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Mirror mode waves: Messengers from the coronal heating region

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[1] An ongoing problem in heliospheric physics is the mechanism for the heating and acceleration of the solar wind. One process that has been identified as a potentially important source of energy input is ion cyclotron waves, but except for some evidence of perpendicular heating of heavy ions obtained by remote sensing, it has proven difficult to establish their overall effectiveness. We suggest that mirror mode waves in the solar wind may be a signature of the presence of these waves in the corona. Mirror mode waves and ion cyclotron waves can be cogenerated by anisotropic ion distribution functions as demonstrated by their joint growth in the low beta conditions of Saturn's inner magnetosphere. We infer from this example and from the high occurrence rates of mirror mode waves at the closest distances to the Sun probed by spacecraft that the inner corona is also replete with ion cyclotron waves. Understanding quantitatively how these two wave modes share the free energy of the corona could help us to understand the ion-cyclotron wave generation process and its role in solar wind heating and acceleration. **Citation:** Russell, C. T., L. K. Jian, J. G. Luhmann, T. L. Zhang, F. M. Neubauer, R. M. Skoug, X. Blanco-Cano, N. Omidi, and M. M. Cowee (2008), Mirror mode waves: Messengers from the coronal heating region, *Geophys. Res. Lett.*, *35*, L15101, doi:10.1029/2008GL034096.

1. Introduction

[2] Waves in a plasma provide two very important functions. First, they are agents for the transfer of energy from one form to another. For instance they can take the free energy of a ring beam distribution produced, for example, by ion pickup in a flowing plasma and heat the core distribution of the plasma when the ion-cyclotron waves damp [e.g., *Cowee et al.*, 2007]. A second role, equally as important, is that they provide remote diagnostics of processes occurring in inaccessible regions of the plasma. Waves may propagate out of the plasma enabling estimates of the conditions within the plasma. Both these roles are evident in planetary magnetospheres where waves are thought to be responsible for many of the loss processes affecting energetic charged particles and are also used frequently to determine the conditions in the magnetosphere remotely.

[3] A particularly useful diagnostic capability ensues for wave modes that are co-generated by the same particle anisotropy, if one propagates or is convected a large distance from the source region while the other damps rapidly. In particular both ion-cyclotron waves and mirror mode waves are produced by perpendicular anisotropies in ion distribution functions. These waves have different growth rates controlled by plasma parameters but this does not mean that only one of the two waves grow in any one situation. *McKean et al.* [1992, 1994] showed that the waves grew simultaneously in 1- and 2-D hybrid simulations under moderate beta conditions where the growth rates were not too dissimilar. That they are co-generated even at low beta where the growth rates are very different was shown observationally by *Russell et al.* [2006], who demonstrated that both mirror mode and ion-cyclotron waves grew together in the low-beta conditions in the Saturnian magnetosphere. Consistent with this low beta study, *Farris* [1993] found that in the high beta conditions behind the Earth's bow shock that the sole generation of mirror mode waves required high beta and a significant heavy ion content. It can be dominant also at low beta if $T_\perp \gg T$ [*Gary*, 1993].

[4] Saturn provides an excellent example of how these two waves modes behave very differently. The ion cyclotron waves are guided by the magnetic field and after growing in the ion pickup region, Saturn's equatorial E-ring torus, they transfer the free energy of the pickup process into heating of the plasma. The ion cyclotron waves thus dissipate their energy close to their source region. In contrast, the mirror mode waves do not propagate or dissipate, but rather stay in the generation region, or in the case of a flowing plasma, such as corotational or radial flows within a magnetosphere, go with the flow. Thus, at Saturn at some radial distance outside the unstable ion distribution or wave growth region, it is possible to infer from the existence of mirror mode waves that free energy had been available for wave growth interior to that point, even if observations of ion-cyclotron waves in the growth region had not been available.

[5] The Saturn system with its radial outflow is similar to, albeit colder and slower than, the solar wind. The solar wind frequently contains mirror mode fluctuations [e.g., *Winterhalter et al.*, 1995]. The question is whether these, like their Saturn counterparts, were generated in a coronal source region rife with ion-cyclotron waves. There is an extensive literature on the possible role of ion-cyclotron waves in heating the solar wind, as well as some indirect evidence from oxygen-ion perpendicular heating inferred

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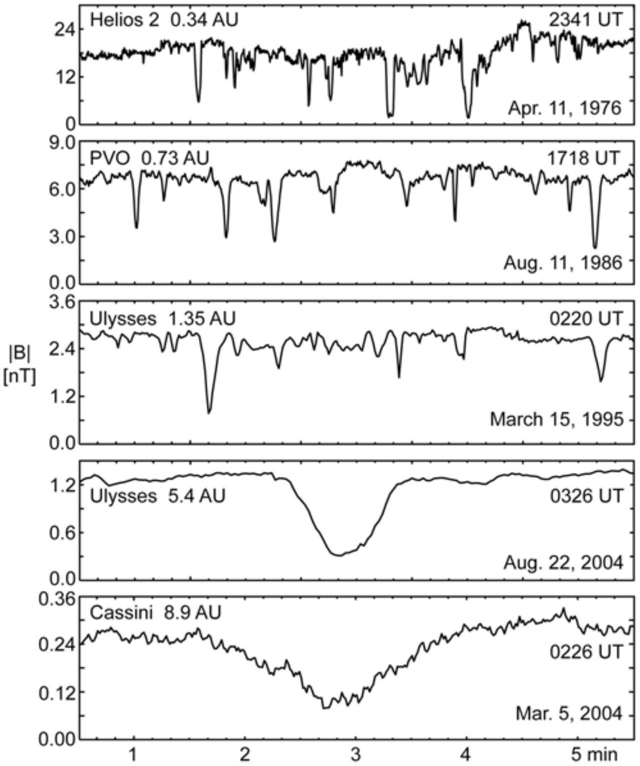

Figure 1. Mirror mode waves seen by Helios, Pioneer Venus, Ulysses and Cassini from 0.34 to 8.9 AU. Each panel is five minutes long.

from remote sensing [e.g., *Cranmer et al.*, 2007; *Hollweg and Isenberg*, 2002, and references therein]. Cogeneration is not a part of the standard picture because mirror mode waves are not essential to the solar wind heating problem. We note that whatever mechanism leads to ion-cyclotron waves could also make mirror mode waves that we might use as a remote diagnostics of coronal ion-cyclotron waves.

2. Radial Distribution of Mirror Mode Waves

[6] If we are to use mirror mode waves as messengers of what is occurring in the inner corona we need to first establish their radial evolution, over the range of distance in which we can observe them with our various interplanetary missions. Figure 1 shows examples of mirror mode waves, displayed all with the same time scale but different vertical scales. The examples are taken from Helios at 0.34 AU [*Porsche*, 1981], from Pioneer Venus at 0.72 AU [*Russell et al.*, 1980], from Ulysses in the ecliptic plane at 1.35 AU and 5.4 AU [*Wenzel et al.*, 1992], and Cassini at 8.9 AU [*Dougherty et al.*, 2004]. In order to maintain a uniform approach to the study we have used a single set of criteria to define mirror mode occurrence in each of the data sets. All of the components of the magnetic field must approach zero without crossing it. We note that the relative depth of the mirror mode wave decreases is similar in all our examples but that the width of the signatures increases with heliocentric distance (or with weaker field strength). We examined a month of data from each of the distances as close to solar minimum as possible and excluded the current sheet and shock regions. We chose only events that reduced the field by more than 50%. We kept track of the occurrence rate, the average and median depths of the mirror mode waves, and their average and median durations. These statistics are listed in Table 1 and displayed graphically in Figure 2. We see that the mirror mode occurrence rate linearly diminishes with increasing heliocentric distance, R, from the sun, while their duration linearly increases and their relative depth remains constant, indicating that their beta is constant.

[7] The plasma in the mirror mode structures will decrease in perpendicular energy when the magnetic field decreases as the structures are convected outward. In order for the width of the structures to increase linearly with R as they appear to do, and, if the beta of the plasma in the mirror mode structure remains constant as it appears to do, then the length of the mirror mode structure (in kilometers) along the field should remain almost constant as the structure is convected outward. If so, then the decrease in occurrence rate is simply due to the decrease in the angular size of the mirror mode structure in its direction along the field. Corrected for this effect the number of mirror mode structures convecting outward is nearly constant and is at most slowly evolving with heliocentric distance. In other words, once created the mirror mode waves appear to be simply convected outward and do not dissipate except for the decrease of the perpendicular gyro energy as they are convected into weaker fields.

3. Discussion

[8] The radial variation of mirror mode waves suggests that they are produced well inside the orbit of Mercury. Because of their apparent lack of dissipation with distance, other than that due to the local plasma and field parameters, we suggest that mirror mode waves can serve as messengers of the conditions in the solar corona. They are telling us that the pressure anisotropy in the coronal plasma is appropriate for mirror mode wave growth and therefore also is probably appropriate for ion-cyclotron wave growth as well. Since the inner corona is a low-beta region and the ion-cyclotron instability growth rate is much stronger than that of mirror

Table 1. Mirror Mode Occurrence Statistics

Spacecraft	Radial Range (AU)	Interval Studied (d)	Events Found	Occurrence Rate (day^{-1})	B_{min}/B_{amb}[a] (%)	Duration[a] (s)
Helios 1&2	0.29 – 0.35	28.9	70	2.43	32.9	4.0
PVO	0.73	23.5	57	2.43	33.6	8.2
Ulysses	1.35	29.8	65	2.18	29.6	17.0
Ulysses	5.40	29.9	41	1.37	29.4	54.1
Cassini	8.90	29.0	20	0.69	32.1	100.9

[a] Median value.

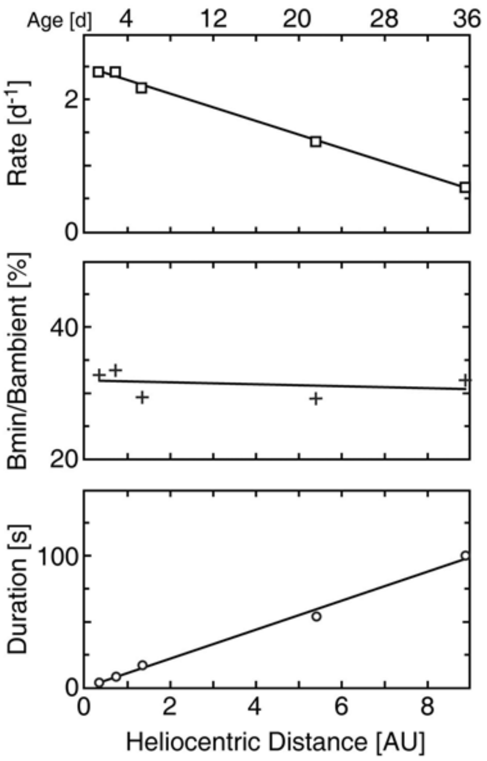

Figure 2. The radial evolution of mirror mode waves: (top) the daily rate, (middle) the ratio of the minimum field in a mirror mode structure element to the surrounding or ambient field, (bottom) duration of individual mirror model elements.

mode waves, we expect that the amount of ion-cyclotron wave generation is much greater than the mirror mode generation. Thus it is reasonable to assume that ion-cyclotron waves are energetically important in the inner corona. However, we are not at the stage where we understand how to interpret the mirror-mode waves at large distances from the corona by extrapolating their amplitudes and/or occurrence rates to those of ion-cyclotron waves in the coronal source region.

[9] It seems reasonable to speculate that the strong anisotropy needed to generate significant ion-cyclotron waves is in fact not so different than the situation of Saturn where pickup ions are the source. Close to the Sun the atmosphere is only partially ionized. Charge exchange and photoionization, followed by exposure to the surrounding moving plasmas and fields, could produce ion ring beams as at Saturn. In a collisional environment this free energy will be isotropized and waves will not grow, but at some altitude, where the plasma becomes nearly collisionless while maintaining its dynamic behavior, and, if the gas remains partially ionized, this ion pickup perpendicular to the magnetic field could lead to ion-cyclotron wave growth and heating. In this scenario, the Poynting flux of electromagnetic waves from the turbulent photosphere transports the energy into the corona where the pick-up process converts it to a form of energy (cyclotron waves) that can heat the plasma. We emphasize that this is not the direction of the energy flow in most of the discussion of ion-cyclotron waves; rather the ion-cyclotron waves are supposed to produce the observed anisotropy, not vice versa. However, if one can create ion anisotropies by ion pickup in an Alfven wave field, efficient energy transfer could ensue.

[10] Another possible source of ring-beam ions is delivery of neutral atoms via vaporizing cometary dust. The strength of this source is unknown and may be quite variable. In either the atmospheric or cometary case, ions distribution functions with perpendicular anisotropies will be present to contribute to mirror mode wave generation as well as ion cyclotron wave heating. The ion cyclotron waves will dissipate their energy locally, but the mirror mode waves will be convected outward with the solar wind. Such coronal dust-produced ions have not yet been reported, but early missions to this region were not so instrumented. A possible third source of ion cyclotron waves is via Alfvenic fluctuations that are generated by the turbulent conditions in the corona that resonantly exchange energy with the magnetized ions in the collisionless regions. This process may not be very efficient and it would not lead to mirror mode wave growth.

[11] In short, the mirror mode waves we see in the solar wind, while not energetically important locally, may provide evidence of energetically important ion-cyclotron wave generation in the corona. To evaluate whether the observed mirror mode waves indicate this, requires a much more detailed and quantitative study. Numerical simulations that consider the generation of these waves in the coronal source region, and their subsequent fate need to be performed. Our purpose here is simply to point out that this investigation is merited, in light of the difficulty of obtaining in-situ observations.

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