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SLAMS at comet 19P/Borrelly: DS1 observations

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ABSTRACT

Comet 19P/Borrelly plasma waves associated with the ion pickup process are being studied for the first time. The compressive plasma waves (short, large-amplitude, magnetic structures, or SLAMS) have peak-to-background magnetic field magnitude amplitudes as large as ~9–1. A new method of analysis has been developed to study the properties these compressive waves (and the bow shock) and is applied in this study. The bow shock at the time of the DS1 crossing was determined to be quasiparallel in nature with $\theta_{Bn} \sim 22^{\circ}$. Using this new technique and minimum variance analyses over single wave cycles, most of the waves were determined to be circularly polarized, but some were noted to have linear and sunglass polarizations. The waves propagated obliquely to the ambient magnetic field B_0, with over 75% of the cases with $\theta_{kB0} > 45^{\circ}$. The intrinsic wave polarization in the plasma frame was investigated by examining waves propagating obliquely to the solar wind direction, $\theta_{kx} > 75^{\circ}$, where x is the solar wind velocity vector. From this analysis, a mix of right-hand (RH) and left-hand (LH) polarization waves were found, with no particular order, either as a function of distance upstream or closeness to the bow shock. Most of the waves were detected when B_0 was oblique to $\boldsymbol{V}_{sw}$. The equal mix of RH and LH waves is not well explained by current theoretical models. It is possible that the Dubouloz and Scholer (1995) scenario could work for this cometary case if both RH and LH waves were generated by ring-beam distributions.

1. Introduction

On 22nd September 2001, the Deep Space 1 (DS1) spacecraft had a flyby of comet 19P/Borrelly at a solar distance of ~1.36 AU. At that distance, comet 19P/Borrelly was quite active, with substantial outgassing, leading to the formation of a bow shock at very large distances from the nucleus, plus other solar wind–comet interaction magnetic field and plasma structures. Details of these structures are given in Richter et al. (2011). Some of the figures from the latter paper will be repeated here to give context to the location of nonlinear cometary plasma waves, the main focus of the present work.

Cometary neutral atoms and molecules sublimate from the surface of an active cometary nucleus and obtain outward radial speeds of ~1 km/s. Some of these atoms and molecules travel ~10^6 km from the nucleus before they are ionized by photo-ionization via solar UV or by charge exchange with solar wind ions. Once ionized, the ions produced form a beam, a ring, or a ring-beam in the solar wind rest frame, depending on the interplanetary magnetic field (IMF) orientation relative to the solar wind flow direction (Wu and Davidson, 1972; Tsurutani et al., 1997b; Tsurutani, 1991a, 1991b). Fig. 1 shows schematics for the formation of a beam in the left-hand panel. This occurs when the IMF is parallel to the solar wind velocity. The relative speed of the neutral atoms and molecules from the nucleus is small in comparison and can be neglected, to the first order. Thus, the ion beam flow has a speed of $-\boldsymbol{V}_{sw}$ relative to the solar wind plasma, where $|\boldsymbol{V}_{sw}|$ is the solar wind speed. In the quiet solar wind, this speed magnitude is ~400 km/s. In high speed streams, this is ~750–800 km/s (Tsurutani et al., 2006). The formation of an ion ring is shown in the right-hand panel of Fig. 1. This occurs when the IMF is orthogonal to the solar wind velocity. As soon as the atom or molecule is ionized, it experiences a Lorentz force associated with magnetic field lines moving past it (at a relative speed of $|\boldsymbol{V}_{sw}|$). This force accelerates the ion into a cycloidal motion (relative to inertial space) or a gyromotion in the solar wind frame. The speed of the gyromotion is $|\boldsymbol{V}_{sw}|$. For all intermediate angles of IMF relative to the solar wind velocity, the newly formed ions will gain both parallel and orthogonal velocity components relative to B_0. The ions will have a corkscrew motion relative to the solar wind. This latter distribution has been called a "ring-beam" distribution.

The formation of an ion-beam, ring- or ring-beam distribution leads to different plasma instabilities (Wu and Davidson, 1972;

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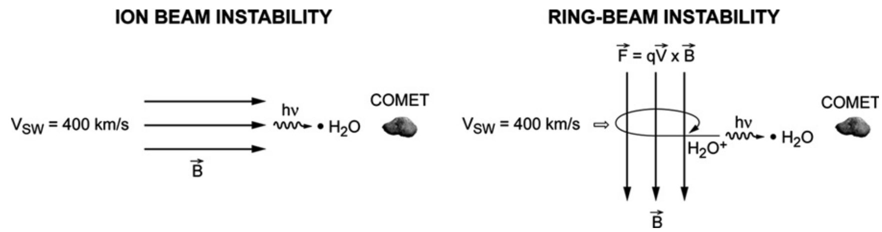

Fig. 1. Schematic of two extreme cases of cometary ion interaction with solar wind. In the left-hand panel, the interplanetary magnetic field (IMF) is parallel to the solar wind flow. In this case, newly formed ions will constitute a beam flowing at $-\boldsymbol{V}_{sw}$ relative to the solar wind plasma. In the right-hand panel, the IMF is orthogonal to the solar wind flow. The pickup ions will form a ring with velocity $|\boldsymbol{V}_{sw}|$ relative to the solar wind plasma. For intermediate cases, the ions will have some beam and some ring properties and has been called a "ring-beam" distribution. The figure is adapted from Tsurutani (1991a, 1991b).

Tsurutani and Smith, 1986a,b; Thorne and Tsurutani, 1987; Brinca and Tsurutani, 1988; Brinca, 1991; Motschmann and Glassmeier, 1998) and consequently the generation of different modes of plasma waves. The waves will cyclotron resonate with the ions and will pitch-angle scatter them so that they will be isotropized and carried by the solar wind. This is the process of ion "pickup" as first described by Wu and Davidson (1972). The above sequence of events is another form of solar wind–comet interaction.

Although intense "wave turbulence" has been present at all previous cometary encounters, the nature of the turbulence was different during each of the encounters. At comet Giacobini–Zinner , the waves were right-hand polarized (magnetosonic or whistler mode) due to anomalous cyclotron resonance with pickup cometary ion beams interacting with the solar wind (Tsurutani and Smith, 1986a,b). At comet Grigg–Skjellerup , the magnetic turbulence was often left-hand polarized (Neubauer et al., 1993; Glassmeier and Neubauer, 1993; Mazelle et al., 1994), presumably due to an ion-ring distribution caused by an oblique interplanetary magnetic field (IMF) orientation relative to the solar wind direction. The IMF configurations for the above two cases are shown in the left-hand and right-hand panels of Fig. 1, respectively. The magnetic turbulence at comet Halley was different still. The waves at Halley had almost no consistent structure (Neubauer et al., 1986). A later study found linearly polarized waves (Tsurutani et al., 1995), and a further study (Tsurutani et al., 1997a) identified arc-, left-hand/arc- (sunglass) and left-hand wave polarized cases. The latter authors concluded that the Halley waves had much more time to evolve and may have been in a fully developed turbulent state.

There are other differences among the magnetic turbulence of the three comets as well. Reviews on these details can be found in Tsurutani (1991a, 1991b), Tsurutani et al. (1995, 1997b), and Glassmeier et al. (1997).

Comet Borrelly is the fourth comet probed by a spacecraft with a magnetometer onboard (Brinza et al., 2001). The magnetometer design is the same as that for the Rosetta spacecraft (Glassmeier et al., 2007), and is described in detail in Richter et al. (2011). We will state here that the turbulence at comet Borrelly is different yet. Nonlinear compressive waves called "short, large-amplitude, magnetic structures" or SLAMS (Schwartz and Burgess, 1991) have been detected and are found to dominate the inbound turbulence. It is noted that similar waves have been previously detected for a short interval at Giacobini–Zinner (Tsurutani et al., 1990) and in and around the Earth's bow shock many times (Mann et al., 1994; Schwartz et al., 1992; Giacolone et al., 1993; Lucek et al., 2004, 2008; Behlke et al., 2004). Nonlinear large-amplitude magnetic field pulses, possibly SLAMS, have been detected in the Jovian magnetosheath (Tsurutani et al., 1993). The latter authors speculated that these waves were formed in the Jovian foreshock/shock and then were convected downstream into the magnetosheath.

Thus, it is also useful to discuss the differences and similarities of SLAMS detected at comet Borrelly with those detected near Giacobini–Zinner and at Earth and Jupiter as well. In particular, clues to the generation and evolution of these SLAMS will be explored.

The purpose of this work is to examine in detail the plasma waves at comet Borrelly associated with pickup ions. In analyzing these compressive waves, it was found that the standard techniques for wave analyses were insufficient. So another purpose of this work is to develop a unified method of wave analysis which can be applied to both noncompressive and compressive waves. The method will be automated so that it can be used to rapidly examine Rosetta cometary plasma waves in the future encounter with comet 67P/Churyumov–Gerasimenko in 2014.

2. Results

2.1. Flyby geometry

The DS1 flyby geometry has been discussed previously by Richter et al. (2011) and in other DS1 articles. However it is useful to review this for the readers here so that they can see where the waves were detected. Fig. 2 shows the DS1 and comet Borrelly trajectory relative to the Earth, Sun and ecliptic plane. Comet Borrelly flew through the ecliptic plane from south to north, while DS1 remained in the ecliptic plane. The relative speed of DS1 relative to Borrelly was $\sim$16.6 km/s.

Fig. 3 gives the flyby geometry in a cometo-centered solar equatorial (CSEQ) coordinate system. This coordinate system will be used throughout the paper. In this system x points toward the Sun, $y = \boldsymbol{\Omega} \times x / |\boldsymbol{\Omega} \times x|$, where Ω is the solar rotation axis, and z completes the right-hand system. In this coordinate system, the DS1 spacecraft approached from the north, crossed the Borrelly bow shock, and then crossed the Borrelly–Sun line. The DS1 data collection ended before the spacecraft crossed the Borrelly bow shock on the outbound pass. The closest approach to the nucleus occurred at $\sim$22:29 UT at a distance of 2171 km.

2.2. Nonlinear plasma waves

An overview of the cometary magnetic field data is shown in Fig. 4. The bow shock (BS) is at $\sim$20:00 UT and the field pileup region near closest approach (CA) is at 22:29:33 UT (Richter et al., 2011). Both times are indicated by vertical dashed lines. The coordinate system used is the cometo-centered solar equatorial system (previously used in Fig. 3). What is remarkable is the high level of magnetic field fluctuations in the three components and field magnitude, particularly after the bow shock (BS) crossing. The Borrelly magnetic turbulence looks somewhat similar to the other three previously encountered comets with this low time-resolution data. There is also significant magnetic turbulence present in the upstream region (upstream of the BS), but this is not obvious in the figure due to the vertical scaling of the panels. This upstream turbulence will be shown in more detail later.