Reply

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Orlowski and Russell [this issue] claim that the energetic electron distributions used by *Wong and Smith* [1994] in a general theoretical study of instabilities at whistler mode frequencies is irrelevant to the wave observations studied by Orlowski and colleagues. We never claimed to model specific electron distributions or to account for particular magnetic wave observations. We begin this reply by clarifying the *Orlowski and Russell* [this issue] description of our work, and we end it by showing that ample justification can be found in the work of Orlowski and colleagues and elsewhere to justify the pursuit of a better theoretical understanding of these instability mechanisms.

Wong and Smith [1994] focuses primarily on the excitation at 1 AU of parallel-propagating waves at whistler mode frequencies with plasma-frame frequencies in the range 10 to 20 Hz. The spacecraft-frame frequencies tend to be similarly valued, so our paper addresses primarily waves that are observable in the lowest channels of plasma wave experiments. *Orlowski and Russell* [1991] and *Orlowski et al.* [1990, 1993, 1995] investigate waves at spacecraft-frame frequencies of ~ 1 Hz observed by magnetometers upstream of Mercury, Venus, and Earth.

The principal motivation for our paper is our own work with whistler mode waves upstream of the Uranian bow shock [*Smith et al.*, 1991]. In that study we report two instances of simultaneous whistler mode waves existing at two different spacecraft frequencies, with different propagation directions and different amplitudes. We conclude that the likely source of the observations is a hot electron beam with $T_{\perp b} > T_{\parallel b}$ originating at or behind the shock. *Wong and Smith* [1994] carries this analysis to 1 AU and searches for the implications this work might have for whistler mode waves in the terrestrial foreshock.

Energetic electron observations recorded close to the shock [*Feldman et al.*, 1983; *Fitzenreiter et al.*, 1984, 1990; *Scudder et al.*, 1986] justify our range of particle distribution parameters. For instance, Figure 1 of *Fitzenreiter et al.* [1990] clearly shows several examples of hot electron beams with $T_{\perp b} > T_{\parallel b}$ and $v_b = (4-8) \times 10^8$ cm/s.

We take as our base parameterization: $n_p = n_e = 6$ cm^{-3}, $T_p = T_e = 10$ eV, $B = 5$ nT, $n_b = 0.6$ cm^{-3}, $T_b = 100$ eV, $T_{\parallel b} = T_{\perp b}$, $v_b = 3.4 \times 10^8$ cm/s. The resulting instability is maximum at parallel propagation with $k = 1.6 \times 10^{-6}$ and $\omega = 130$ rad/s (21 Hz). This yields spacecraft-frame frequencies greater than 11 Hz (if the solar wind speed is 400 km/s and the wave propagates sunward along a radial magnetic field) and frequencies as high as 21 Hz if the wave propagates at right angles to the solar wind velocity. These frequencies are well above the range of any magnetometers used by Orlowski and collaborators.

From this starting point, we vary the above parameters and make use of an anisotropic electron beam. This destabilizes the obliquely propagating waves through the same mechanism as *Sentman et al.* [1983] and shows that the generation of two simultaneous whistler mode waves at distinct frequencies and propagation directions is again possible at 1 AU as it is at 20 AU. We also demonstrate that the beam-plasma system possesses an unstable mode that is left-hand polarized at whistler mode frequencies. We examine the full range of oblique propagation using numerical codes and develop a simple analytical treatment of the parallel-propagating instabilities.

It is possible to produce parallel-propagating waves with Doppler-shifted spacecraft-frame frequencies as low as 1 Hz if the beam speed is small. We show one such solution in Figure 4 of our paper. However, it is more likely that 1-Hz waves are obliquely propagating when generated by this mechanism and Figures 1, 3, 4, and 6 of our paper demonstrate this fact. All of the oblique solutions with large growth rates shown in these figures have spacecraft-frame frequencies of the order of 1 Hz. While *Orlowski et al.* [1995] contend that a seven-temperature distribution of energetic electrons is essential to the interpretation of the oblique whistler mode instability, it is at best desirable for the interpretation of specific events. Our paper is a more general theoretical treatment of the basic instability.

Wong and Smith [1994] does not attempt to link the theoretical treatment discussed above to any specific magnetic wave observations. It is strictly a theoretical discussion of instabilities leading to electromagnetic waves at whistler mode frequencies that may be present in the Earth's foreshock. However, we note that *Orlowski and Russell* [1991] and *Orlowski et al.* [1990, 1995] claim that 1-Hz magnetic waves originate near the shock and propagate into the upstream region. They also acknowledge that the electron distributions observed concurrent with 1-Hz waves in the upstream region may result from the interaction of the beam with preexisting waves and may not represent the source of the 1-Hz fluctuations. The instabilities we discuss could be operating closer to the shock and may be a source of the 1-Hz waves seen further upstream.

Orlowski et al. [1990] report that the majority of 1-Hz waves upstream of Mercury and Venus are left-hand polarized. Since only *Newman et al.* [1988] and *Wong and Smith* [1994] demonstrate the ability to produce left-hand polarized waves at whistler mode frequencies, the possibility that this mechanism may explain the left-handed waves is worthy of further examination. The relevance of this instability should not be minimized. *Orlowski et al.* [1990, p. 2295] write about 1-Hz waves upstream of Venus:

> The only waves with sufficient group velocity to stand in the flow are whistler mode waves. ...the observed waves must be in fact right-handed in the plasma frame... This explains the apparent paradox of a left-handed wave having a compressional component.

The electron population responsible for the whistler waves upstream of Saturn [*Orlowski et al.*, 1992] is not resolved by observations. The implication by Orlowski and Russell that further discussion of possible source mechanisms for these waves is irrelevant seems premature.

In summary, *Wong and Smith* [1994] is a theoretical discussion of electron beam instabilities at 1 AU that emphasized anisotropic temperature distributions in the generation of right- and left-hand polarized electromagnetic waves at whistler mode frequencies. That paper lays the groundwork for an improved theoretical description of these instabilities and provides an analytical treatment of the instabilities. Waves at whistler mode frequencies upstream of planetary bow shocks possess a wide variety of possible sources. We have no quarrel with arguments by Orlowski and coauthors that whistler mode waves in planetary foreshocks may originate close to the shock and may not be excited by the more distant upstream energetic electron distributions observed concurrent with the waves. In fact, we contend that the broad class of energetic electron observations observed close to the shock may provide the source for at least a class of upstream whistler waves. We believe that pursuit of these instabilities over a wide range of parameter space is worthwhile.

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