SOLAR DIAMETER AND SOLAR ROTATION DURING THE MAUNDER MINIMUM

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ABSTRACT. The Paris observatory is in possession of a 53 y record of solar diameters and sunspot positions during the Maunder minimum (1666 - 1719). For the period (1666 to 1684), the solar diameter was 32'9" and slowly decreased down to 32'6" when sunspot activity had resumed. Nowadays, the solar diameter is 32'2" when taking into account of the solar irradiance. During the same period, the sunspot rotation was smaller than the present one (3% less near the equator), and the differential rotation was greater.

The two phenomena (a larger Sun and a slower rotation) suggest that the Sun undergoes a cyclic expansion and contraction, on time-scale of several centuries.

METHOD OF OBSERVATIONS

Two methods have been used to measure the solar diameter. One method developed by Picard (1682), denoted hereafter method 1, uses a filar micrometer in the focal plane of the refractor (focal length : 2m). The accuracy on each measurement is about ± 1" (Danjon and Couderc, 1983). The second method also developed by Picard and extensively used by Ph. La Hire (1683-1718) consists of recording the transit time of the solar image formed by a meridian refractor. The transit time was recorded with an accuracy of 1/2 second, giving an error of ± 7" on each measurement. The latter method was also applied to sunspots whenever they were observed. The height of the upper limb and of sunspot above the horizon were also measured with a 6 foot sextant, with an accuracy of ± 5".

Apparent horizontal diameters have been corrected from seasonal variations and reduced to one astronomical unit distance. The Sun's position and orientation have been calculated from the formulae provided by the Bureau des Longitudes (1985). So, the position of individual sunspots on the solar disc have been reconstructed and

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expressed in terms of the usual heliographic coordinate systems.

RESULTS

1. SOLAR RADIUS DURING THE MAUNDER MINIMUM

We have calculated the yearly average of the solar radius obtained with the two independent methods, as well as the root mean square deviation and the statistical error of the mean (Fig. 1)

We can distinguish two periods : the deep Maunder minimum (1666 to 1684), and the end of the Maunder minimum (1685-1719). During the first period, the solar diameter derived from method 1 gives a mean radius of 964".5, with a root mean square deviation $\sigma = +$ 0".19 and a statistical error of the mean of σ±0".011, where N = 297 is the number of observing days. The second method gives a solar radius of 964".5 over 48 days, with a σ of ± 4" and a statistical error of the mean,±0"6. For the period (1685-1719), the meridian circle observations have been much used : the number of observing days per year ranged from 136 to 231 days, and the standard error of the yearly average radius never exceeds 0"47. Are there other systematic errors ?

Method 1 is sensitive to defects in the 17th century optics. Spherical and chromatic aberrations could add a systematic error of 2"2 on the horizontal diameter (Parkinson et al., 1980). On the other hand, method 2 which relies on transit times is little affected by the geometry of the instrument, and is more sensitive to the personal bias. However, observations from 1684 to 1718 made by the same skilled observer clearly show a decrease trend in the radius. Even though the absolute value of the solar diameter during the Maunder minimum can be exaggerated by at most 2"2, the reality of the phenomenon (that is a larger diameter and a regular decrease associated with a rise in the sunspot activity level) is unquestionable.

2. SOLAR ROTATION DURING THE MAUNDER MINIMUM

About 100 sunspots have been observed for more than 4 days. We have calculated synodic rotational rates of sunspots (Ribes et al. 1986), as well as a mean rate R for each 5° latitude belt, between -25% and 20° (Fig. 2) We have also plotted rotational rates by Balthasar and Wohl (1986) in the period (1940-1980), and those of Hevelius calculated independently by Eddy et al. (1976) and Abarbanell and Wohl (1981) in the period 1642-1644. The bars show estimates of the standard deviation for the mean rotation rate for each latitude belt (Fig.2). A few return spots have been identified in our sampling. They give a very reliable estimate of the rotational velocity and rule out any systematic error coming from a possible overestimate of the solar diameter. The rotation profile of La Hire's data is significantly slower than the present one : 3% less at the equator. Moreover, the differential rotation is greater. Rotational rates obtained from Hevelius' data diverge from our analysis of La Hire's

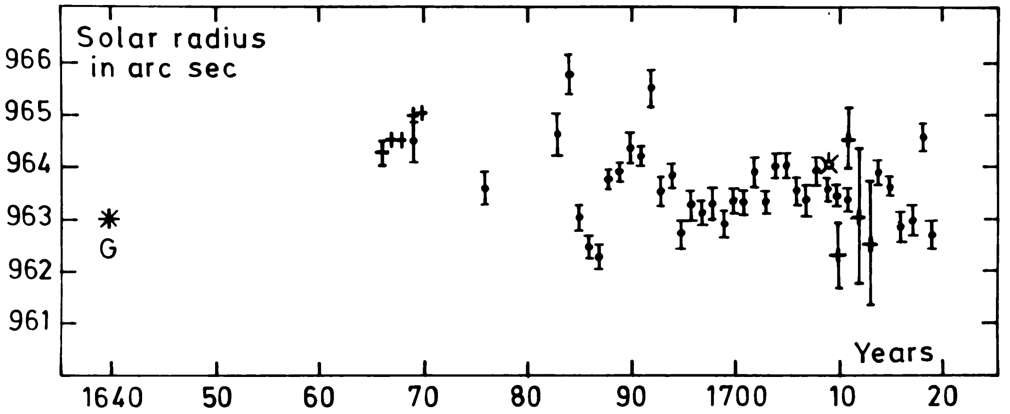

Fig.1 : yearly averages of the solar radiusduring the Maunder minimum. crosses refer to method 1 (filar micrometer), while circles refer to the transit observations. symbol is the diameter measured with the filar micrometer at the time of an eclipse. symbol corresponds to observations by Gascoygne.

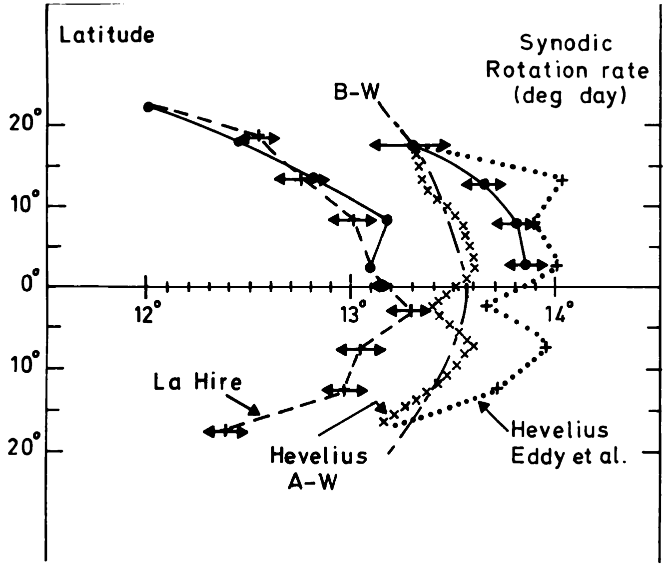

Fig.2 : Rotational rate of hundred sunspots deduced from La Hire observations during the Maunder minimum : dashed line represents the rotational rate of sunspots in each hemisphere, while solid line is the combination of data. Dotted line and crossed line correspond to the Hevelius data (1642-1644) examined independently by Eddy et al. and Abarbanell and Wohl. For comparison, is also shown the present rotational curve.

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data. One should remember that Hevelius drawings are more subject to systematic errors, underestimating the disc circle, for example. Cassini (1730) made his own analysis of Hevelius data as well as Scheiner's data taken at a time when the Sun was still active. He found that the solar rotation before the Maunder minimum was similar to the present rotation, thus confirming Abarbanell and Wohl's claim.

CONCLUSION

The historical data of the Paris observatory are unique. We have shown for the first time, that the Sun's diameter was definitely larger than it is nowadays. The departure from the present value (7" at most) exceeds several times the possible systematic errors. On the other hand, the solar rotation derived from the sunspot's motion across the solar disc is smaller than the present surface rotation rate, with an enhanced differential slippage. These two phenomena indicate that there was a real expansion of the solar envelope during the Maunder minimum, suggesting a periodic modulation of the convective zone on a time scale of several centuries (Eddy and Boornazian 1979). Such an expansion is obviously related to the dearth of sunspots observed during the 17th century. This finding has important consequences on the solar evolution and the earth climatology (Gilliland, 1981) (Ribes et al. 1986).

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