Again, I refer to modern observations of the solar cycle as well as recent to helioseismological data. The convective zone does not exhibit the radial velocity gradient required to drive the dynamo (Libbrecht 1990). Moreover, convective motions in a fluid dominated by rotation would have the form of meridional cells. No such cells have yet been observed on the Sun. Instead, the large-scale circulation detected by means of the magnetic tracers are azimuthal rolls, i.e. orthogonal to the expected meridional cells (Ribes *et al.* 1985; Ribes 1986). These observational facts seem to question the convective dynamo. Moreover, the recent findings that the interior of the Sun rotates rigidly (that is, without the differential rotation characteristics of the surface (Brown & Morrow 1987)), and that solar activity rotates rigidly when emerging, all support the idea of a deep-seated magnetic field source. Although a core-driven solar cycle is completely beyond the scope of this paper, such speculations would shed light on the variability of solar neutrinos detected by Davies.

It is clear that the Sun pulsates magnetically with different periods, and with concomitant modulations of the solar envelope. Whether or not this pulsation leads to any significant change of the solar output cannot be answered yet, since long and accurate time series of the solar constant are not available. Deeply confined magnetic fields could also be preferable for causing significant changes in the solar output, although the thermal timescale is a constraint on short-term variations.

It remains that the Sun's shape changes in the course of its cycle as well as its rotation, as the result of a strong coupling between the magnetic fields and the solar envelope. The relation between solar variability and stratospheric winds is a very promising investigation, even though we are as yet far from modelling it.

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Discussion

J. S. Stanford (*Department of Atmospheric, Oceanic and Planetary Physics, University of Oxford, U.K.*). I am interested in the solar diameter oscillations Dr Ribes mentioned, with periods of seasonal length (150–180 days). Can she comment further on these?

Elizabeth Ribes. The strongest periodicity occurring at the time of the Maunder Minimum is a semi-annual one (at 182.5 days). Such a periodicity would show up if the solar shape were elliptical. The reason for this is that meridian timings measure the horizontal diameter in a plane that wobbles 26° to either side of the Sun's equator due to the difference between the Sun's and the Earth's axes of rotation. An apparent oblateness of 10^{-2} is required to account for the 182.5-day peak amplitude in the Fourier spectrum. Moreover, there is a phase shift of 70 days between a constant oblateness and an apparent oblateness due to the concentration of solar activity near the equator. Therefore, I surmise that the semi-annual peak during the Maunder Minimum was the consequence of the concentration of sunspot activity in a very narrow range of latitudes (0–18°)

Other periodicities (from 50 to 155 days) seem to be common to solar (irradiance, radius, sunspot number) geomagnetic and Earth atmosphere indicators. The causal relation is not well understood at present.

P. Foukal (*CRI, Cambridge, Massachusetts, U.S.A.*). 1. Dr Ribes mentioned that during the Maunder Minimum the butterfly diagram lost one of its wings, yet she showed rotation measurements by La Hire from that epoch which refer to both hemispheres. Am I misunderstanding something?

2. Is she concerned about the fact that the most accurate diameter data – those of Brown at HAO – show no variation down to about 0.03 arcsec per year precision?

Elizabeth Ribes. 1. From 1666 to 1712 the sunspot activity was concentrated in the Southern Hemisphere only, giving the corresponding rotation curve shown in figure 2. From 1712 onwards, the sunspot activity resumed in the Northern Hemisphere, leading to the corresponding rotation rate in figure 2.

2. The diameter data obtained at the high-altitude observatory (HAO) rely on an objective definition of the solar limb. There is, however, a fundamental problem which affects ground-based observations of the solar diameter: the solar limb definition is distorted by the Earth's atmosphere. The photoelectric method aims to decouple the atmospheric effects from the solar signal. This is a difficult problem to solve, however. The HAO data and solar activity indicators have been subjected to a multi-correlation analysis: the atmospheric correction in the HAO data is found to be significantly correlated with solar activity. This means that the residual HAO diameters are likely to have been overcorrected. At this point, it is preferable to be cautious about drawing any strong conclusions on the basis of the HAO data.