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Global properties of Sun and stars: what can we learn from irradiance and shape?

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Abstract. During the first years of operation, the VLTI Interferometer has demonstrated its ability to determine very accurate fundamental parameters for a large variety of bright stars. Precise stellar diameters have been measured and rotation-induced asymmetries have been detected through accurate determination of the visibility function. In some specific cases, oblateness can be measured with an unequalled accuracy. In this paper, we will report direct interferometric measurements of some specific stars that we will compare to the same parameters of our Sun (mainly oblateness). The gravity darkening effect, which makes the polar region hotter than the equator, yields a distorted shape. The case of the Sun is thus investigated and consequences on the irradiance modeling are analyzed. It is shown, to first order, that irradiance variability (over a solar cycle) is related to the radius variability (on the same period of time) according to the values of the effective temperature of the Sun. The best fit is obtained for $dT = 1.2\ K$ (over two solar cycles), a value very close to that deduced by B. Caccin by other means. However, for smaller values of dT $\in [0, 0.8]K$, the fit can be obtained with a phase-shift, supporting new results obtained by W. Livingston at Kitt Peak. It thus emphasizes the need to measure simultaneously global properties of Stars and Sun, in particular observations of the radius, irradiance and rotation. Dedicated space missions, or SDS flights must be considered in a near future.

Key words. Sun: radius – Sun: irradiance – Sun: effective temperature – Sun: variability

1. Introduction

In the same way we define the geoid for the Earth, which is an equipotential surface of gravity, we can define the helioid for the Sun and a "stelioid" for the other stars. These words illustrate the fact that the surface of the Sun and stars is distorted by their own rotation and possibly by their magnetism. For the Earth, precise space measurements of the surface shape allow us to access information on the internal terrestrial structure, mainly the density inhomogeneities or the angular momentum variations for example. The idea to apply the same method for the Sun and now the stars is on its way. In these cases, the study of the outer shape of the body can allows us to access not only density inhomogeneities under the surface

Send offprint requests to: S. Lefebvre but also the different rotation velocity rates, which are known to be non uniform, on the surface and in depth. With the advent of sophisticated techniques such as interferometry, one is now able to accurately determine the geometrical shape of the free boundary of stars, such as Altair or Achernar, two rapid rotators for which observations of the geometrical envelope have been made by Van Belle et al. (2001) and Domiciano de Souza et al. (2003) respectively . Curiously, for the Sun, the situation is hardly that of the Earth which prevailed before 1957. The flattening of the Sun is still poorly estimated and we hardly know if there is a variability of this flattening related to the solar cycle. One of the main reasons is that the Sun is a slow rotator. If there are no surface stresses, such as those introduced by the fluid velocity rates distribution or magnetic fields, then the Von Zeipel's theorem states that the gravitational surface coincides with those of constant pressure or constant temperature. The visual (or apparent) figure is a surface of constant gravitational potential, which shows small departures from a perfect sphere, called asphericities, and this equipotential level must match the physical Sun's surface. If we are able to determine by accurate observations such asphericities, then we will learn about the solar interior by adjusting the perturbated gravitational field (a fact that G. Isaak describes as *"a new window open over the Sun's interior"*, see Godier and Rozelot, 2001; such a program is part of the objectives of new space missions). In many cases, it is sufficient to model the Sun as a sphere to explain most of the physics. But we now arrive at the limit of precision, particularly in subsurface layers, where the behavior of the Sun is still questioning (mainly due to density variations and to the change of the sign of $d\Omega/dr$ at mid latitudes). This is why, solar and stellar models need accurate measurements of global parameters, mainly:

- the radius, $R(\theta)$, where θ is the colatitude, i.e. the precise shape of the Sun and stars;
- the irradiance, I;
- the effective temperature, $T_{\mathrm{eff}}(\theta)$;
- the rotation law, $\Omega(r, \theta)$, where r is the depth;
- etc...

The challenge in a near future is to provide precise measurements of these values and particularly astrometric measurements of the shape of the Sun and other stars. In this paper, we will first present the state of the art in shape measurements of the Sun and stars, followed by a study concerning the modeling of solar irradiance through radius and effective temperature variations. This will be discussed and concluded by some perspectives.

2. State of the art in shape measurements of the Sun and Stars

Presently, advanced techniques such as interferometry yield a precision never achieved for the oblateness of rapid rotator stars. For example McAlister et al. (2005) have recently determined the oblateness of Regulus (αLeo) to be $a/b = 0.845 \pm 0.029$, where a is the equatorial radius and b the polar one. Domiciano de Souza et al. (2003) were the first to measure the shape of Achernar (αEri), the flattest star ever seen: the best ellipse fits leads to $a/b = 1.56 \pm 0.05$ or $2a - 2b = 0.91 \pm 0.05$ mas which gives a relative precision of 5%! Van Belle et al. (2001) have measured the size of Altair (αAqu) and obtained a value $a/b = 1.140 \pm 0.029$ or $2a - 2b = 0.424 \pm 0.079$ mas (19%). For the Sun, Rozelot et al. (2003) obtained accurate values of the solar shape by means of the Pic du Midi heliometer: they measured the difference $a - b$ to be 9.45 ± 1.41 mas, that is 15% of relative precision, less than the precision for Achernar (other measurements exist, see a review in Godier & Rozelot (2000)). Thus, we are presently confronted to a paradox: a better determination of the shape of other stars than that for our own Sun exist. And this, even if precise measurements of the solar radius can be made, such as those obtained by Kuhn et al. (2004) thanks to SOHO/MDI, leading to a mean value of 959.2757 ± 0.151667 arcsec.

3. Radius variations and irradiance modeling

Solar irradiance models have progressed to the point that subtle features are now being searched for. If it is now well established from the past decades of irradiance observations that solar irradiance varies on all time scales from minutes to several years, causes to these changes are far to be understood. On the long term, effects of sunspots, faculae, and other photospheric or chromospheric changes have been the first effects taken into account to explain the undecennal cycle. On the short term, granulation and supergranulation effects may explain hourly variations in the irradiance, while p-mode oscillations may justify periods of few minutes. Magnetic activity can influence the solar irradiance depending on the way the energy is dissipated. The debate is not yet conclusive to know if the medium term variations represent real luminosity changes or not (see also Fazel et al. (2005)). Albeit all these mechanisms are discussed in several ways, it is clear that modeling irradiance variations on all time scales clearly becomes a puzzling problem. To progress, it is not without interest to consider effects that have been neglected up to now and, among them, the variations of the solar shape.

In this paper, we study the effect of radius variations on irradiance modeling. Presently we know that modeling TSI (Total Solar Irradiance) through spots and faculae explains 95% of the total variation. This paper is an attempt to clarify if some of the 5% left could be of other origin, and why not due to the variability of the global distorted shape of the Sun. This point has been partially studied by Rozelot et al. (2004). The luminosity of the Sun is classically related to the effective surface temperature and to the size of the surface by Stefan's law. The size of the surface is directly related to the shape and then to the radius considered as a function of the colatitude:

$$A = 4\pi \int_0^{\pi/2} R(\theta) \left[1 + \left(\frac{dR(\theta)}{d\theta} \right)^2 \right]^{\frac{1}{2}} d\theta \qquad (1)$$

Moreover we know that the effective surface temperature is related to the gravity by the so-called "gravity-darkening" effect (Von Zeipel 1924, Zahn 1992). This effect implies that the local effective temperature is proportional to gravity and so directly related to the gravitational distortion of the star. In order to check the influence of tiny solar radius variations on the luminosity L (and then on irradiance I), we assume $dI/I = dL/L$ and the outer

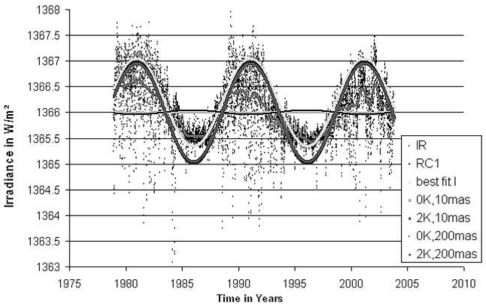

Fig. 1. Irradiance variations with time. This figure shows the observed composite irradiance versus time (called IR, dots), according to dataset updated to October 1, 2003 (Fröhlich & Lean 1998); the first component $RC1$ in the Singular Spectrum Analysis (trend); the best sinusoidal curve fit to the observed composite data with $P = 10.09$ yrs and $\phi = 1.026$ rad; and four sinusoidal models with different appropriate pairs of [T (in K) and dR (in mas)], as indicated in the right box.

shape of the Sun to vary with time, according to a simple periodic function of period P equal to the solar cycle one. Variations of the solar irradiance, assumed to be due to the sole variations of parameters $T_{\rm eff}$ and R are now adjusted to the mean value I_o and modelled by a temporal sinusoidal variation

$$I_{model} = I_o + sin(2\pi t/P + \phi)dI \qquad (2)$$

with the following relation derived from Stefan's law

$$dI/I = dL/L = 4dT/T + dA/A \qquad (3)$$

The irradiance model can now be compared to observations. More details on the computations can be found in Fazel et al. (2005 a and b) by using the irradiance composite dataset updated to October 1, 2003 (Fröhlich & Lean 1998). The best fit of these data by I_{model} gives $P = 10.09$ yrs and $\phi = 1.026$ rad.

Fig. 1 shows the observed irradiance together with the I_{model} best fit and the first component in the Singular Spectrum Analysis ($RC1$, i.e. the trend). The $RC1$ fit is $\chi^2 = 0.76$, better than the sinusoidal I_{model} fit for which $\chi^2 = 1.17$. Four other curves are shown: the computed irradiance through Eq. 2 for a *solar ellipsoidal surface* with different (dR, dT).

4. Discussion

The irradiance computed with this model is very sensitive to the effective surface temperature. As plotted on Fig. 1, observed irradiance variations can be reproduced with dR = 200 mas and $dT \approx 2$ K, but such a large radius change is rather unlikely because not observed from space and it would imply astrophysical consequences never put in evidence. The best fit to observed irradiance variations (considering $RC1$), over nearly two solar cycles, is obtained for $dT = 1.2$ K at $dR = 10$ mas. Such a temporal variation of the effective temperature $T_{\rm eff}$ is close to that obtained by Gray & Livingston (1997) and Caccin et al. (2002). They report a systematic variation of $T_{\rm eff}$ during the activity cycle with an amplitude modulation of 1.5 ± 0.2 K. However, other measurements made by Livingston & Wallace (2003) and Livingston et al. (2005) at Kitt Peak Observatory, using a different method, show an "immutable basal photosphere temperature" within the observational accuracy. Following these results, our fit to the observed irradiance has be refined by investigating smaller solar surface effective temperature variations. Fazel et al. (2005, a and b) showed that a phase transition curve exists in the (dR, dT)-plane, and this curve distinguishes between correlated (above the $dT_{critical}$) and anticorrelated (below the $dT_{critical}$) solar radius variations with irradiance variations. By using the interval $dR \in [0, 200]$ mas, the authors found that $dT_{critical} \in [0, 0.085]$. Hence, we understand the sensitivity of irradiance modeling to very small temperature variations.

5. Conclusions and perspectives

In this study, we have shown that temporal and latitudinal solar radius variations must be taken into account in the present efforts to modelize solar irradiance. We have shown that irradiance variation modeling is very sensitive to faint surface effective temperature variation and we underlined a phase-shift in the (dR, dT)-parameter plane between correlated or anticorrelated radius versus irradiance variations. To determine the phase of radius variations with respect to solar cycle activity, further fine observations of dT might be crucial. Moreover dedicated space missions (such as GOLF-NG, PICARD or SDO, within the NASA International program "Living with our Star", and scheduled for a next future – 2008,2010–) are essential to obtain accurate measurements of the solar shape. Waiting for such data, it is planned to reactivate the SDS (Solar Disk Sextant) program of balloon flights (Sofia et al. 1994, Lydon & Sofia 1996 and Rozelot & Sofia 2004).

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