Comparative Magnetic Minima:
Characterizing quiet times in the Sun and Stars
Proceedings IAU Symposium No. 286, 2011
C. H. Mandrini & D. F. Webb, eds.

doi:10.1017/S1743921312005157

Potential energy stored by planets and grand minima events

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Abstract. Recently, Wolff & Patrone (2010), have developed a simple but very interesting model by which the movement of the Sun around the barycentre of the Solar system could create potential energy that could be released by flows pre-existing inside the Sun. The authors claim that it is the first mechanism showing how planetary movements can modify internal structure in the Sun that can be related to solar cycle. In this work we point out limitations of mentioned mechanism (which is based on interchange arguments), which could be inapplicable to a real star. Then, we calculate the temporal evolution of potential energy stored in zones of Sun's interior in which the potential energy could be most efficiently stored taking into account detailed barycentric Sun dynamics. We show strong variations of potential energy related to Maunder Minimum, Dalton Minimum and the maximum of Cycle 22, around 1990. We discuss briefly possible implications of this putative mechanism to solar cycle specially Grand Minima events.

Keywords. Sun: activity - Sun: interior, sunspots.

1. Aim and Methods

Wolff & Patrone (2010) presented the first mechanism devoted to explain modifications of stellar interiors by planetary gravity. They claimed that a cell inside a rotating star with orbiting planets (i. e. with measurable barycentric motion), can creates potential energy per unit mass (PE) that can be released by internal processes. The authors used interchange arguments; i. e., the cell is composed by two masses that, by interchanging their positions, can release PE but conserving angular momentum.

There are two points which seem to have not been discussed by these authors, which limit the applicability to a real star (Svalgaard, private communication):

First of all, remaining in an inertial frame, which simplifies the governing equations, but complicates the boundary conditions substantially, because they are now moving (with the star) relative to the static interchange. Wolff & Patrone appear not even to have considered boundary conditions, neither explicitly nor implicitly.

Second, one should also keep in mind that instability can never be proved by interchange arguments, unless one can demonstrate that the interchanges considered can be realized by the fluid. One can, in principle, demonstrate stability; however, by showing that no displacement, realizable or not, can liberate energy to drive the instability. However, when the interchange is carried out in a plausible manner which avoids this complication, as did Rayleigh and Chandrasekhar, the outcome can be usefully suggestive. The interchange considered by Wolff and Patrone leaves the fluid elements (apparently filling the spaces into which they have been displaced, yet) moving with respect to them;

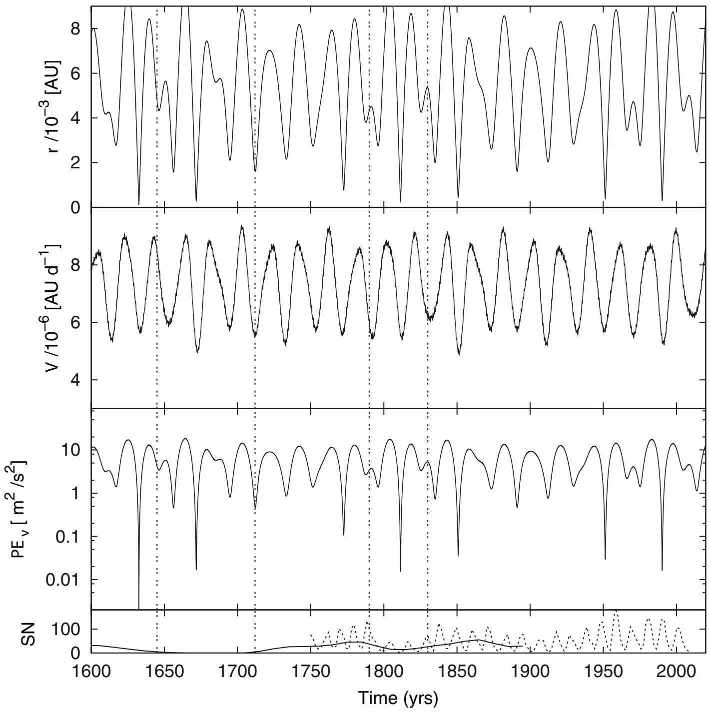

Figure 1. Barycentric solar distance r, barycentric solar velocity V; PE storage at 0.16 solar radius facing the barycentre (PE_v), and the sunspots series (SN) observed/smoothed (dashed line) and reconstructed (solid line). Following to Wolff & Patrone (2010), the particular dynamics around 1632, 1811 and 1990 produce a dramatically decrease of PE in the studied solar zone, related to Maunder Minimum, Dalton Minimum and the maximum of Cycle 22.

therefore it is valid dynamically, for the purposes of energy computation, only for an interval of time of measure zero, which is insufficient to take the temporal derivatives required to determine subsequent evolution, essential, of course, for assessing stability.

In this context, these authors have shown that the strongest case is the vertical one, i.e., the larger storage would occurs when the cell is near in the Sun's centre-barycentre direction (Fig. 3 in that paper). The authors presented graphics showing the values of PE stored in these locations. They mentioned possible effects in PE due to occasional variations of certain dynamical parameters (e. g., barycentric distance r and velocity V of the Sun).

The movement of the Sun around the barycentre of the Solar System (the *solar inertial motion*) has had important irregularities in the past, e.g., angular momentum inversions related to Maunder and Dalton minimums and at the maximum of Cycle 22 in 1990, and related to Gnevyshev-Ohl rule violations (Fairbridge & Shirley 1987; Javaraiah 2005; Perrymann & Schulze-Hartung 2011). Also, the solar inertial motion was related to solar cycle (i.e., the planetary hypothesis of solar cycles, see e.g. Perrymann & Schulze-Hartung 2011). In particular, Fairbridge & Shirley (1988) were able to show that only at times of Grand Minima (GM) events, a substitute of the apsidal axis of the solar barycentric orbit has had strong oscillations, but in their work there is no hypothesis related to any particular forcing mechanism in connection with this phenomenon. They also found a strong oscillation in 1990, so the authors, extrapolating these findings, argued for a new imminent GM event.

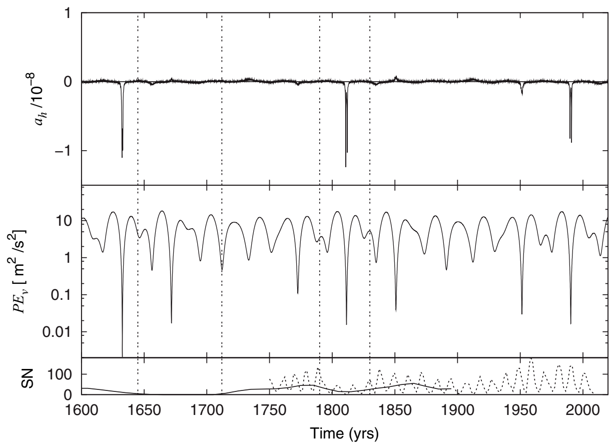

Figure 2. PE storage at 0.16 solar radius facing the barycentre (PE_v), and the sunspots series SN (pointed-line: observed-smoothed; solid line: reconstruction by Solanki *et al.* (2004)). a_h is the angular momentum projection (scaled) in the Sun's acceleration direction. Following to Wolff & Patrone (2010), the particular dynamics around these impulsive events (1632, 1811 and 1990) produce a dramatically decrease of PE in the studied solar zone, related to Maunder Minimum, Dalton Minimum and the maximum of Cycle 22, before the present extended minimum.

Then, in the light of this new hypothesis of Sun-planets interaction, taking into account its limitations and the particularities of solar inertial motion, it is interesting to check what could be the possible PE variations with regards to these last GM events and the mentioned cycle. In addition, Cionco & Compagnucci (this volume) showed that the Sun acceleration has presented impulsive manifestation before the Maunder Minimum (MM), around 1632; in the middle of Dalton Minimum (DM), in 1811; and in the maximum of Cycle 22, around 1990, before the present extended minimum. To show the possible influence of real barycentric sun-dynamics in PE storage, we calculate the specific PE stored in the vertical case (PE_v), supposing a near coplanar solar movement but using the actual velocity and position obtained in our SIM simulations.

2. Results

Fig. 1 shows that the Sun's closest approaches to the barycentre (that also coincide with drops in velocity; keep in mind that the Sun's movement is not keplerian) has associated big drops in PE_v. The dashed vertical lines indicate Maunder Minimum and Dalton Minimum.

Fig. 2 shows the PE_v stored at 0.16 solar radius facing the barycentre and the sunspots series SN (observed-smoothed and reconstructed by Solanki *et al.* 2004). The a_h quantitie is the angular momentum projection on the Sun acceleration direction. The particular dynamics around these impulsive events (1632, 1811 and 1990) produce a dramatically decrease of PE in the studied solar zone, consistent with Maunder Minimum, Dalton Minimum and the maximum of Cycle 22. Clearly PE variations are correlated with these GM events and show that, following this formalism, the Sun barycentric dynamics should be a measurable effect in the Sun's interior.

3. Conclusions and hypothesis

If the results of Wolff & Patrone were valid for a real star and taking into account our results, one can think that Maunder Minimum, Dalton Minimum and the maximum of

Cycle 22, shared certain changes due to planetary accelerations that could have a significant effect in the solar interior, which could be a global support to planetary hypothesis of solar cycles.

Then it is very important to clarify the true scope of the work of Wolff and Patrone due to the chaotic nature of the solar dynamo can amplify the effects of a weak external periodic forcing through resonances, collective synchronization and feedback mechanisms.

Acknowledgments

The author is indebted to Dr. Leif Svalgaard who pointed out the limitations of Wolff and Patrone work. The author acknowledges the support of a grant from IAU to attend the Symposium 286 and PID-UTN 1351 *Forzantes externos al planeta y variabilidad climática* of UTN, Argentina.

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