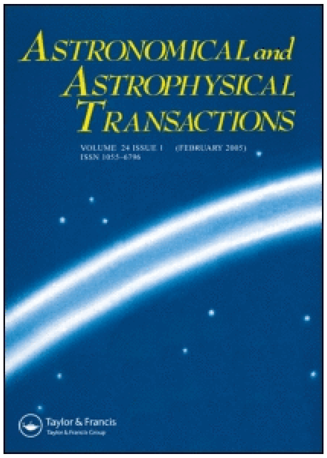


Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 October 2001
To cite this Article: Godier, S. and Rozelot, J. P. (2001) 'A new window on the solar variabilities', Astronomical & Astrophysical Transactions, 20:3, 483 - 490
To link to this article: DOI: 10.1080/10556790108213587
URL: http://dx.doi.org/10.1080/10556790108213587

*Astronomical and Astrophysical Transactions*, 2001,
Vol. 20, pp. 483–490
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# A NEW WINDOW ON THE SOLAR VARIABILITIES

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*(Received October 11, 2000)*

The main objectives of the space mission Picard, currently scheduled for the end of 2003 and under construction, are to measure simultaneously the solar diameter, differential rotation and its total irradiance (and according to the choice of the orbit, its gravity modes). A mission of seven years will permit the study of the temporal variabilities of these quantities over a half solar cycle and it will be possible to determine the multiple regressions along the magnetic cycle. In this paper, we emphasize the physical effects, namely magnetic, thermal, and gravitational, which may explain such relationships. Moreover, the study of the latitudinal variabilities of the diameter will be a test for our 'differential theory', which consists in determining the successive differential gravitational moments, in order to probe the solar interior.

KEY WORDS Sun, radius, irradiance, quadrupole moment, oblateness

## 1 INTRODUCTION

The study of the variabilities of solar parameters, such as the total irradiance or the solar diameter permits one to analyze the problem of the solar activity and to try to answer the question: how does the solar magnetic cycle work? In order to illustrate the problem, let us quote two results. The first concerns the ACRIM space experiment which shows that the sunspots and the faculae have a preponderant influence on the recorded variations of the total irradiance (Foukal and Lean, 1988). The second, still controversial, concerns the measurements of the solar diameter, performed with ground-based instruments over several years, which shows variations with the solar cycle [Laclare *et al.*, 1996; Noël, 1999). The understanding of the relationships between these parameters (radius and luminosity) and the solar activity is crucial to understand the consequences of their variabilities both for stellar physics and for the terrestrial climate.

Several space experiments have existed for measurements of the total irradiance for more than a decade (Fröhlich and Lean, 1998; Pap *et al.*, 1998) but such space measurements do not yet exist for the solar diameter. This lack of space measurements does not permit one to resolve the debate which exists around a possible temporal variation of the diameter. Indeed, for a number of years, the solar diameter has been regularly measured by means of ground-based experiments (in France by F. Laclare, in Chile by F. Noël, but also in Brazil, in Tenerife, and in USA). All the measurements show a variation on a time scale of around 11-years. But these data are not all in agreement, few being correlated with the solar cycle (Chile and USA data) and the others anti-correlated (France and Brazil). One obvious objection is the influence of atmospheric turbulence on the ground-based data, which may distort the measurements.

In order to try to close this debate and to study both the diameter and the irradiance variabilities in a more consistent way, several space missions (one in France named PICARD and the other in the USA named SPHERIS) are proposed to performe simultaneous measurements of the total irradiance and the solar diameter (section 1). These missions will allow us to put in evidence the relationships between these parameters (section 2) and their correlation with tracers of solar activity. Moreover, these missions will also allow us to study the shape of the Sun with high accuracy by means of measurements of the surface distortions (section 3) and its behavior on a temporal scale.

## 2 SPACE MEASUREMENTS TO STUDY THE SOLAR VARIABILITIES

An American space mission is currently submitted to NASA in the framework of future solar space missions (Kuhn *et al.*, 2000). This project is named SPHERIS, which stands for 'Solar PHysics Explorer for Radius, Irradiance and Shape'. A French mission (financed by the CNES agency) is under construction and is due for launch at the end of 2003. We briefly describe here the PICARD microsatellite (after the Picard abbot of the XVIIth century, astronomer at the Paris Observatory) and its scientific objectives (see for more details Damé *et al.*, 2000).

The Picard microsatellite is composed of three sets of instruments: (i) the SODISM telescope (SOlar Diameter Imager Surface Mapper) which will measure the solar diameter from entire images of the Sun, at 230 nm in the UV continuum and at 548 nm in the visible, (ii) the SOVAP radiometer (Solar Variability Picard) dedicated to the total irradiance measurements and (iii) the PREMOS photometers (PREcision Monitor for Oscillations measurements) for the photometric calibration†. The mission provides two sets of diameter measurements which will be performed over at least two years (the nominal time of the mission) and perhaps over seven years if the mission is extended. The first set of diameter measurements will be performed in the UV in order to obtain the mean value of the solar diameter at a wavelength where the centre-edge darkening is lowest, where the edge is the

†SODISM built by the 'Aeronomy Service' of Verrières-le-Buisson in France, SOVAP is operated by the Royal Meteorological Institute of Belgium, and PREMOS was constructed by the Physical Meteorological Observatory of Davos in Switzerland.

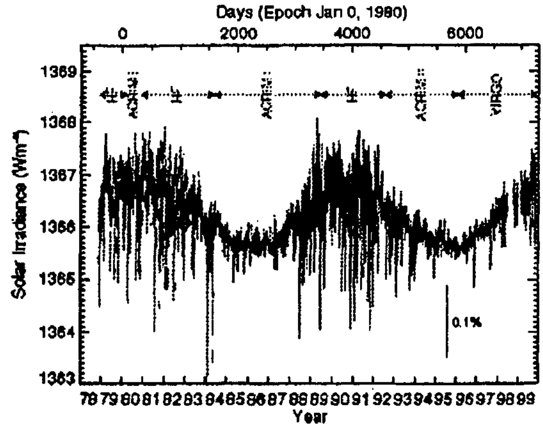


**Figure 1** Composite total solar irradiance for 1978–1997 (after Fröhlich and Lean, 1998).

sharpest, and where the activity traces are the least marked. These measurements of the diameter, performed on a time scale of at least two years, will allow us to know if the solar diameter presents temporal variations or not. If this is the case, as expected by different observers, the variations could be associated with irradiance variations over a long time period and thus possible correlation with the cycle could be detected. The second set of diameter measurements will be performed in the visible, at 548 nm, in order to compare the space and the ground-based diameter data, which have existed for a great number of years. Specially, the comparison of space measurements will be realised between the data of F. Laclare (1996) obtained since 1976 by means of a solar astrolabe at 538 nm, and those provided by the PICARD telescope, which will be installed in south France, as near as possible to the solar astrolabe, at the end of 2001. These sets of comparisons will be certainly of great interest to study the standard errors of ground-based measurements. Finally, the two sets of diameter measurements in space will be analyzed over their latitudinal ranges in order to determine the solar shape, besides the absolute mean value of the solar diameter. This analysis should permit us to understand the role of the local solar distortion on the shape of the Sun.

## 3 INTEREST OF THE STUDY OF SOLAR TEMPORAL VARIABILITIES

Both helioseismic and photospheric solar observations imply that a number of solar parameters change with the activity cycle. Indeed space observations of the irradiance (both bolometric and at various specific wavelengths) have shown that solar irradiance changes on time scales ranging from minutes to the 11-year solar cycle (Figure 1). The largest amplitude variances of up to a few tenths of a percent occur on time scales from days to several months and are related to the photospheric features of solar activity: the irradiance decreases during the appearance of sunspots

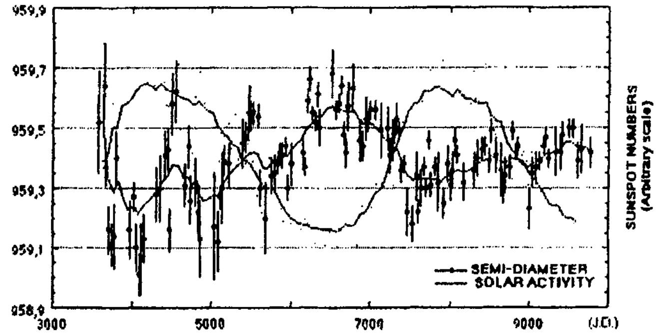


**Figure 2** Semi-diameter variations and sunspot numbers obtained by Laclare *et al.* (1996). Note that the radius variations have drastically reduced since 1988.

and increases during the presence of faculae. Note that all physical processes are wavelength dependent: for example, the contrast of the magnetic structures. The sunspots and the faculae modulate the irradiance at $\lambda > 300$ nm (Lean, 2000). The long term modulation by the 11-year activity cycle is not yet very well understood, in particular the mechanisms which govern the variations have not been explained in details. The sources which may explain the irradiance variability are the surface magnetic field, the magnetic field at the bottom of the convective zone, the changes in convection caused by the toroidal field, and the torsional oscillations... (Solanki, 2000). The Maunder Minimum, associated with the Little Ice Age in Europe, exemplifies a long term modulation not well explained. Thus, understanding the origin of solar variabilities is essential to reconstruct and to predict the solar climate forcings and also to study the ozone depletion and space weather.

Surface brightness changes have also been detected. These correspond to variations of the effective temperature (Kuhn *et al.*, 1988). It seems very likely that dynamical and thermal modulations of the Sun's internal structure imply surface expressions of such changes in irradiance and certainly in the radius, as has been shown by several observers and was pointed out for the first time by Sofia *et al.* (1979). Figure 2 shows an example of the diameter variations (from 1978 to 1996) in opposite phase with the cycle. Nevertheless, historical measurements of the diameter also exist which show that the diameter was larger during the Maunder Minimum (Ribes *et al.*, 1987; Rozelot, 2001). Thus, we can ask the question: which solar processes can explain these changes in the irradiance and in the solar radius, and is there a correlation between these variations, at least for the changes not explained by other factors? To answer this question, two prospects are proposed: the first one concerns the reconstruction of the total irradiance over a long period and its comparison with the evolution of the solar radius, the second one concerns the simultaneous measurements of the total irradiance and the solar diameter, in real time, a comparison that can be done only by means of a space mission. Now, we can ask which physical effects participate in the temporal variations of the diameter. These temporal variations seem related to the activity cycle through the

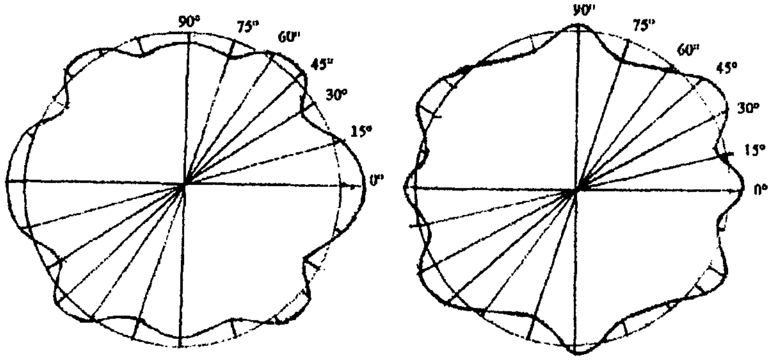


**Figure 3**

effects of surface magnetic fields on the energy emission of the solar surface (Spruit, 1991), through the temperature variations (Kuhn, 2000) and through the luminosity changes (Pap *et al.*, 1998). These sets of changes could be the consequence of the 'contraction' of the Sun during the periods of stronger activity and of the 'relaxation' during the periods of weaker activity which distort the Sun and modify its energetic emission (visible through the irradiance). The changes in the solar radiation on this long time scale present the largest amplitude in the spectrum of irradiance. Furthermore, the possibility of an internal reservoir in which the gravitational energy will be stored and released at a rate depending on the observed intensity fluctuations of the surface is for the time being one of the most plausible explanations.

## 4 INTEREST OF THE STUDY OF SOLAR LATITUDINAL VARIABILITIES

This type of variability is related to the shape of the solar surface and the latitudinal variations of the diameter. To illustrate these types of changes, we propose to consider two different sets of heliographic latitude data which have been statistically treated and obtained respectively by F. Nöel (1999) at Santiago in Chile and by F. Laclare (1996) at CERGA in France. These two sets of data, compared to the mean diameter show a greater diameter near 45° and lower diameters near 25° and near 70°. Figure 3 shows an approximate and amplified representation of these latitudinal measured variations of the solar diameter. The mean amplitude of the distortions, around $0.05 \pm 0.02$ arcsec, still seems large but will be adjusted when space measurements are available. These distortions of the shape of the Sun can be explained by means of the quadrupole moment and the oblateness (at least to the first order).

Indeed, the solar limb is potentially a sharp spatial reference with which we can detect the effects both of the solar oscillations (pression and gravitation modes) and of the true shape of the heliod linked to the changes in the solar radius.

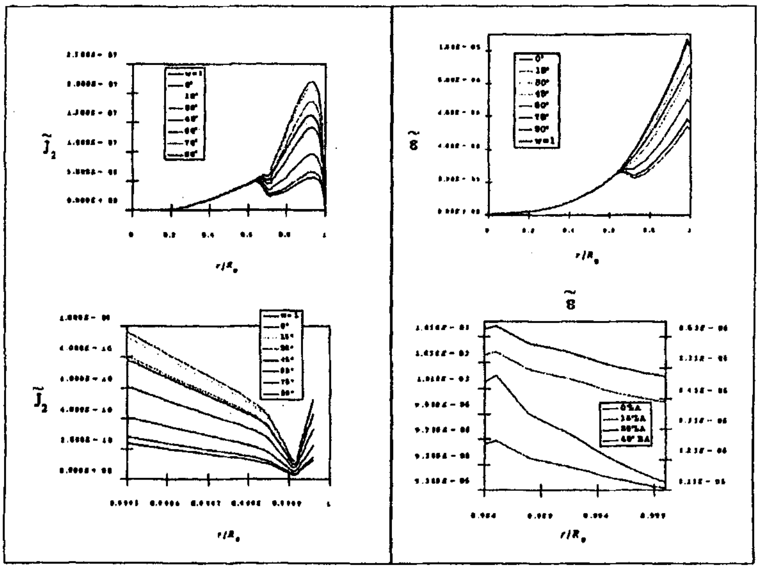

**Figure 4**

An accurate determination of the successive differential gravitational moments is useful to probe the solar surface and the internal structure (Godier and Rozelot, 1999). The quadrupole moment $J_2$ is the coefficient at the first order in the expansion of the perturbation of the gravitational potential. The oblateness $\varepsilon$ is a function which depends on $J_2$, thus the perturbative gravitational potential $y(r,\theta$ such as:

$$J_2 = y(r,\theta)\frac{\Omega_s^2 r^3}{GM_s}, \quad \varepsilon = \frac{\Omega_s^2 r^3}{GM_s}\left(\frac{3}{2}y(r,\theta) - 1\right).$$

The theoretical determinations of $J_2$ and of $\varepsilon$ are obtained taking into account the variation of the rotation with respect to the latitude and to the depth. Figure 4 shows two decreases on the differential quadupole moment profiles which are related to the shear layers, the tachocline which separates the radiative and convective zones and the leptocline located just below the surface (Godier and Rozelot, 1999).

Figure 4 shows also changes of curvature in the profiles of the differential oblateness which are linked to solar processes. In particular, the variations visible near the surface seem to be the signature of both the meridional flows and the zonal bands. Other changes of curvature are associated with seismic events or with the storage of magnetic fields (Godier and Rozelot, 2000). The integration of these two sets of curves allows us to determine the amplitude of the surface distortions. This last one will be measured by means of the PICARD microsatellite, through analysis of the diameter data over several latitudinal ranges.

If there are some arguments for any latitudinal diameter variations, how can we explain these distortions of the heliod? Several local effects are latitudinal dependent (Kroll, 1994), such as the magnetic structures of the photosphere as well as the chromosphere features, the transport of dynamo waves and the rotation rate. The magnetic structures imply local temperature and density variations. There also exists a regular local exchange between the magnetic and the gravitational energy, more likely around the transition zones, the tachocline and the leptocline (Godier et al., 2000). From these effects, we might conclude that the structures in flux tubes globally adjust, in a local way, the solar latitudinal diameter variations and this adjustment is modulated according to the latitude by the shear of the transition zones.

## 5 CONCLUSION

To study the variabilities of shape, radius, and irradiance, we have seen in the previous sections that two next space missions will be fully dedicated to this task (PICARD which is currently under construction and SPHERIS which is a candidate). The scientific objectives of these space missions are to measure the solar diameter in any direction (latitudinal dependence) and the total irradiance simultaneously, in order to study their variabilities on time scales ranging from minutes to months. These studies will permit one to compare their variations according to the cycle and to determine with accuracy the distortions of the solar heliod. From these measurements, some Earth climatological effects might be deduced as irradiance (and radius if well correlated) is one of the main drivers of space weather.

The measurements of the solar diameter will permit one to determine the successive gravitational moments (the quadrupole moment and perhaps octopole and hexadecapole moment) and the oblateness of the Sun. The study of the diameter variations along the heliographic latitude will be compared with the behavior of the differential parameters which also vary with the latitude. This variation is the signature of the distortion of the solar surface.

Moreover, knowing that the presence of magnetic structures at the surface of the Sun is a large effect of the local latitudinal diameter variation and that these structures evolve on a large time scale, and knowing that the differential rotation and the cycle of magnetic activity are intimately linked to dynamical processes within the deep shell of highly turbulent convection (Toomre *et al.*, 2000) – which can also explain the latitudinal diameter variation, it seems evident that the latitudinal variations are coupled to the temporal variations of the diameter. It remains to study the couplage between the solar diameter and the total irradiance (solely based on magnetic effects). We expect to do this by means of the coming space missions.

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