Mem. S.A.It. Vol. 80, 259

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High kinetic energy density jets in the Earth's magnetosheath: preliminary results

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Abstract. Plasma jets in the magnetosheath near the Earth magnetopause are commonly observed and are usually related to magnetic reconnection between the geomagnetic field and the magnetic field carried by the solar wind. However, evidence has been shown in the last years of jets which cannot be explained through reconnection. In this paper we review past observations of high kinetic energy density jets in the magnetosheath and present preliminary evidence of additional similar observations. Finally, we argue that further work has to be done on this matter, as such jets could represent a phenomenon of general occurrence which still needs to be explained.

Key words. magnetosheath – solar wind – plasma jets

1. Introduction

The undisturbed solar wind streams at the Earth's orbit with magnetosonic Mach number, M_{ms}, ranging from 5 to 12. Because M_{ms} is larger than the critical Mach number $M_{cr} \simeq 2.6$, the solar wind flow is supercritical. At the Earth's bow shock the solar wind is slowed down so that $M_{ms} < 1$, is thermalized and is compressed by roughly a factor of 4. The flow downstream of the bow shock is highly disturbed and gradually becomes turbulent. However, as the magnetosheath is not spacious enough, the turbulence does not reach quasi-stationarity, but remains not fully developed, intermittent and structured in time and space. In this framework, the passage of solar wind features such as shocks and tangential discontinuities has been invoked to account for the observation of magnetosheath fluctuations and transient events (e.g. Sibeck & Croley 1991). Lin et al. (1996a) used MHD simulations to argue that rotational discontinuities interact with the bow shock so as to form transient pressure pulses in the magnetosheath. Moreover, Lin et al. (1996b) suggested that packets of upstream Alfven waves, generated by ions reflected at the bow shock, can propagate through the bow shock and cause trains of pressure pulses in the magnetosheath. Nemecek et al. (1998) presented evidence, based on Interball-1 and Magion-4 data, for abrupt strong ion flux increases or decreases in the flank magnetosheath, which they called Transient Flux

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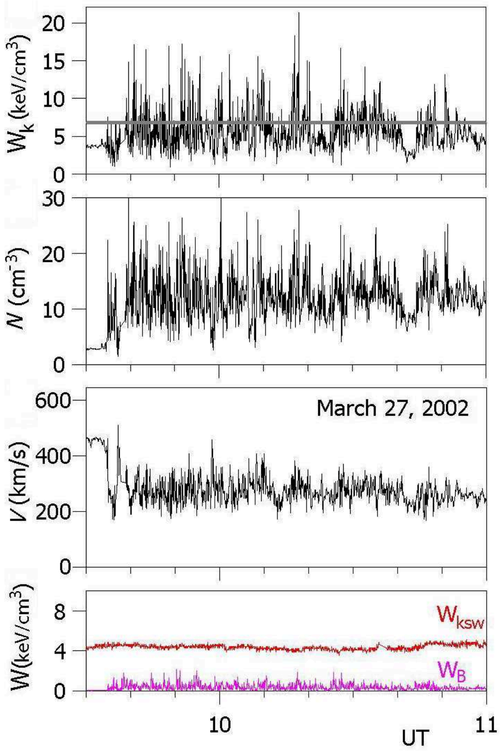

Fig. 1. The Cluster 1 magnetosheath inbound crossing of 27 March 2002 (see details in text).

Events (TFE). To this regard, they argued that TFEs could not be interpreted as slow mode transitions such as those reported by Song et al. (1992), as they did not show any anticorrelation of the density and magnetic field strength. Instead, Nemecek et al. (1998) suggested that mechanisms like those proposed by Lin et al. (1996a,b) could be at play, although they did not observe any clear correlation between the IMF orientation in the foreshock and the occurrence of TFEs. In the next two sections of this paper we review and discuss some recent results of Savin et al. (2008), which resemble the Nemecek et al. (1998) TFEs but are based on more recent Cluster data, and briefly present an event based on Double Star data, which is part of a large collection of events which will be further studied in the near future. The last section contains a brief summary.

2. The March 27, 2002, jets

Figure 1 (adapted from Savin et al. 2008) shows data from 09:00 to 11:00 UT on March 27, 2002. From top to bottom: Cluster 1 kinetic energy density W_k , plasma density N, speed V and magnetic pressure W_b. The bottom panel also displays solar wind kinetic energy density W_{kSW} from the WIND spacecraft. The horizontal threshold line drawn in the top panel is defined in the description of Fig.2. This same period of Cluster data has been the object of yet another paper, by Retino et al. (2007), who studied magnetic reconnection in the magnetosheath at scales of 100 km corresponding to thin current sheets. On the contrary, following Savin et al. (2008), we will concentrate here on scales larger by at least one order of magnitude. During the whole period shown in Fig.1 WIND was outside the foreshock and observed a quiet and steady solar wind, whose average speed, particle density and kinetic energy density were $V_{SW} \simeq 470km/s$, $N_{SW} \simeq 4cm^{-3}$ and $W_{kSW} \simeq 4.5keV/cm^3$. Cluster entered the magnetosheath inbound from the solar wind in front of the southern magnetospheric cusp region at about 09:35 UT and observed an extremely high level of fluctuations until 11:00 UT. As shown in the central panels of Fig.1, the W_k peaks result from a combination of peaks in N and in V^2 and are usually dominated by those in N, corresponding to plasma compressions moving at enhanced magnetosheath speeds. After 11:00 UT the level of fluctuations reduced greatly, while the upstream solar wind plasma parameters did not change significantly (not shown in the figure).

Figure 2 shows the Probability Density Functions (PDFs) of the magnetosheath kinetic energy density for the 10:00-11:00 UT period (black dots on dashed black line) and for 11:00-11:30 UT (red dots on solid red line), which we use as a reference period for a quieter magnetosheath, and the PDFs of the solar wind kinetic energy density for the same periods (black crosses for 10:00-11:00 UT and red crosses for 11:00-11:30 UT). It is clear that the two magnetosheath regimes are very different, while the solar wind PDFs are very similar. A Gaussian equilibrium distribution is

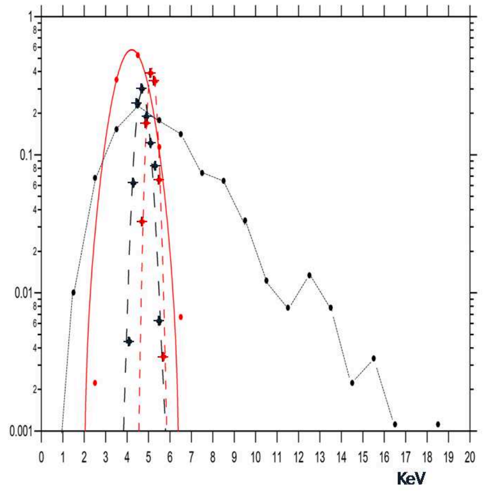

Fig. 2. Probability Density Functions (PDFs) of the magnetosheath (dots) and solar wind (crosses) kinetic energy density for a quiet (red lines) and for a jet dominated (black lines) magnetosheath (see text for details).

found to fit the quiet 11:00-11:30 UT magnetosheath PDF with a peak at $4.1 keV/cm^3$, which is consistent with the corresponding solar wind Gaussian distribution peaking at $5.1 keV/cm^3$. The fact that a small fraction of magnetosheath energy density values exceeds the maximum solar wind energy density can be reasonably attributed to short time scale inhomogeneities due to the magnetosheath turbulence. Apart from that, the decrease of the most probable energy density is clearly due to the solar wind deceleration and thermalization through the bow shock. On the opposite, for the 10:00-11:00 UT period the magnetosheath PDF has a most probable energy density lower than the corresponding solar wind value (4.3 compared to $4.7 keV/cm^3$), but it also exhibits a clear non-Gaussian shape with a tail extending to very large values above $15 keV/cm^3$, by a factor of 3 larger than the solar wind energy density. The strong asymmetry of the 10:00-11:00 UT PDF points towards the presence of an extra non-equilibrium contribution arising from the plasma jets. We notice that all the 11:00-11:30 UT magnetosheath points fall below $W_k = 6.7 keV/cm^3$. This value of the energy density, which happens to be $1.5\ W_{kSW}$, can be reasonably taken as the maximum kinetic energy density which should be expected for the equilibrium magnetosheath plasma between 09:40 and 11:00 UT. and, as such, is drawn as a horizontal line in the top panel of Fig.1.

Turning back again to Fig.1, we notice that the W_k threshold line in the top panel is exceeded by quite a number of peaks in W_k by up to a factor of 3. In the following we call such peaks High Kinetic energy density Plasma Jets (HKPJ). The fact that HKPJs by far exceed the solar wind kinetic energy density implies that they are of magnetosheath or bow shock origin. Close inspection of the peaks has led to count 83 HPKJs during the period under study, having an average duration of 28 s (i.e. $\simeq 6000 km$). In 77 cases a velocity increase relative to the ambient magnetosheath is also seen. In 26 cases density enhancements are seen close to the HKPJ edges suggesting piling up of the ambient plasma. In 57 cases the N and V peaks do not coincide. The W_k peak corresponds in time to the N peak in 29 and to the V peak in 10 cases.

It is most interesting to notice that the magnetic pressure W_b is very low throughout this magnetosheath crossing and is negligible compared with the kinetic energy density. Moreover, in most of the observed jets the magnetic field increases do not coincide with the jet maxima, nor does the magnetic pressure exhibit a minimum at the jet center (which would be required for a plane current layer). The important conclusion from this comparison is that local reconnection in the magnetosheath cannot be the cause of HKPJs simply because there is not sufficient energy stored in the magnetic field. On the other side, during the whole period considered in Fig.1 Cluster 1 was very far from the magnetopause, so that the observed jets can in no way be attributed to magnetic reconnection near the magnetopause subsolar point.

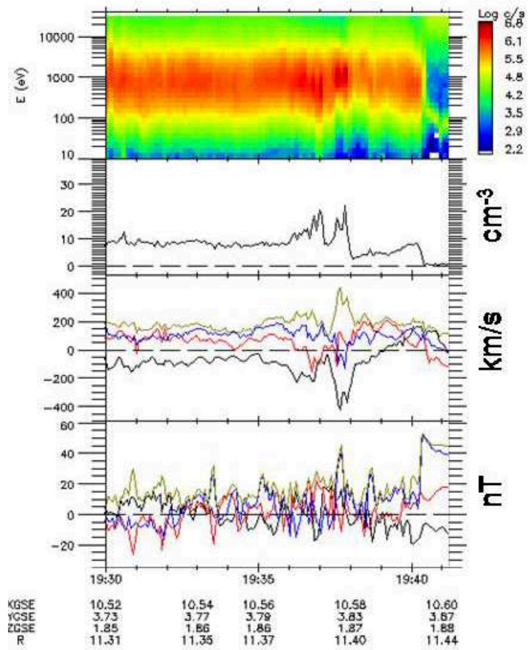

Fig. 3. From top to bottom: proton energy spectra, density, velocity and magnetic field observations made on February 11, 2005, by the HIA and FGM instruments on board the Double Star equatorial spacecraft (GSE position is given below the UT time axis).

3. The February 11, 2005, jets

In this section we present an event during which two anomalous plasma jest were observed in the magnetosheath by the Double Star spacecraft on February 11, 2005, in proximity of the magnetopause subsolar point, when the spacecraft was moving slightly outbound close to the orbit apogee and its average position was $X_{gse} = 10.55R_E$, $Y_{gse} = 3.8R_E$, $Z_{gse} = 1.86R_E$. At that time the conditions of the solar wind were quiet and steady. Fig. 3 shows colour coded omnidirectional proton energy spectra (top panel), proton density (second panel from top), proton velocity components and intensity (third panel) and magnetic field components and intensity (bottom panel). The vector components are in GSE (x in black, y in red, z in blue, while intensities are in green). It is evident that at the beginning of the displayed time period the spacecraft was in the magnetosheath, as shown by the large spread of the energy spectra in the top panel, by the density values close to $10cm^{-3}$ and by the velocity close or slightly smaller than 200 km/s and directed at an angle of 30 – 40° relative to the GSE x axis. On the other side, towards the end of the considered time interval, the spacecraft clearly crossed the magnetopause, as shown by the rotation and large increase of the magnetic field and by the dramatic decrease of the proton number density. Moreover, the very large positive value of B_z just inside the magnetopause suggests that indeed the boundary has been crossed close to the subsolar point. What is unusual and difficult to explain in these observations are the two large density peaks, of the order of $20cm^{-3}$, observed between 19:36 and 19:58 UT, very close to the magnetopause crossing. Such peaks are accompanied by noticeable increases of the proton velocity and, in particular, by very large negative, i.e. anti-solar, values of its x component. As a result, with respect to the ambient magnetosheath, the kinetic energy density increases by a factor of 4.5 at the first jet and by a factor of 8 at the second one. The most striking property of the two jets is that the flow is mostly aligned to the GSE x axis, which, from a gas dynamic point of view, is totally unexpected close to the magnetopause subsolar point. In particular, the second jet forms with the GSE x axis an angle less than 10°. Such orientation is completely incompatible with the one that should be expected for any jet due to reconnection at the magnetopause. Moreover, the magnetic field before and after the two jets displays a positive B_z component.

4. Summary and conclusions

We have shown evidence, based on Cluster and Double Star data, of plasma jets in the magnetosheath, both far and close to the magnetopause, which cannot be explained through reconnection at the magnetopause between the geomagnetic field and the magnetic field carried by the solar wind. These observations suggest that high energy density plasma jets in the magnetosheath may represent a phenomenon of general occurrence which still needs to be explained and which could be relevant to astrophysical plasma in general. It is desirable that work be continued on this topic in the near future, first of all by increasing the statistics of similar observations by the Cluster and Double Star spacecraft, and, in the second place, by developing theoretical models to explain such novel observations.

Acknowledgements. This work was supported by ASI (the Italian Space Agency). We thank the WIND plasma team for the use of WIND plasma data obtained from CDAWeb.

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