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Realistic modelling of the termination shock position using Voyager 2 solar wind data

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Abstract: The termination shock position in time is calculated from Voyager 2 solar wind data, using a multi species hydrodynamic model, also including the latitudinal variations in the solar wind velocity and density due to the 11-year solar cycle. The results are compared to those obtained by Webber (2005) and the possibility of Voyager 2 crossing the termination shock in the near future is investigated.

Introduction

Although the Voyager 1 spacecraft crossed the solar wind (SW) termination shock (TS) in December 2004, its approach to the TS is still a topic of interest. Specifically, in [1] the > 0.5 MeV proton intensities measured by Voyager 1 from 2002.6 onward is explained as a result of Voyager 1 coming close to the TS in 2002. After 2002 the TS moved outward with a velocity comparable to that of Voyager 1, causing the spacecraft to have several close encounters with the shock before finally crossing it in December 2004.

The position of the TS with time is calculated in [1] using both long and short term SW pressure variations observed at Voyager 2. In [1] the Voyager 2 SW data is extrapolated back to 1 AU and used to calculate the subsequent TS response using results from a range of models, notably [2, 3, 4, 5, 6] and [7]. The approach followed by [1] is empirical, and 'response coefficients' are defined in correlation with results from the studies cited above.

In this paper, we would like to add to the result from [1] in the following ways: in extrapolating the Voyager 2 SW data back to 1 AU, [1] assumes a r^{-2} dependence for the SW density (where r denotes distance from the Sun) as well as a constant SW velocity. The former assumption is almost exact, even in a heliosphere where the multi-species interaction between the SW and the local interstellar medium (LISM) are considered. However, we extend the study by assuming that the SW velocity decreases with increasing radial distance due to the interaction between the SW and neutral hydrogen producing pick-up ions (PUI's). Furthermore we use the extrapolated values as SW boundary conditions in a hydrodynamic model of the heliosphere, which includes the mutual effects of protons, neutral hydrogen and PUI's self consistently together with the 11-year solar cycle. Results are calculated in a plane parallel to the solar rotation axis, which allows for a realistic inclusion of latitudinal effects, such as the appearance and disappearance of the fast SW.

Model and data

The hydrodynamical model used in this study is derived from [8], where the Euler equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla P = 0 \qquad (2)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left(\mathbf{u} \left(\frac{P}{\gamma - 1} + \frac{1}{2}\rho u^2 \right) \right) = 0 \qquad (3)$$

are solved for each different particle species, on a plane-polar grid, corresponding to a plane parallel to the solar axis of rotation. The model takes into account the mutual effect of protons, hydrogen and PUI's. The model was adapted to include the latitudinal variation of both the SW density and velocity (see [9] and [10]) over the 11-year solar cycle.

From the model results (see [8]) the SW density is almost exactly proportional to r^{-2}, while the SW velocity decreases almost linearly with increasing radial distance. Using

$$v_p = mr + c \qquad (4)$$

to approximate the decrease of the SW velocity v_p with r, and assuming that the SW decreases to 5% of its original value, the values of m and c are

$$m = -1.69 \times 10^{-9}\ \text{s}^{-1} \quad c = 401.26\ \text{km.s}^{-1} \qquad (5)$$

It should be noted that the choice of 5% depends on the assumed SW density at 1 AU as well as the assumed LISM hydrogen density outside the heliosphere. The choice of 5% is fairly accurate for SW densities between 5 cm^{-3} and 7 cm^{-3}, with a LISM hydrogen density assumed to be 0.1 cm^{-3}. The time Δt it took for a fluid particle to travel a distance r and reach a velocity v_p is calculated to be

$$\Delta t = \frac{1}{m} \ln \left| \frac{mr}{c} + 1 \right|. \qquad (6)$$

Using Eq.(4), the SW velocity observed at a certain radial position r and time t is extrapolated back to a velocity at 1 AU. From Eq.(6) the corresponding time value is calculated as $t - \Delta t$. In using this procedure, the daily averaged Voyager 2 SW data is extrapolated back to 1 AU and the corresponding 26-day average values are calculated and shown in Figure 1.

The 26-day averaged values from Figure 1 are used as an inner boundary condition to the hydrodynamic model. During solar maximum it is assumed that the Voyager 2 data extends over all latitudes. As the model progresses to solar minimum, the influence of the Voyager 2 data is gradually decreased at higher latitudes, so that during solar minimum the density and velocity over high latitudes are smooth. This corresponds to observations made by Ulysses, indicating less solar wind variability at high latitudes (see high latitude Ulysses data from http://cohoweb.gsfc.nasa.gov for example). The time dependent position of the TS that is subsequently calculated is normalised to coincide with Voyager 1 crossing the TS in 2004.9. Results are presented in the next section.

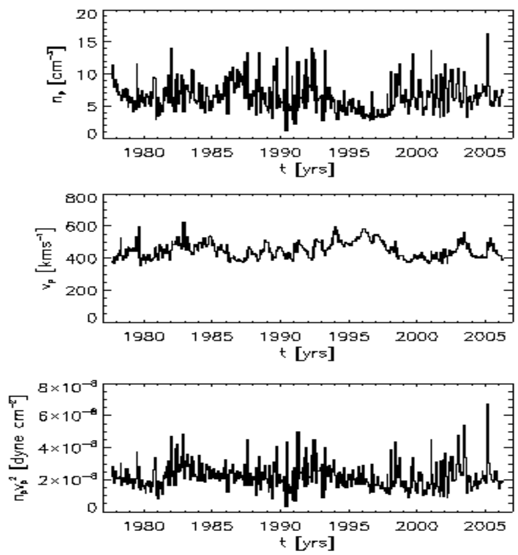

Figure 1: 26-day averages of Voyager 2 solar wind (SW) data, extrapolated back to 1 AU. Original data taken from http://cohoweb.gsfc.nasa.gov

Results

The position of the termination shock r_{TS} is calculated as it varies in time due to the SW fluctuations measured by Voyager 2 and normalised to be consistent with Voyager 1 crossing the TS in 2004.9. The results are shown in Figure 2. The results show that Voyager 1 and the TS had comparable outward velocities between 2002 and 2004 (which agrees with [1]), whereafter the TS moved inward, result-

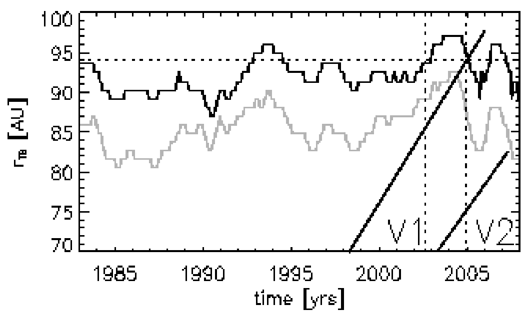

Figure 2: The termination shock (TS) position as it varies with time, where it is assumed that Voyager 1 crossed the TS in 2004.9. The solid black line shows the TS position along Voyager 1's trajectory, while the grey line shows the TS position along the trajectory of Voyager 2. The dotted vertical lines correspond to 2002.6 and 2004.9 respectively, while the horisontal dotted line corresponds to 94 AU.

ing in Voyager 1 crossing the TS in 2004.9. Furthermore, the projected motion of the TS implies that Voyager 2 will probably encounter the TS as early as 2007.5, with a first order estimate of the margin of error on this result being approximately a year.

Given the results noted above, the crossing of the TS by Voyager 2 offers an important control of our understanding of the heliosphere as a dynamic structure. Furthermore, should Voyager 2 cross the TS as predicted above, the > 0.5 MeV data shown in [1] together with the approach of the TS by Voyager 1 provides an interesting challenge regarding modulation close (~ 10 AU) to the TS.

Lastly is should be noted that neither the effects of the heliospheric magnetic field (HMF) nor that of the inter stellar magnetic field (IMF) are included in the model. The inclusion of the HMF and IMF can alter the geometry of the heliosphere, which in turn will have an effect on the predicted time at which Voyager 2 will cross the shock as well as charged particle intensities seen by both spacecraft close to the TS (see [11, 12] and [13]).

Summary and conclusion

Using Voyager 2 SW observations to calculate the time dependent position of the TS indicates that, as Voyager 1 approached the TS, the TS itself was moving outward with a velocity comparable to that of Voyager 1. This resulted in Voyager 1 moving close to the shock for a prolonged period of time (between 2002 and 2004) before finally crossing the shock. Exactly how close still needs to be constrained by investigating < 0.5 MeV proton intensities close to the shock. In assuming that Voyager 1 crossed the TS in 2004.9, it is found that Voyager 2 is likely to cross the TS as early as 2007.5, with an estimated error of 1 year.

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