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Solar wind, mass and momentum losses during the solar cycle

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Abstract. We study the connections between the sun's convection zone evolution and the dynamics of the solar wind and corona. We input the magnetic fields generated by a 2.5D axisymmetric kinematic dynamo code (STELEM) into a 2.5D axisymmetric coronal MHD code (DIP). The computations were carried out for an 11 year cycle. We show that the solar wind's velocity and mass flux vary in latitude and in time in good agreement with the well known time-latitude assymptotic wind speed diagram. Overall sun's mass loss rate, momentum flux and magnetic breaking torque are maximal near the solar minimum.

1. Introduction

The subject of the evolution of the corona and solar wind's properties during the solar cycle has been studied mostly based on observations of surface magnetic fields and/or coronal imaging. We follow a different approach here and focus on the connections between atmospheric and sub-surface phenomena and their variation during the solar cycle. Two 2.5D MHD models were used: STELEM for the convection zone dynamo (Jouve & Brun, 2007) and DIP for the wind and corona (Grappin, *et al.* 2000). A time series of dynamo generated field's were used as source fields in the DIP code. The solar wind flow develops in the domain until the system relaxes to stable steady state. Successive realisations of the procedure allow us to build a general picture of the evolution of the sun's coronal environment in response to the cyclic evolution of the dynamo source field.

2. Results

Fig. 1 shows the first 3 $R_\odot$ of the northern hemisphere at four different instants ($t =$ 0, 3, 3.5, 10 years). Orange and blue shades trace different **B**-field polarities in the open-field regions. The coronal (poloidal) magnetic field is globally dipolar faraway from the surface, except during the polarity reversal. Close to the surface, the magnetic topology is much more complex. The polarity reversal happens *quickly* in the corona, even if the underlying **B**-field evolves *slowly*. For $r \gg R_\odot$, $|\mathbf{B}| \approx B_r$, as the solar wind "opens up" the field lines. Furthermore, B_r is nearly independent of the latitude faraway from the sun. The magnetic field decomposes mainly in low-order multipolar components at the minimum, while higher order components appear at the maximum. The *multiple* current sheets shown in Fig. 1 may be interpreted as a highly warped current sheet in the non-axisymmetric corona. Fast solar wind originates essentially from high latitude regions, while the slow wind flows mostly aside the *streamers* at lower latitudes. Exceptions may occur, though. Wind speed and flux tube expansion factor are well correlated at all latitudes. From solar minimum to solar maximum (Fig. 2), the global $|\mathbf{B}|$ increases, the mean Alfvén radius $\langle r_A \rangle$ decreases, the total surface open flux decreases, the coronal hole/streamer boundaries approach the poles and $\dot{M}$ falls. Angular momentum flux and breaking torque τ weaken, with $\tau < 0$, all the time (Matt & Pudritz, 2008; Weber & Davis, 1967).

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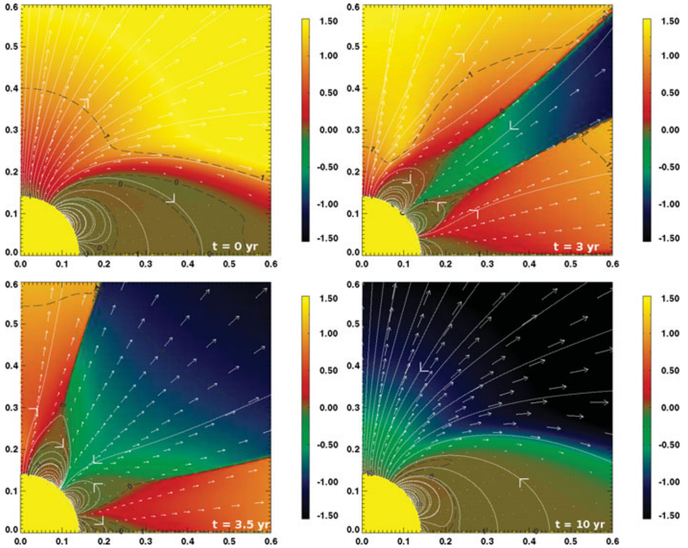

Figure 1. Snapshots of the evolution of the corona during the solar cycle (only the first $\sim 3\ R_\odot$ and northern hemisphere are shown). White lines are magnetic field lines. The colorscale represents the wind flow velocity (Mach number) projected onto the signed magnetic field. This quantity traces the B-field's polarity in the open field regions. Red/orange means positive polarity, while green/blue means negative polarity. The large arrowheads show the local **B**-field orientation. The black contours trace Mach numbers $0, 1$.

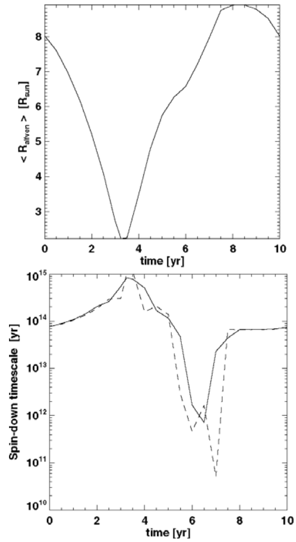

Figure 2. Mean Alfvén radius $\langle r_A \rangle$ (top) and magnetic breaking time-scale $\tau = J_\odot / \dot{J}$ (bottom) during the solar cycle. $J_\odot$ is the sun's angular momentum (Gilman, *et al.* 1989); $\dot{J}$ is the wind's angular momentum loss rate.

3. Conclusions

The surface magnetic field, coronal topology and assymptotic wind speed computed are all in good agreement with observations (*e.g* Wang & Sheeley, 2006). Overall sun's mass loss rate is dominated by outward flows originating at low latitudes. Their predominance depends on the time-varying magnetic field geometry and how it restrains the solar wind from "opening-up" outflow channels. The global angular momentum flux is maximum near the solar minimum, and so is the resulting magnetic breaking torque. Note that this is the moment when the total photospheric surface that is magnetically connected open flux regions (where the solar wind flows) is maximal. At the same time the coronal magnetic field is at it's *least multipolar* configuration, meaning that it decays the slowest with radial distance and the Alfvén radius (*lever arm* length) is naturally the highest. Variations in the radial and transverse large scale magnetic gradients may be pertinent to the study of the triggering of eruptive phenomena. Future work will include a more detailed treatment of the chromospheric dense layers.

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