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Stability of the magnetosonic wave in a cometary multi-ion plasma

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Abstract

A generalized dispersion relation of the magnetosonic wave in a four component plasma consisting of electrons and hydrogen ions of solar origin and positively and negatively charged oxygen ions of cometary origin has been derived by using the Vlasov-Maxwell kinetic model. Parallel to the magnetic field, the hydrogen and electron components are modeled by a drifting Maxwellian distribution; perpendicular to the magnetic field, we use a loss cone type distribution obtained by the subtraction of two Maxwellian distributions having different temperatures. The effect of change in the drift velocity of streaming components and number densities and temperatures of each species in driving the instability has been analyzed both analytically and numerically. For typical parameters at comet Halley, we find that both positively and negatively charged oxygen ions can drive the wave unstable.

Keywords: Magnetosonic wave; Growth rate; Stability; Multi-ion plasma

1. Introduction

The magnetosonic wave is a low frequency electromagnetic, longitudinal wave with wave vector direction nearly perpendicular to the ambient magnetic field. The resultant low value of the parallel component of the wave number $k_{\parallel}$ and the consequent Landau damping has been proposed as important for the heating of radiation belt electrons (Horne et al., 2000; Liu et al., 2011). The wave also called the "fast magnetosonic wave" (Gul'elmi et al., 1975) was first observed by the OGO 3 spacecraft at frequencies between twice the local proton gyrofrequency (f_{cp}) and half the lower hybrid frequency (f_{LHR}) and was confined to within 2° of the magnetic equator (Russell et al., 1970). Recent observations, however, indicate that the frequencies could extend from frequencies slightly below f_{cp} to slightly above f_{LHR} (Boardsen et al., 2016).

These fast magnetosonic waves are also known as "equatorial noise" (EN); they occur in the inner magnetosphere of the Earth at radial distances between about 2 and $7R_E$ and latitudes within about 10° from the geomagnetic equator (Laakso et al., 1990; Kasahara et al., 1994). They have also been observed as far as 20° from the equator but with lower intensities (Tsurutani et al., 2014).

Global surveys of magnetosonic waves show that these waves have higher occurrence rates outside the plasmapause than inside it, due to their strong dependence on the presence of ion ring distributions (Meredith et al., 2008; Ma et al., 2014a). It may be pointed here that some of the earliest studies where the ring distribution was suggested as a source of energy were that by Gul'elmi et al. (1975) and Perraut et al. (1982). Intense equatorial magnetosonic waves have been observed inside the plasmasphere by the Van Allen Probes, in association with a pronounced

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proton ring distribution, which provides the free energy for wave excitation. Simultaneous wave and particle observations, combined with instability calculations, show that these waves can be driven by a proton ring distribution at energies of ≈10 keV (Boardsen et al., 1992; Horne et al., 2000). Recently, Němec et al. (2015) analyzing more than 2000 EN events, identified in the Cluster spacecraft data during the years 2001–2010, found that these emissions have higher frequencies and, on an average, larger total intensities in the plasma trough than in the plasmasphere. Analysis of occurrence rates as a function of magnetic local time (MLT) shows strong variations outside of the plasmasphere (with a peak around 15 MLT), while the occurrence rate inside the plasmasphere is almost independent of MLT. This is consistent with the hypothesis that EN is generated in the afternoon sector of the plasmapause region and wave vector direction both inward and outward (Hrbáčková et al., 2015).

In addition to this terrestrial observation, magnetosonic waves have also been observed upstream of the Martian atmosphere (Ruhunusiri et al., 2015), in the interplanetary space (Tsurutani and Ho, 1999), in the solar wind and coronal regions (Belcher and Davis, 1971; Roberts et al., 1984; Williams et al., 2001, 2002; Cooper et al., 2003), at comets Halley and Giacobini-Zinner (Savin et al., 1987; Tsurutani et al., 1987) and in other astrophysical fluids like the interstellar medium and stellar winds (Armstrong et al., 1995).

Magnetosonic waves have been shown to heat protons and electrons near the magnetic equator (Horne et al., 2000) and accelerate electrons in the Van Allen radiation belts (Thorne et al., 2007). Simulation studies also show that these waves can heat and accelerate ions (Lembege et al., 1983); extension of these simulation studies show that they are also good at stochastic heating of ions (Gao et al., 2012). Very recently, in yet another interesting application, magnetosonic waves have been put forward as an alternate mechanism for the generation of proton aurora (Xiao et al., 2014).

In addition to the above, magnetosonic waves observed outside of Mars can be driven unstable due to the pickup of exospheric protons by the solar wind. Thus the strength of these waves is an indirect measure of the loss rate of exospheric hydrogen (Ruhunusiri et al., 2015). They have also been used to explain heating of the solar coronal regions (Kalomeni et al., 2001). As regards comets, non-linear magnetosonic waves with oblique wave vector directions have been shown to accelerate water group pick up ions at comet Giacobini-Zinner (Srivastava et al., 1993).

Comets sublime due to solar heating releasing a cloud of neutral water molecules. These molecules are dissociated by the action of solar UV radiation, charge exchange with solar wind protons and electron impact. Once ionized, the particles are "picked up" in the crossed electric and magnetic fields of the solar wind forming a ring distribution in velocity space (Staines et al., 1991). One popular model that arrives at a ring distribution is by the subtraction of two Maxwellian distributions with different temperatures. Using such a distribution, Brinca and Tsurutani (1987a) found a new hydromagnetic mode that was excited by the pickup of heavy ions with large perpendicular energies. This mode had a maximum growth for angles of wave vector direction between 6^o – 15^o. These ions could also excite an electromagnetic mode with frequencies of the order of the heavy ion gyro-frequencies. Though the maximum growth rates were still in the same range, the wave vector direction angle was extended to about 40^o (Brinca and Tsurutani, 1987b). Later, Brinca and Tsurutani (1989) investigated cyclotron harmonic waves in two distinct regions – the perpendicular region upstream of comet Halley and the quasi-parallel region as defined by Glassmeier et al. (1989). In addition, for solar wind conditions where the IMF is $< 70°$ relative to the solar wind velocity, generation of the right circularly polarized magnetosonic waves can be expected; the source being the ion ring beam instability due to the pickup of water group ions (Tsurutani et al., 1997).

The region upstream of comets Halley and Giacobini-Zinner has received a great deal of attention ever since the detection of large-amplitude, low-frequency fluctuations in the magnetic field amplitude (Smith et al., 1986; Riedler et al., 1986; Saito et al., 1986; Neubauer et al., 1986; Yumoto et al., 1986), the plasma density (Bame et al., 1986; Gosling et al., 1986), and the solar wind proton velocity (Johnstone et al., 1987).

Very large scale amplitude fluctuations in electron density, temperature, and flow velocity were a prominent aspect of the solar wind interaction with comet Giacobini-Zinner during the ICE encounter. These fluctuations were detected at a distance of at least 9×10^5 km and grew in amplitude as ICE approached the comet, peaking in amplitude 6×10^4 km from closest approach. A typical period associated with the fluctuation was ~2 min, which corresponds to a scale length in solar wind frame of $\sim 5 \times 10^4$ km. For the most part these fluctuations appear to be a product of one or more plasma instabilities associated with the solar wind pick up of cometary ions (Gosling et al., 1986).

Extremely Low Frequency (ELF) waves have been observed by spacecrafts Vega 1 and Vega 2 in the plasma environments of comet Halley. Thus the plasma waves in the inner coma, connected with plasma density enhancements, were identified as oblique high frequency magnetosonic waves (Galeev et al., 1986). In yet another study (Savin et al., 1987) found a peak near 15 rad/s which was identified either as a magnetosonic or lower hybrid wave. The other peak at 100 rad/s was assigned to the "fan" instability or the oblique Langmuir waves with frequencies $f = (1/5–1/3)\, f_{ce}$ (f_{ce} is the electron gyro-frequency) identified by Klimov et al. (1986). In the quasi-perpendicular