Stellar Rotation
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Gravitational Distortions of the Shape of the Sun: Constraints on the Models

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Abstract. Due to its own rotation, it is expected that the visual figure of the Sun is a spheroid; this is not truly the case because the solar rotation is not constant both over all heliographic latitudes and in depth. The photospheric shape is thus sensitive to the interior structure: accurate measurements of both limb shape distortions and solar rotation rates determination provide useful constraints on the internal layers (density, shear zones, ...). We show why and how the implication of the successive gravitational moments are important to probe the solar interior, and we compare measurements obtained either from space (SOHO/MDI) or from ground-based experiments (scanning heliometer at the Pic du Midi). The found faint departures to the sphericity, not exceeding 22 mas, could explain fluctuations that are not yet taken into account in the classical modelling of the solar irradiance. A crude model could explain the asphericities which is based on a core rotating at a nearly uniform rate combined with a prolate tachocline and an oblate outer convective zone.

1. The theory of Figures

What is the true shape of the Sun and why it is important in astrophysics to know it with a great accuracy? Essentially because the outer shape of the Sun deviates from the sphere by a non negligible quantity and that such a departure has significant impacts on various issues such as the knowledge of the Sun's interior, the determination of the planetary orbits and in general relativity. However the deviation parameter is hard to compute as the rotation rate of the Sun, a rotating fluid body, is far from being uniform, both at the surface and with depth. The Sun's surface is an equipotential and the total potential ϕ is the sum of the gravitational ϕ_1 and centrifugal ϕ_2 potentials. ϕ_1 may be developed on the basis of Legendre's polynomials in a traditional way. ϕ_2 is calculated from a law of the form

$$\omega = \omega_{pol}\left[1+\sum_{i=1}^{\infty} a_{2i} r_p^{2i}\sin^{2i}(\psi)\right]^{1/2}$$

where r_p is the radius vector at a depth p. Using the solar Greenwich data base, Javaraiah & Rozelot have computed at the surface $a_2 = 0.442$, $a_4 = 0.056$ and $\omega_{pol} = 2.399\ \mu rad/s$. This constitutes the originality of this work, as the frequently used law $\omega = \omega_{pol} + \omega_2 sin^2(\psi) + \omega_4 sin^4(\psi)$ cannot be used any longer, otherwise the centrifugal force does not derive from a potential.

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2. Results

The theory of figures applied to the Sun permit to determine the two first moments as $J_2 = 9.02\ 10^{-7}$ and $J_4 = 4.24\ 10^{-7}$ values that could be seem large but explained by the surfacic velocity. One can compare with these obtained by Lydon & Sabatino (1996), $J_2 = 1.84\ 10^{-7}$ and $J_4 = 9.83\ 10^{-7}$, Pijpers (1998), $J_2 = 2.23\ 10^{-7}$, Paterno et al. (1996), $J_2 = 2.22\ 10^{-7}$ or Armstrong & Kuhn (1999), $J_2 = -2.22\ 10^{-7}$ and $J_4 = 3.84\ 10^{-9}$.

The shape parameters c_{2n} can be computed from the development of r on the basis of the Legendre polynomials (Rozelot & Lefebvre, 2002). Recent campaigns at the Pic du Midi Observatory have permit by means of the scanning heliometer to determine c_2 and c_4 as $c_2 = -(1.3 \pm 0.51)\ 10^{-6}$ and c_4 below than $-3.4\ 10^{-7}$. These values can be compared with these found by Armstrong & Kuhn(1999): $c_2 = -(5.27 \pm 0.38)\ 10^{-6}$ and $c_4 = -(1.1 \pm 0.5)\ 10^{-9}$.

3. A Possible Theoretical Model

A tentative explanation can be ruled out as follows. Helioseismic observations of the Sun's interior show that the tachocline is prolate (Dikpati & Gilman, 2001). If we assume this simplified system to be representative of the current state of our knowledge, it results that the corotation of the core and the tachocline with the oblate outer shells, which all rotate at different velocities, lead to a quadrupole moment (and other higher terms) that could explain the observed corrugated surface. However, as discussed by Rozelot & Bois (1998), the solar quadrupole moment must be upper bounded, otherwise indirect effects, such as lunar physical librations would be no more compatible with accurate observations. The apparent dependence of the semi-diameter of the Sun versus the heliographic latitude derived from ground-based observations is thus compatible with this upper limit, taken into account the difficulties of such observations.

4. Conclusion

It is rather hard to determine the successive moments of the Sun from the ground. Only dedicated astrometric space missions, such as the PICARD microsatellite (France, Belgium and Swizerland), scheduled for flight by 2007 and already under construction in France, will help to get better view on this question.

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