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The Kelvin–Helmholtz instability at Mercury: An assessment

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ABSTRACT

The Kelvin–Helmholtz instability is believed to be an important means for the transfer of energy, plasma, and momentum from the solar wind into planetary magnetospheres, with *in situ* measurements reported from Earth, Saturn, and Venus. During the first MESSENGER flyby of Mercury, three periodic rotations were observed in the magnetic field data possibly related to a Kelvin–Helmholtz wave on the dusk side magnetopause. We present an analysis of the event, along with comparisons to previous Kelvin–Helmholtz observations and an investigation of what influence finite ion gyro radius effects, believed to be of importance in the Hermean magnetosphere, may have on the instability. The wave signature does not correspond to that of typical Kelvin–Helmholtz events, and the magnetopause direction does not show any signs of major deviation from the unperturbed case. There is thus no indication of any high amplitude surface waves. On the other hand, the wave period corresponds to that expected for a Kelvin–Helmholtz wave, and as the dusk side is shown to be more stable than the dawn side, we judge the observed waves not to be fully developed Kelvin–Helmholtz waves, but they may be an initial perturbation that could cause Kelvin–Helmholtz waves further down the tail.

1. Introduction

There is plenty of observational evidence that the Kelvin–Helmholtz instability (KHI) can develop on the terrestrial magnetopause. Kelvin–Helmholtz wave observations have been reported on both the dusk and the dawn flank, with a location spread from the dawn–dusk line and far down the tail (Chen and Kivelson, 1993; Chen et al., 1993; Kokubun et al., 1994; Kawano et al., 1994; Fairfield et al., 2000, 2003, 2007; Hasegawa et al., 2004a; Owen et al., 2004; Nykyri et al., 2006). The *in situ* wave observations are almost exclusively obtained under northward interplanetary magnetic field (IMF) conditions, and several studies have shown clear indirect evidence that the plasma and energy transfer into the boundary layer and the plasma sheet increases for northward IMF, likely related to an increase in the Kelvin–Helmholtz activity on the magnetospheric flanks (e.g., Mitchell et al., 1987; Terasawa et al., 1997; Hasegawa et al., 2006; Sundberg et al., 2009). Magnetopause wave observations of the KHI have also been reported from Saturn (Masters et al., 2009) and Venus (Pope et al., 2009), and there is reason to believe that the instability would develop at the Hermean magnetopause as well (e.g., Glassmeier and Espley, 2006; Fujimoto et al., 2007).

Most terrestrial wave observations have shown a periodicity on the order of 2–5 min, and a wavelength on the order of 4–8 R_E (e.g., Fairfield et al., 2000; Hasegawa et al., 2006). Spacecraft observations of Kelvin–Helmholtz waves can be generalized to two different types of wave signatures:

(1) A surface wave giving rise to a long series of periodically occurring inbound (magnetosheath to magnetosphere) and outbound (magnetosphere to magnetosheath) crossings of a well-defined magnetopause. Such wave characteristics have for example been reported by Lepping and Burlaga (1979), Fairfield et al. (2000) and Masters et al. (2009). If the wave is Kelvin–Helmholtz unstable, the KHI leads to wave growth and a steeper inclination of the magnetopause on the leading edge of the wave, as can be shown by a minimum variance analysis (MVA) of the magnetopause magnetic field (Fairfield et al., 2000).
(2) Waves with a series of well-defined outbound magnetopause crossings, followed by a gradual return to magnetospheric values, as in the events studied by Hasegawa et al. (2004a) and Fairfield et al. (2007). This behavior gives rise to a saw-tooth like pattern in both the particle and magnetic field data, as is shown in Fig. 1. The lack of a well-defined inbound

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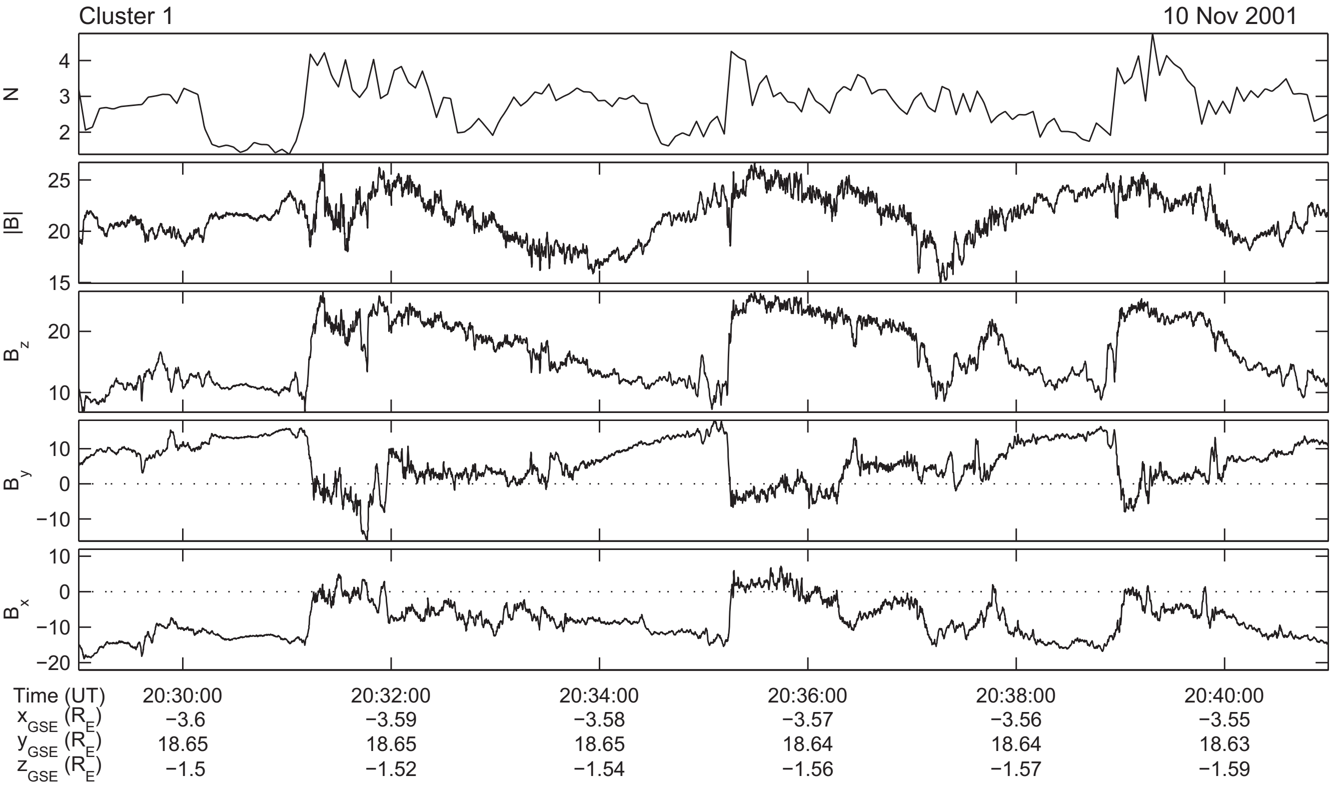

Fig. 1. The number density and magnetic field vectors of a rolled-up Kelvin–Helmholtz wave observed by Cluster 1 on 20 November 2001. The event has previously been analyzed by Hasegawa et al. (2004a), Chaston et al. (2007), Foullon et al. (2008) and Hasegawa et al. (2009). The wavelength has been determined to 6–9 Earth radii (Hasegawa et al., 2004a). Clear outbound magnetopause crossings can be seen at 20:31:30 UT and 20:35:05 with a gradual change in the magnetic properties over the inbound crossing in between, likely related to a well-developed mixing region at the leading edge of the wave.

magnetopause crossing is likely due to the formation of a mixing region on the leading edge of the wave, giving rise to a gradual transition from magnetosheath to magnetospheric properties (Fairfield et al., 2007).

The two wave types likely correspond to different stages of the Kelvin–Helmholtz instability, and an interpretation of the two waveforms is illustrated in Fig. 2. The upper part of the figure shows a surface wave in the linear phase of a Kelvin–Helmholtz instability where a steepening occurs on the leading edge of the wave. The lower part of the figure shows a rolled-up Kelvin–Helmholtz vortex, which allows a mixing region to form on the leading edge of the wave. Intermediate cases of the two types exist as well.

Due to the smaller scale size of the Hermean system and the presence of heavy planetary ions, finite Larmor radius (FLR) effects are expected to play a significant role in the dynamics of the magnetosphere, which likely will affect the properties of the KHI. A difference between the dawn and the dusk side of the magnetosphere has previously been predicted due to the difference in the direction of the gyro motion compared to the velocity shear (Nagano, 1979; Huba, 1996; Glassmeier and Espley, 2006) as shown in Fig. 3. The sense of the ion gyration will thus affect the velocity shear, and in that way change the growth rates of the Kelvin–Helmholtz waves. On the dawn side, the vorticity of a Kelvin–Helmholtz vortex coincides with that of the ion gyration, whereas they will be oppositely directed on the dusk side. However, it is not obvious where the gyro motion will have a stabilizing or destabilizing effect and the results presented in the literature so far are in contradiction: Glassmeier and Espley (2006) predicted the Hermean dusk side to be more unstable, whereas Nagano (1979) reported the opposite for the Earth, although the dipole direction is the same for both planets. Both predictions were based on an FLR extension of the magnetohydrodynamic equations, as presented here in Section 3.

2. MESSENGER observations

During MESSENGER's first flyby of Mercury on 14 January 2008 (Anderson et al., 2008), the magnetometer instrument (MAG) (Anderson et al., 2007) observed wave activity just inside the dusk side magnetopause. Slavin et al. (2009) labeled the rotations as possible Kelvin–Helmholtz vortices. The magnetic field was predominantly northward before the entry into the Hermean magnetosphere as well as after the exit approximately 36 min later. As the dusk side magnetopause crossing occurred close to the equatorial plane, 2.4 Mercury radii (1 $R_M = 2440$ km) down the tail, both the solar wind conditions and the MESSENGER trajectory were well suited for observations of Kelvin–Helmholtz waves. The flyby occurred when the planet was close to perihelion. Using an empirical modeling technique combined with a numerical solar wind model Baker et al. (2009) derived a solar wind velocity for the event on the order of 400 km/s and a solar wind density of approximately 60 cm^{-3}, which indicates that the solar wind conditions were close to the average for a perihelion passage.

The magnetic field observations, shown in Fig. 4, showed three rotations of the magnetic field component in the equatorial plane, occurring with a periodicity of roughly 70 s. The coordinate system used hereon is Mercury Solar Orbital (MSO) (e.g., Slavin et al., 2008), where the $\vec{e}_x$ axis is directed from the center of the