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Cometary ion instabilities in the solar wind

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ABSTRACT

We review some of the processes that characterize the interaction of the solar wind with newborn cometary ions. Instabilities generated by the typical ring-beam velocity-space configuration of the pick-up ions in the solar wind frame are studied by means of one- and two-dimensional hybrid numerical simulations. In agreement with previous studies, we find that instabilities generated by the cometary ions play an important role in shaping the properties of the plasma. The resulting ion distributions are in good agreement with observations, showing the presence of energy shells in velocity space. Bi-spherical shells for the heavy oxygen ions are also observed in the late phase of the simulations. Moreover, we also investigate some new aspects of the dynamics, such as the generation of turbulent cascade from the initial spectra of unstable waves, and the related heating and back reaction of the solar wind plasma. We also consider the case of initial non-gyrotropic pick-up ion distributions, and we focus on the polarization of the associated waves, suggesting that linear polarization can be a signature of this configuration, possibly observed by the Rosetta spacecraft in orbit around comet 67P/CG.

1. Introduction

The interaction of the solar wind with comets is characterized by many interesting and fundamental plasma processes which govern cometary magnetospheres and their vicinity. One of the main mechanisms which controls the whole cometary environment is instabilities generated by cometary ions as they interact with the interplanetary magnetic field advected by the supersonic solar wind flow. Despite the kinetic nature of these processes, which originate from highly unstable particle phase-space configurations, the associated wave activity can grow to macroscopic scale and is able to significantly affect the dynamics and the energetics of both the cometary and solar wind plasmas.

Large amplitude waves have been observed in situ by past encounters of spacecraft with comets, and a large literature is available (see for example reviews by Cravens and Gombosi, 2004; Coates, 2004; Ip, 2004). Simultaneous direct observations of particle distribution functions of different ions originating from the cometary gas confirm that the shape of the ions in velocity space is consistent with the pitch angle scattering produced by waves locally produced at comets (Coates et al., 1990; Neugebauer et al., 1989, 1990; Huddleston et al., 1993b; Johnstone, 1995).

Despite the general good agreement between theoretical modeling and observations obtained in the past (e.g., Winske et al., 1985; Karimabadi et al., 1994), some aspects of the dynamics have not yet been fully understood, such as the different properties of different pick-up ion species (Neugebauer et al., 1990), the generation of linearly polarized waves (Tsurutani and Smith, 1986), and the role of non-gyrotropic distributions (Coates et al., 1993). Moreover, the current Rosetta ESA mission (Carr et al., 2007; Glassmeier et al., 2007), the first close encounter of a spacecraft with a comet monitoring its activity from large distances to perihelion, together with the increase of numerical resources available at present for computer simulations, motivates new theoretical investigations of solar wind-comet interactions.

In this paper we discuss results from numerical simulations of microinstabilities generated by pick-up ions in the solar wind plasma. Our findings confirm conclusions from previous studies and extend the results to regimes which could be relevant for low-activity and distant comets, as expected for the Rosetta observations of comet 67P. In Section 2 we recall the basic properties of the pick-up process, as well as its dependence on the magnetic field orientation and the associated relevant sources of free energy for instabilities. In Section 3 we show results from hybrid numerical simulations performed with different magnetic field geometries, ion species, and initial pick-up distributions. In Section 4 we summarize our findings and we discuss the possible implications of our simulations as well of possible future extensions, in

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the framework of interpreting the current and forthcoming measurements by Rosetta.

2. The cometary ion pick-up

When the cometary gas (being approximately at rest with the comet, due to its negligible outflow compared to solar wind speed V_{SW}) is ionized by solar UV, the newborn ions are instantaneously accelerated by the motional electric field $\mathbf{E} = -\mathbf{V}_{SW} \times \mathbf{B}$, and then picked-up by the solar wind. The velocity acquired by the cometary ions coincides with the component of the solar wind velocity transverse to the magnetic field $V_{SW} \sin\theta_{BV}$, where θ_{BV} is the angle between $\mathbf{V}_{SW}$ and $\mathbf{B}$. The resulting phase-space distribution of the cometary ions strongly depends on the interplanetary magnetic field (IMF) orientation. Such a configuration, due to the large initial difference in velocity between the solar wind and the cometary material, typically leads to a large amount of free energy available for driving plasma microinstabilities. Different instabilities can be generated through the interaction of the newborn cometary ions with the solar wind plasma (see e.g. Wu and Davidson, 1972; Winske and Gary, 1986; Galeev and Sagdeev, 1988; Gary et al., 1989; Brinca et al., 1992; Cao et al., 1995). The dynamics is schematically summarized in Fig. 1, in the frame of the solar wind (blue circle, centered at the origin), for the two extreme cases, when θ_{BV} is 0° and 90° degrees. When $\mathbf{B}$ is perpendicular to the solar wind speed, cometary ions (indicated in red) are picked-up at the solar wind speed and form a phase-space ring co-moving with the solar wind (left). Due to the large radius of the ring (corresponding to the solar wind speed), this configuration results in a very large perpendicular temperature $T_\perp$, leading to a temperature anisotropy $T_\perp \gg T_\parallel$, a possible source of free energy for kinetic instabilities at both parallel (Gary and Madland, 1988) and oblique (Wu et al., 1988; Price, 1989) propagation. When the interplanetary magnetic field is purely radial, then there is no pick-up and the cometary ions are seen as a backward propagating field-aligned beam by the solar wind plasma, with a drift $\Delta v = V_{SW}$ which typically corresponds to several times the local Alfvén speed v_A. This configuration can be unstable with respect to beam-type instabilities (see e.g. Daughton and Gary, 1998, for proton beams). For intermediate, and more realistic, orientation of the magnetic field, the effective temperature anisotropy and the relative ion drift can both contribute to the unstable dynamics.

3. Hybrid simulations

In order to investigate more in detail the properties of the processes associated with the pick-up ions, we discuss numerical simulations performed with a hybrid code (Matthews, 1994) where ions are treated as particles and electrons as a massless charge-neutralizing fluid. Such a modeling is suitable to focus on kinetic processes that take place at ion scales. Units of time and space are the inverse proton cyclotron frequency Ω_p^{-1} and the proton inertial length v_A/Ω_p respectively, where v_A is the Alfvén speed. We have performed one-dimensional (1-D) and two-dimensional (2-D) runs, for various geometries of the magnetic field and of the cometary ion distribution. Simulations are carried out in the electron frame (plasma frame), corresponding to the frame where also the total (solar wind + cometary) ion current vanishes. Note that this does not coincide in general with the center of mass frame, and especially in the case of heavy pick-up ions the difference between the two frames can be significant for the instability dynamics. Periodic boundaries are used in the simulation and the magnetic field lies along the x-axis. Due to the expected rapid pick-up process with respect to the timescales

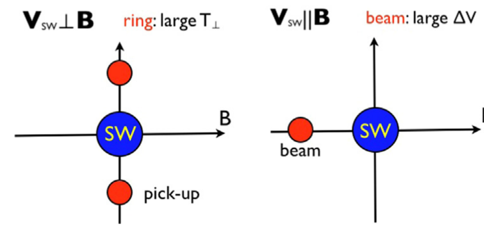

Fig. 1. Schematic representation of the cometary ion pick-up by the solar wind magnetic field. Case of $\mathbf{B}$ perpendicular to the solar wind velocity $\mathbf{V}$ (left) leading to the *ring* distribution and with strictly radial magnetic field (right), when the pick-up does not take place, and the cometary ions are seen as a backward propagating field aligned *beam* in the solar wind frame. The former case gives raise to large temperature anisotropy $T_\perp > T_\parallel$ in the pick-up ions, while in the latter the free energy of the distribution is provided by the relative drift Δv which corresponds to the solar wind speed V, thus largely exceeding the local Alfvén speed v_A. Kinetic instabilities associated to these extreme configurations are discussed in the text.

associated to wave-particle interactions, particles are injected already in the corresponding ring-beam configuration in phase space, which depends on the magnetic field orientation as discussed in previous section. Initial ion distributions then contain some free energy for the generation of instabilities and are let evolve towards equilibrium. The amount of free energy available in the system is regulated mainly by the density of the cometary ions and the relative drift between them and the solar wind protons assumed in each case. Note that in our approach the injection of cometary ions only occurs at the beginning of the simulation and then the system relaxes in time; this could be then considered as representative of some intermittent outgassing, possibly relevant in the early phase of the cometary activity. On the other hand, for a more realistic description of a steady state pick-up process, a continuous injection of ions into the solar wind should be used, see for example Cowee et al. (2008); Cowee and Gary (2012). In the next sessions we review the results of simulations with different configurations and geometry.

3.1. 1-D simulations

We start our analysis by verifying the stability of the two configurations discussed in Fig. 1. Since in this case we are only interested in modes that propagate along the magnetic field, a 1-D simulation grid is used, with 1200 collocation points, spatial resolution $\Delta x = 1$, and with 10^4 particles per cell (ppc) for each species. We focus on the case of Oxygen O^+ ($m = 16 m_p$) pick-up with density $n_O = 5\% n_e$. We assume that equal proton and electron plasma betas in the solar wind $\beta_p = \beta_e = 0.5$ and $\beta_O = 0.1$ for pick-up ions. The relative speed between the solar wind and cometary frames is $V_{SW} = 2v_A$, so that the pick-up velocity is $2v_A \sin\theta_{BV}$.

The first case (Fig. 1, left panel) with $\theta_{BV} = 90^o$ and radius of the ring $v_\perp = 2v_A$ leads to a large (effective) temperature anisotropy $T_\perp > T_\parallel$ contained in the pick-up ion distribution. This may destabilize low frequency left-handed oxygen-cyclotron waves, propagating along the ambient magnetic field (e.g., Gary and Madland, 1988). The expected dispersion relation is shown in red (ρ_p is here the proton Larmor radius), while the dashed line shows the non-dispersive Alfvén wave branch, corresponding to waves propagating at v_A. Results from the hybrid numerical simulation are also displayed in color contours, showing a very good agreement between the linear prediction (e.g., Vandas and Hellinger, 2015) and the dispersion relation measured in the simulation, as expected for the moderately unstable case considered here.

In the case of a radial IMF ($\theta_{BV} = 0^o$), the instability triggered is analogous to a beam-type instability (Fig. 1, right panel), where the O^+ ions travels at $v_\parallel = 2v_A$ with respect to solar wind protons. This drives an instability of the right-handed magnetosonic-whistler branch, characterized by a higher real frequency than in