ION ACOUSTIC WAVES IN THE HELIOSPHERE

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Abstract. Observations of ion acoustic waves in the solar wind during the first and second orbit of the *Ulysses* spacecraft are presented. The observations show variations of the wave activity with the heliolatitude and with the phase of the solar cycle. The interrelationships between the wave intensity and the electron heat flux and the ratio of electron to proton temperature, T_e/T_p, are examined.

1. Overview of Ion Acoustic Wave Observations

Electrostatic noise at a few kHz has been observed frequently in the solar wind (e.g., Gurnett and Frank, 1978; Hess *et al.*, 1998; Lin *et al.*, 1999). These waves are believed to propagate in the ion acoustic mode, which is strongly Doppler shifted by the solar wind, and whose energy sources may be the electron heat flux or the ion beams in the solar wind (e.g., Gary, 1978). Figure 1 displays *Ulysses* observations of ion acoustic waves (IAWs) from March 1, 1992 to July 31, 2000, represented by 30 min averaged electric wave power measured in the channel of 1.12 kHz, obtained by the plasma frequency receiver (PFR). During the southward transit (panel 1), we observed typical latitude variations of the wave activity in the declining phase of the solar cycle. At low latitudes ($< 13°$ S) when the spacecraft was embedded in the slow and intermediate speed (300–550 km s^{-1}) solar wind, and frequently encountered enhanced solar wind turbulence, we saw frequent occurrences of strong wave bursts. This feature extends to midlatitudes ($< 40°$ S) where *Ulysses* encounter alternating high- and slow-speed solar wind streams, but the occurrence frequency and the wave intensity are gradually decreasing. At high latitudes ($> 40°$ S) where the spacecraft was in the less variable fast ($\sim$700–800 km s^{-1}) solar wind the wave occurrences are less frequent and the wave intensity also becomes much weaker.

The above features are similarly seen in the northward transit during *Ulysses*' 'fast latitude scan' between $\pm 80°$ (panels 2 and 3). Due to the rapid motion of *Ulysses* during this period, the number of data points in panels 2 or 3 is only $\sim \frac{1}{5}$

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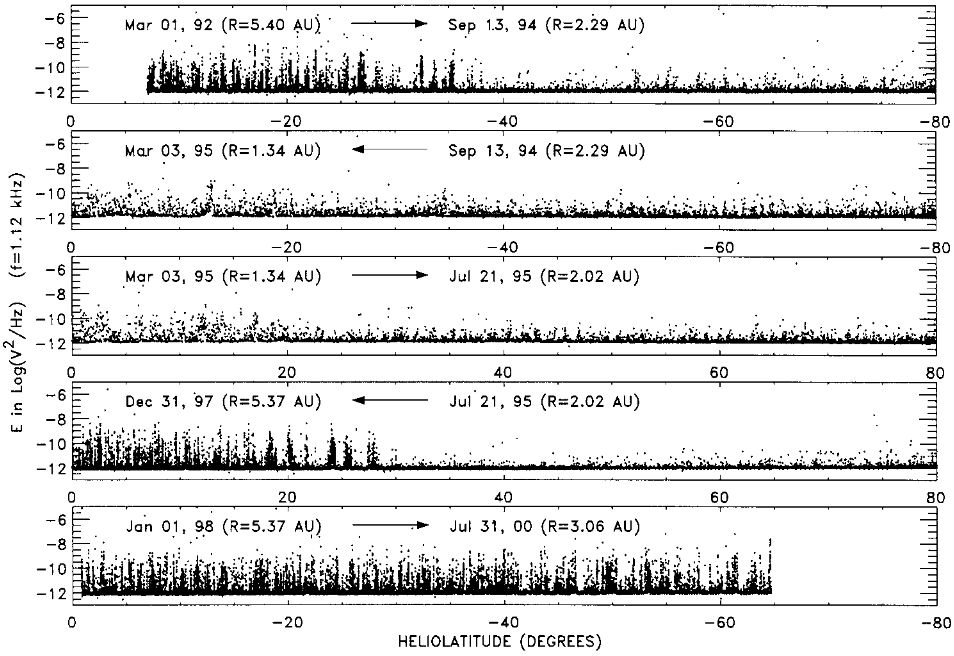

Figure 1. Electric wave power plotted in log scale vs heliolatitude and displayed in chronological order. The arrows indicate the direction of *Ulysses*'s motion.

of that in panel 1, which makes the occurrences of the wave bursts in panels 2 and 3 look less frequent compared to those in panel 1. The fourth panel shows observations of *Ulysses* returning to the ecliptic plane from northern high latitudes. Latitude variations similar to those in panel 1 were seen. This period includes solar minimum (February of 1996 when *Ulysses* was at $\sim$ 25° N) followed by increasing solar activity. As *Ulysses* started the second orbit (panel 5) the Sun was approaching maximum activity conditions. In this period, strong and frequent wave activity are observed not only near the ecliptic plane and at midlatitudes, but also at high latitudes, and up to the highest latitudes shown in the data ($\sim$ 65° S), no sign of reducing or weakening of wave activity is seen. The plasma conditions of slow and intermediate solar wind occur at all latitudes during the second orbit, and are responsible for the lack of latitudinal variations of the wave activity. Throughout the ten years of observations, there seems to be no significant variations in the wave intensity with the radial distance from the Sun.

2. Interrelation with T_e/T_p and Electron Heat Flux

Enhancements of the electron heat flux, q_e, in the solar wind may favor the excitation of IAWs. The kinetic theory requires a large ratio of T_e/T_p for ion acoustic mode to be driven unstable. In the solar wind, T_e/T_p and q_e vary considerably.

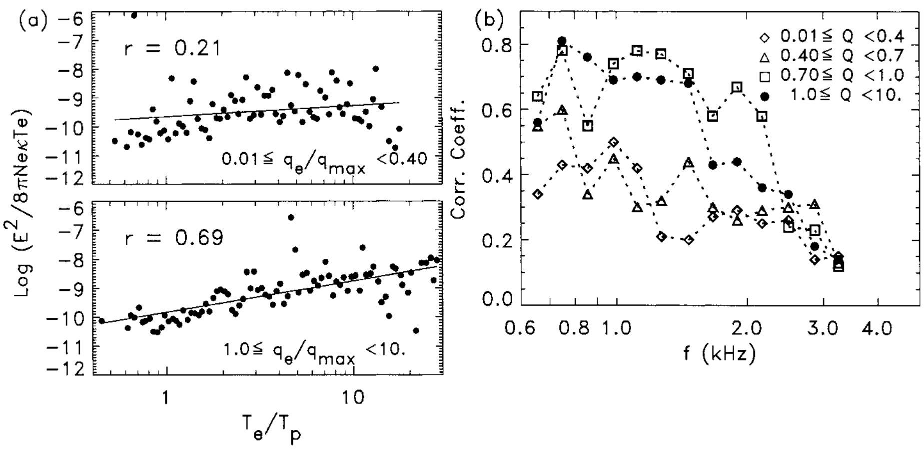

Figure 2. (a) Averaged E_N for the channel of 1.27 kHz vs T_e/T_p for the lowest and highest $q_e/q_{\max}$ ranges. The correlation coefficients, r, are marked in each panel. The solid lines are the least-squares fit of the data. (b) Correlation coefficients between E_N and T_e/T_p vs frequencies in four $Q = q_e/q_{\max}$ ranges for 13 PFR channels.

The variation in the wave intensity may be the combined effects of the two quantities. We have examined the interrelationships between the wave intensity and the two parameters using the data of 1991 which were measured between 0.8° S and 5.8° S latitudes at ~1.5–5 AU. The wave electric field is normalized as $E_N = E^2/8\pi n_e \kappa T_e$, and the dimensionless electron heat flux is $q_e/q_{\max}$, where $q_{\max} \equiv 3m_e n_e V_c^3/2$, V_c is the parallel velocity of core electrons, and m_e, n_e are the electron mass and density, respectively.

The correlation between E_N and T_e/T_p is examined in four $q_e/q_{\max}$ ranges: (1) $0.01 \leq q_e/q_{\max} < 0.40$, (2) $0.40 \leq q_e/q_{\max} < 0.70$, (3) $0.70 \leq q_e/q_{\max} < 1.0$, and (4) $1.0 \leq q_e/q_{\max} < 10.0$. For each $q_e/q_{\max}$ range, we grouped the T-ratio into 86 bins so that the center values of the bins are equally spaced in the log scale, and then averaged the T ratio and the corresponding E_N values within each bin. The correlation coefficients between averaged E_N and averaged T_e/T_p are then calculated. The results are shown in Figure 2. It can be seen that the correlation coefficient increases with increasing $q_e/q_{\max}$. High correlations are seen only in the IAW frequency range ($f <\sim 2.5$ kHz). These results suggest that at higher heat flux levels, an increase in T_e/T_p may enhance the excitation of IAWs more significantly than in the case of lower heat flux.

The correlation between E_N and $q_e/q_{\max}$ is examined in four T_e/T_p ranges: (1) $0.1 \leq T_e/T_p < 1.5$, (2) $1.5 \leq T_e/T_p < 3.0$, (3) $3.0 \leq T_e/T_p < 6.0$, and (4) $6.0 \leq T_e/T_p < 20.0$. The results (see Figure 3) show that at $f <\sim 2.5$ kHz, for the two lowest T-ratio ranges, there is virtually no correlation between E_N and $q_e/q_{\max}$, with the exception of some irregularities in some channels at the lowest T_e/T_p range. The correlation becomes more significant for higher T_e/T_p. When

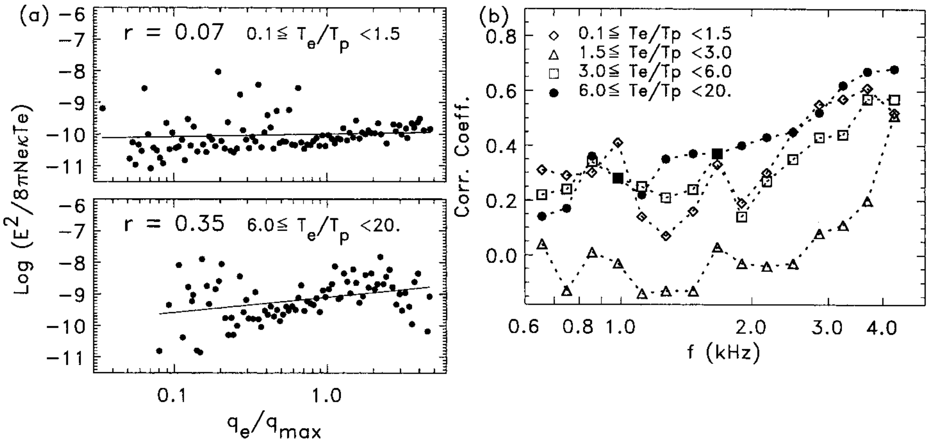

Figure 3. (a) Averaged E_N for the channel of 1.27 kHz vs $q_e/q_{\max}$ for the lowest and highest T_e/T_p ranges. (b) Correlation coefficients between E_N and $q_e/q_{\max}$ vs frequencies in four T_e/T_p ranges for 15 PFR channels.

T_e/T_p is low, the increase in $q_e/q_{\max}$ does not enhance the IAW effectively. The overall correlation between E_N and $q_e/q_{\max}$ is low ($r < 0.4$). We noted that the correlation increases at high frequencies (> 3 kHz) and found a positive correlation between E_N and $q_e/q_{\max}$, which maximized at frequencies centered near the electron plasma frequency, and was independent of T_e/T_p (Lin *et al.*, 2001).

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