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A comparative study of solar wind and foreshock turbulence near Uranus orbit

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ABSTRACT

In this work we have used statistical and wavelet techniques to characterize some properties from the Uranus foreshock and the nearby background solar wind. Results of the wavelet spectra showed that the dominant waves have common periodicities at ~12 min, ~31 min and ~65 min for both the background and foreshock regions. However, the average wave power for the foreshock interval was about 10 times higher than for the background solar wind. These common periods found both in the foreshock and solar wind may be an indicative of the nature of the turbulent flow at this distance from the Sun. The foreshock to background magnetic field variance ratio is about 3.0. Minimum variance results show that most of waves have a compression factor of 0.65 and propagate obliquely to the magnetic field direction. The main period found at ~10–15 min is close to the frequency observed for upstream waves based on observations of other planets and that are interpreted in terms of ion cyclotron resonance. Results from kurtosis parameter showed a Gaussian behavior indicating there is no significant intermittent physical processes acting over these components in the background solar wind. Further, over larger scales, some components presented a sub-Gaussian behavior, possibly associated to quasi-periodic waves with finite amplitudes.

1. Introduction

Uranus was discovered in 1781 from ground based observations, although it has been observed earlier but not identified as a planet (Bergstralh and Miner, 1991). It has been visited so far only by the Voyager-2 spacecraft in 1986 (Stone, 1987).

Uranus has an equatorial radius of 25,600 km, less than half that of Saturn. It has a mean density of 1.25 g cm^{-3} and rotates with a period of 17.2 h (Bergstralh and Miner, 1991). The unique fact about Uranus is that it rotates with a large angle, with its rotation axis inclined by ~98°, to the pole of the orbital plane (Bergstralh and Miner, 1991; Russell and Luhmann, 1997). Further, Voyager-2 measurements showed surprisingly that the magnetic field dipole axis is inclined at a large angle, 59°, in relation to the rotation axis (Ness et al., 1986; Stone, 1987; Russell and Walker, 1995; Russell and Luhmann, 1997; Kivelson and Bagenal, 1999; Russell, 2001, 2004).

Overall, the Uranus magnetosphere is very similar to the terrestrial magnetosphere. There is a bow shock that deflects the supersonic flow of the solar wind in front of the magnetospheric cavity and a magnetic tail extending far downstream. The forward part of the magnetosphere extends to approximately 25 planetary radii and the bow shock (BS) to about 33 planetary radii (Ness et al., 1986).

Voyager-2 flyby by the Uranus planetary system occurred between days 24 and 30 January 1986 (Stone, 1987). Upstream waves in the inbound, diurnal magnetosphere have not been found. The flank outbound trajectory occurred in the dawn sector, during a highly disturbed magnetospheric condition, with several BS crossings observed (Bridge et al., 1986; Ness et al., 1986). Downstream of the planet, Russell et al. (1990) reported waves immediately after the last BS crossing, which occurred around 04:48–17:45 UT on 30 January 1996 (Zhang et al., 1991).

Russell et al. (1990) have studied the Uranus magnetosheath and foreshock waves, adjacent to the last BS crossings. They have used Fourier and minimum variance analyses (MVA) and have found a spectral peak near 0.001 Hz for upstream waves. They have also found that those waves were propagating obliquely to the magnetic field.

Zhang et al. (1991) have studied Uranus upstream waves, but for a much longer interval, over 2 weeks. They have identified these waves as having quasi-parallel propagation to the magnetic

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field, with a spectral peak near 0.001 Hz, and concluded they were Alfvén waves generated in the upstream region by a proton beam resonant instability.

Echer (2009) have applied wavelet analysis to Voyager-2 magnetic field data at Uranus and Neptune magnetosheaths and foreshocks. For Uranus foreshock, it has been found that major periodicities occurred for quasi-continuous waves with periods around 5–15 min.

The foreshock region is characterized by the portion of space upstream of planetary bow shocks where charged particles with speeds higher than the solar wind velocity magnitude (Vsw from ~400 to 700 km/s) can flow (Tsurutani and Rodriguez, 1981). The sources of the particles are those that have been reflected/accelerated at the bow shock or those that have leaked from the magnetosheath (magnetospheric particles). The beamed energetic electrons and ions are subjected to plasma instabilities, thus the foreshock region is filled with nonlinear plasma waves and particles. The low-frequency (LF) electromagnetic waves generated by proton/ion instabilities have phase velocities that are much less than the solar wind speed, so after their generation in the foreshock region, they are convected back to the bow shock by the solar wind (Tsurutani and Rodriguez, 1981; Burgess, 1997). Waves have been detected upstream of all planetary shocks (e.g, at Jupiter, Tsurutani et al., 1993), and interplanetary shocks (Kennel et al., 1984a, b; Zank et al., 1993).

It is the aim of this paper to use statistical and wavelet techniques to characterize some properties from the Uranus foreshock and background solar wind. This is important for space plasma physics and turbulence since the Voyager-2 data are the only in-situ observation we will have for the foreseen future of the Uranus plasma environment.

2. Data and methodology analysis

2.1. Voyager-2 magnetometer data and intervals of analysis

Magnetic field vector data from the magnetometer instrument onboard Voyager-2 spacecraft during its flyby by Uranus system are used. These data were obtained from the Planetary Data System-PDS (http://pds.jpl.nasa.gov) (McMahon, 1996). The resolution available for the magnetic field data is 1.92 s. In order to have a more homogeneous dataset and to remove a few data gaps, all data were 3-s averaged. The magnetometer experiment is a triaxial fluxgate magnetometer and it is described in detail by Behannon et al. (1977). Magnetometer data are used in the RTN coordinate system. In this system, **R** points radially outward from the Sun toward the spacecraft, **T** is defined as $\mathbf{\Omega}\times\mathbf{R}/(|\mathbf{\Omega}\times\mathbf{R}|)$, where $\mathbf{\Omega}$ is along the north solar rotation pole direction, and **N** completes the right-hand system.

The foreshock interval chosen is the same used in Echer (2009), and it is shown in Table 1. An interval of background solar wind, upstream of Uranus magnetosphere, on 21 January 1986 has been selected and is also shown in Table 1.

Table 1
Selected intervals of background solar wind and foreshock waves during Voyager-2 flyby of Uranus.

Background solar wind	Foreshock
10:00–16:00 UT 21 January 1986	18:00–24:00 UT 30 January 1986

2.2. Data analysis techniques

The main purpose of this work is to use the statistical tools to quantify the occurrence of the intermittent phenomena in the magnetic field vector components in the foreshock and background solar wind near Uranus. In order to perform this study, we use a test to search for the deviations from Gaussianity of the PDFs of fluctuations through of the differences in magnetic fields, $\delta B_r = B(t) - B(t+r)$, where r is the increment scale chosen. If the PDF presents a shape far from Gaussianity, is the striking of the intermittency phenomenon presence. Also, a way to quantify this Gaussianity deviation is given by the statistical parameter called kurtosis, which is defined by:

$$K_r = \frac{\left\langle \delta B^4 \right\rangle}{\left\langle \delta B^2 \right\rangle^2} \tag{1}$$

The kurtosis of a normally distributed process is equal to 3 (Frisch, 1995). A way to study the time variability of the energy from these intermittent phenomena is to employ the wavelet analysis. The Wavelet Transform (WT), is able to show how the energy is distributed in the time and frequencies, given by Torrence and Compo (1998):

$$Wf(s,b) = \frac{1}{s}\int f(x).\psi^*\left[\frac{x-b}{s}\right]dx \tag{2}$$

where s is the scaling factor, b is the location parameter, ψ^* is the complex conjugate of continuous wavelet function and $f(x)$ is the time series under analysis (Kumar and Foufoula-Georgiou, 1997).

Bolzan (2005) and Bolzan and Echer (2014) applied the WT on the solar wind and Jupiter magnetosheath time series, respectively, to analyze the variability degree of the energy into time and frequency domains. The results show that the energy variability is given by intermittency and Coherent Structures (CS) present on the time series. This is the main objective of the wavelet analyzes applied in present data sets.

In order to study the wave properties, the minimum variance analysis (MVA) is used. This analysis is applied to many space plasma physics problems such as magnetopause orientation (Sonnerup and Cahill, 1967), magnetic cloud axis orientation (Echer et al., 2006), and plasma wave parameter determination (Tsurutani et al., 2013). The MVA, also known as the principal component, principal axis or empirical orthogonal function method, has the aim to reduce a dataset containing a large number of variables to a data set with a lower number of variables that represents a large fraction of the variability contained in the original data. Basically, one does a coordinate system transformation. As a result, one of the new system axis points in the direction of the maximum joint variability of data (Wilks, 2011).

The MVA enables one to obtain several informations about the wave properties, as: polarization in the s/c frame; wave propagation angle in relation to the ambient magnetic field (this is determined from the angle between the minimum variance eigenvector and the ambient magnetic field vector); wave propagation angle in relation to solar wind speed, wave amplitude and compressibility. Wave compressibility is defined as:

$$Compr = \frac{(B_0^{max} - B_0^{min})}{< B_0 >}$$

and wave amplitude as:

$$Amp = \frac{(B_1^{max} - B_1^{min})}{< B_0 >}$$

where B_1 is the magnetic field component in the maximum variance direction of the minimum variance frame (Tsurutani et al., 2013).