



# The occurrence of upstream waves in relation with the solar wind parameters: A statistical approach to estimate the size of the foreshock region

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## ABSTRACT

We studied the occurrence of upstream waves in the foreshock region and their relationship with the solar wind and interplanetary magnetic field parameters. To this purpose, we developed a method for a careful identification of the upstream wave events. The results of the statistical analyses based on Cluster data (2003–2010 years) confirm that the angle between the bow shock normal direction and the interplanetary magnetic field is the key element for the wave generation; they also show the relationship between the wave occurrence and the solar wind speed and density. We focused our attention on the occurrence of wave events as a function of the distance from the bow shock. The results show that the foreshock region, where we can observe upstream waves, is characterized by an effective size that decreases with the increase of both the solar wind speed and the wave frequency. Due to the relationship between the solar wind speed and the wave frequency, we suggest that such distance is simply a function of the solar wind speed, becoming smaller when the solar wind speed increases, and then the occurring higher frequency upstream waves are confined in a more restricted region.

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## 1. Introduction

The main source for Ultra-Low-Frequency (ULF) magnetospheric waves in the mid-frequency range (10–100 mHz) is supposed to be the solar wind (SW), in particular upstream waves driven in the Earth's foreshock region by a wave-particle interaction between already existing waves and SW protons reflected off the bow shock along the interplanetary magnetic field (IMF) lines (see the review by Menk (2011)). The wave generation mostly occurs in the region of quasi-parallel bow shock, i.e. where the IMF makes a small angle  $\theta_{n,B}$  ( $< 45^\circ$ ) with the shock normal (Greenstadt et al., 1980; Russell et al., 1983), and thus, given the average spiral IMF orientation, mostly in the morning side. The wave frequency is expected to be linearly dependent on the IMF strength and, effectively, the relationship  $f$  (mHz)  $\sim 6B$  (nT) is found in several investigations (Troitskaia and Bol'Shakova, 1988). Many properties of waves in the foreshock are known, mostly through case studies (Burgess, 1997; Mazelle et al., 2003; Archer et al., 2005). They are typically a few Earth's radii ( $R_E$ ) in size along their wave vector and propagate  $\sim 20$ – $40^\circ$  from the local magnetic field. They propagate sunwards at speeds close to the local Alfvén speed in the plasma frame but are convected by

the faster SW flow through the bow shock and the magnetosheath towards the magnetopause; then, they can be transmitted into the magnetosphere without significant changes to their spectrum (Krauss-Varban and Omid, 1991).

In this work we statistically investigated the occurrence of the upstream waves in the foreshock region in dependence on the SW parameters during the years 2003–2010. The results lead us to suggest a possible estimate of the size of the region across which upstream waves can be observed on the basis of the wave frequency.

## 2. Data analysis and experimental results

We used magnetic field data from the triaxial fluxgate magnetometer (FGM; Balogh et al., 2001) and plasma data from Cluster Ion Spectrometer experiment (CIS; Rème et al., 2001) on Cluster 1 satellite; the instruments provide measurements in the GSE coordinate system with a time resolution of 4 s. For the study of upstream wave dependence on the interplanetary conditions, we estimated the 20-min averages of the following parameters: the angle  $\theta_{n,B}$  between the IMF and the bow shock normal where the IMF line at the satellite position encounters the bow shock, estimated through the dynamic model by Peredo et al. (1995), the SW speed  $V_{SW}$ , the plasma density  $n$  and the Alfvénic Mach Number  $M_A$ . The 20-min representative time interval has been

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selected on the basis of an autocorrelation analysis: using the 3-s magnetic data from the WIND spacecraft at the L1 and 1-min plasma data from OMNIweb, we computed the autocorrelation coefficient  $r$  of 3-h data series for different time lags, and we considered significant only  $r$  values higher than the threshold corresponding to the 95% confidence level. Fig. 1 shows the occurrence of significant autocorrelation at the different time lags  $T_{ac}$  for a sufficiently high number (1000) of 3-h intervals. The results show a maximum at  $\sim 20$ – $25$  min for the IMF and at  $\sim 0.5$ – $1.5$  h for  $V_{SW}$ ,  $n$ , and temperature  $T$ , suggesting that at least over a 20-min interval the interplanetary conditions can be considered stable.

We identified the 20-min intervals during which the Cluster satellite was in the upstream region on the basis of the anisotropy temperature ratio ( $T_{\parallel}/T_{\perp} \geq 2$ ; Fig. 2(a); further, we selected only the intervals when the satellite was magnetically connected with the bow shock. Fig. 2b shows the Cluster satellite average position in correspondence to the 17,125 selected 20-min intervals during the years 2003–2010 (black points), together with the bow shock and magnetopause projected in the GSE X–Y and X–Z plane, for usual interplanetary conditions (Kobel and Flückiger, 1994).

### 2.1. Upstream wave occurrence

For each 20-min interval we performed the spectral analysis by computing the Power Spectral Density (PSD, 100% Tukey window). The resulting spectra were smoothed over 9 adjacent frequency bands using a triangular moving average filter (final frequency resolution of  $\sim 4$  mHz). The described spectral procedure has been applied to the three IMF components  $B_x$ ,  $B_y$ , and  $B_z$ .

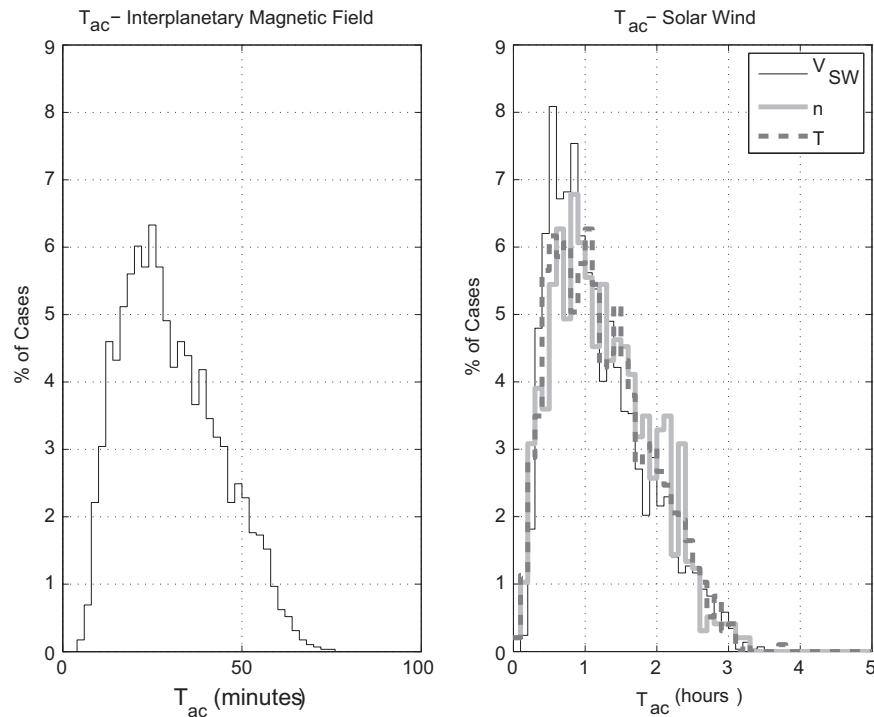
To identify upstream wave events, we computed the signal-to-noise ratio  $R$  (De Lauretis et al., 2010), defining a signal event when  $R$  reaches a given threshold in the 10–100 mHz frequency range. The adopted threshold is  $R_{th}=9$ , which corresponds to a signal power equal to 90% of the total power. The selected events were 7201,  $\sim 42\%$  of the 17,125 intervals of interest.

In Fig. 3 we show the percentage of occurrence of the upstream events with respect to the angle  $\theta_{n,B}$ . The black circles indicate the occurrences  $\nu=k/n$  where  $k$  and  $n$  are respectively the number of selected events and the number of intervals, and the vertical bars represent the uncertainties at the 99% confidence level, estimated through Clopper–Pearson method basing on the binomial distribution (Clopper and Pearson, 1934; Johnson et al., 1993).

The event occurrence depends essentially on  $\theta_{n,B}$ , with maximum values of  $\sim 80$ – $90\%$  for  $\theta_{n,B} < 30^\circ$ . As  $\theta_{n,B}$  increases,  $\nu$  decreases rapidly and attains values  $< 20\%$  for  $\theta_{n,B} > 60^\circ$ . This result is well consistent with Greenstadt et al. (1980) and Russell et al. (1983) findings.

For the events occurring at quasi-parallel shocks ( $\theta_{n,B} < 45^\circ$ ), clearly related to upstream waves, we show in Fig. 4 the occurrence in dependence on the SW density  $n$ , speed  $V_{SW}$  and Mach number  $M_A$ . The events are almost uniformly distributed for  $n$  in the range  $3$ – $8 \text{ cm}^{-3}$  (panel a). On the other hand, for  $n < 3 \text{ cm}^{-3}$  there is a tendency to decrease, but the uncertainty becomes greater than 30%, making this result less reliable. However, Heilig et al. (2010) and Francia et al. (2013) also observed that ULF activity strongly decreased for SW density lower than  $\sim 2 \text{ cm}^{-3}$ .

In the (b) and (c) panels the event occurrence is shown in dependence on the SW speed  $V_{SW}$  and Alfvénic Mach Number  $M_A$ , respectively. In both cases the occurrence attains a clear maximum, respectively at  $\sim 400$ – $450 \text{ km/s}$  and  $\sim 5$ – $7$ . The number of events decreases when both  $V_{SW}$  and  $M_A$  decrease, and becomes unreliable at  $V_{SW} < 300 \text{ km/s}$  and  $M_A < 4$ , for which the number of available intervals is low. In addition, it shows a clear decrease also for  $V_{SW}$  increasing above  $500 \text{ km/s}$  and for  $M_A > 9$ , becoming unreliable for  $V_{SW} > 650 \text{ km/s}$  and  $M_A > 12$ . De Lauretis et al. (2010) showed that, on the ground, the occurrence of upstream wave related pulsations increases both at high and low latitude as  $V_{SW}$  increases, at least up to  $700 \text{ km/s}$ ; they invoked different mechanisms to explain such dependence, such as an enhanced transmission or amplification of upstream waves by the Kelvin–Helmholtz instability (Engebretson et al., 1986) or an increasing efficiency of the ion cyclotron instability for producing upstream



**Fig. 1.** The distribution of the auto-correlation time lags for the IMF (left panel) and SW (right panel) speed  $V_{SW}$  (black), plasma density  $n$  (light gray) and plasma temperature  $T$  (dashed gray).

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