A SURVEY OF FIELD-ALIGNED MACH NUMBER AND PLASMA BETA IN THE SOLAR WIND

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Abstract. We have surveyed solar wind plasma beta and field-aligned Alfvénic Mach number using Ulysses and Wind data. We show the characteristic timescale and occurrence frequency of 'magnetically dominated' solar wind, whose interaction with a planetary magnetosphere may produce a bow shock with multiple shock fronts. We discuss radial, latitudinal, and solar cycle effects.

1. Introduction

We survey *Wind* and *Ulysses* solar wind observations to obtain the distributions of the field-aligned Alfvénic Mach number and of plasma beta. Recent magneto-hydrodynamic simulations show that the interaction of 'magnetically dominated' solar wind with the Earth's magnetosphere does not lead to the well-known fast-type bow shock, but to a complex shock front with parts of different types and/or additional shocks (e.g., slow shocks) in the magnetosheath (De Sterck, 1999; De Sterck and Poedts, 1999, 2000). In this paper we (1) determine the typical duration of the 'magnetically dominated' regime, (2) establish its dependence on radial distance, heliographic latitude, and on the solar cycle, (3) identify it with solar wind structures, and (4) assess whether the theoretical complex bow shock topology actually occurs.

2. Observations

We use January–March 1995 Wind observations of 1 AU low-latitude solar wind (mix of slow and fast wind, typical sector structure). The 46/92 s averaged magnetometer and 90 s plasma data (R. Lepping and K. Ogilvie, NASA GSFC, USA) were interpolated to a common time resolution of 112.5 s ($\frac{1}{32}$ hour). The *Ulysses* data (October 1990 to present) range from 1 to 5.4 AU and from $-80°$ to $+80°$ in latitude. Intent on covering large timescales, we interpolated the 256 s averaged magnetic field (A. Balogh, Imperial College, London, U.K.) and 1792 s ion data (D. McComas, Los Alamos National Laboratory, U.S.A.) to $\frac{1}{2}$ hour resolution.
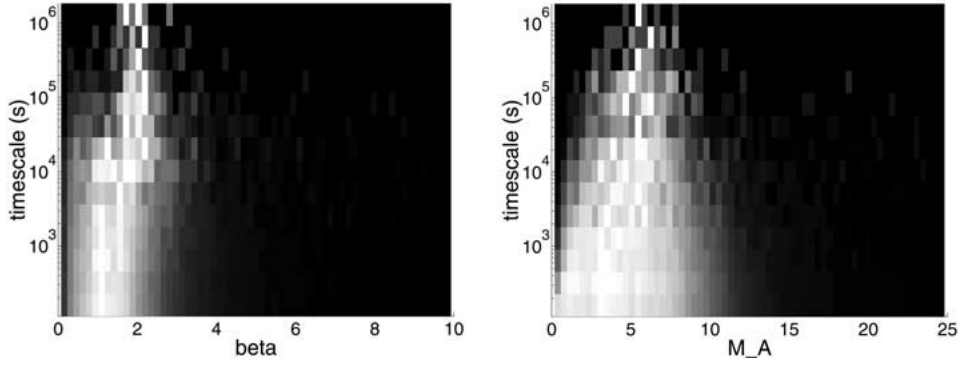
Figure 1. Multi-timescale distribution of solar wind plasma beta β and Alfvénic Mach number M_A observed by Wind at 1 AU in January–March 1995.

Solar wind plasma beta is $\beta = P_{th}/P_{mag}$, with a magnetic pressure $P_{mag} = B^2/2\mu_0$. The thermal pressure $P_{th} = \sum_i k_B n_i T_i$ includes contributions from all plasma populations (k_B is Boltzmann's constant). Because electron data were not available (data gaps, non-Maxwellian distributions, . . .), we take the electron and ion pressures equal. We ignore temperature anisotropy and heavy ions. The uncertainty on β is ~30%. The field-aligned Alfvénic Mach number is $M_A = v \cos \theta_{vB}/v_A$, where v is the solar wind speed, v_A the Alfvén speed, and θ_{vB} the angle between the flow and the magnetic field. While solar wind usually is super-fast ($v/v_A \gg 1$), for slow wind speed, strong field, low density, and/or $\boldsymbol{B}$ nearly perpendicular to $\boldsymbol{v}$, M_A is small. As planetary bow shocks are curved, nature and strength of the shock change from point to point, whatever the field orientation. Where the field is perpendicular to the shock, the switch-on shock regime occurs if

$$1 < M_A < \sqrt{\frac{\gamma(1 - \beta) + 1}{\gamma - 1}}, \tag{1}$$

where $\gamma = \frac{5}{3}$; complex bow shocks can form in this regime (De Sterck and Poedts, 1999).

Figure 1 shows the distributions of β and M_A at 1 AU obtained by averaging the *Wind* data over increasingly longer time periods. Low β and M_A conditions typically last up to ~10^4 s, that is, a few hours at most. The switch-on regime is found about 5% of the time. Most low M_A situations occur when $\theta_{vB} \approx 90°$, but then there exists no point on the Earth's dayside bow shock (where the shock is strongest and its structure most pronounced) where the field is perpendicular to it. Assuming the bow shock flaring angle to be about 45° on the magnetospheric flanks ($|\theta_{vB}| < 45°$), conditions for a 'magnetically dominated' dayside bow shock occur ~2% of the time.

Figure 2 displays the monthly β and M_A distributions throughout the *Ulysses* mission: first during the in-ecliptic trajectory (0–5.4 AU, month 0–20), then at increasingly southern latitude (above the south pole at ~2 AU, month 45), across
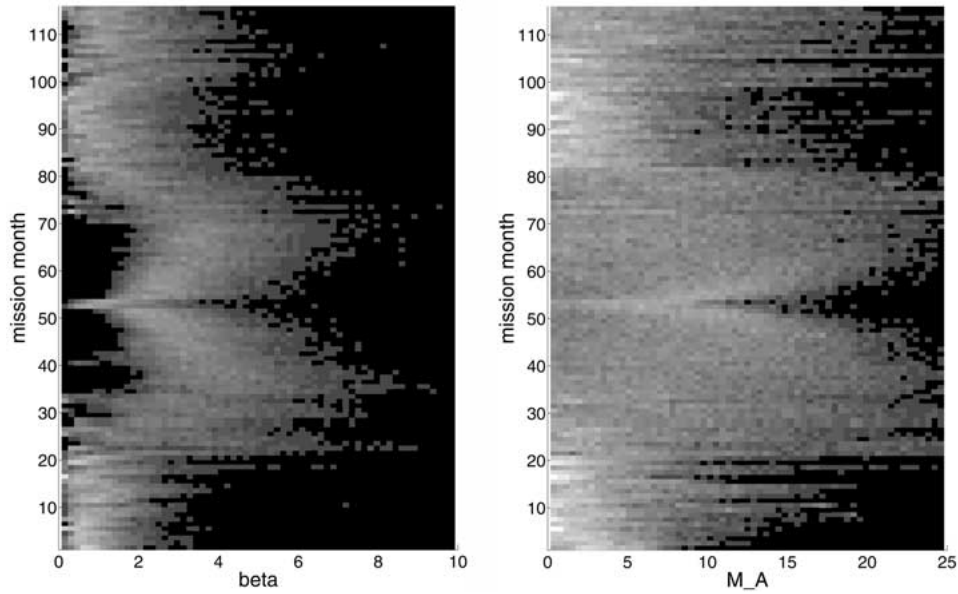
Figure 2. Distribution of plasma beta β and Alfvénic Mach number M_A during the *Ulysses* mission, based on $\frac{1}{2}$ hour averaged data.
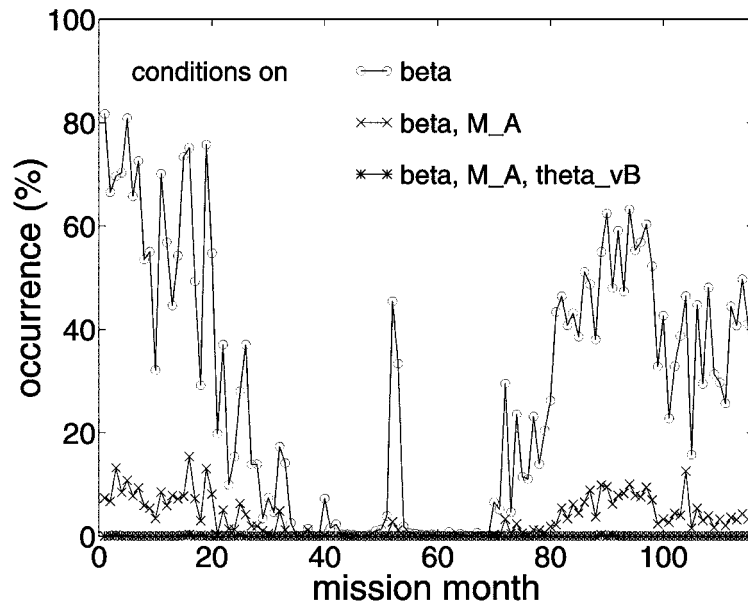

Figure 3. The fraction of time that $\beta < \sqrt{2/\gamma}$, that M_A satisfies condition (1), and that in addition $|\theta_{vB}| < 45°$, throughout the *Ulysses* mission.

the equator (∼1 AU, month 53), to the north pole, and back to aphelion (5.4 AU, around month 90). The stronger magnetic field at low latitudes leads to lower β; slow wind speed and higher v_A result in lower M_A. At large distances M_A decreases as v_A increases (mainly due to lower density); the trend in β is less clear. After month 100, solar activity becomes important: β and M_A retain distributions similar to the quiet Sun, low-latitude ones, though somewhat broader, in spite of the increasing latitude. Figure 3 shows the occurrence of 'magnetically dominated' flow along the trajectory. As the Parker angle (typical θ_{vB}) increases farther away from the Sun (about 80° at 5 AU), dayside 'magnetically dominated' bow shocks become even less probable.

3. Conclusions

We found that near solar minimum, at 1 AU, and at low latitude, 'magnetically dominated' solar wind conditions occur up to 5% of the time, and can last a few hours. About 2% of the time the field orientation allows a complex dayside bow shock to develop (De Sterck and Poedts, 1999, 2000). If this regime does not last long enough or if it is too variable, transient slow shocks might form in the magnetosheath; evidence for these exists (Song *et al.*, 1992). We tentatively associate 'magnetically dominated' conditions with corotating interaction regions and magnetic clouds, with their high magnetic pressure and low beta. They also have the same characteristic duration. This explains why *Ulysses* finds low β and M_A only at low latitude during solar minimum but everywhere at solar maximum, when CMEs are abundant and slow/fast stream interactions exist at all latitudes.

Acknowledgements

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