COMPARISON OF PROPERTIES OF UPSTREAM WHISTLERS AT DIFFERENT PLANETS

D. S. Orlowski and C. T. Russell

University of California, Los Angeles, CA 90024-1567, U.S.A.

ABSTRACT

Whistler mode waves have been recorded in the upstream region of Mercury, Venus, Earth and Saturn. They are elliptically polarized and observed typically at frequencies between 0.1 to 4 Hz. These intrinsically right handed waves can be left-hand polarized in the spacecraft frame as a result of strong negative Doppler shift. The waves propagate at an angle between 10 and 60 deg to the background magnetic field, with ΔB/B rarely exceeding 0.1. Comprehensive studies of these waves at Earth and Venus indicate that upstream whistlers are generated at the shock rather than locally in the foreshock. In this paper we compare properties of upstream whistlers at all these planets. We also discuss the utilization of selected properties of these waves to evaluate the effective Alfvenic Mach number and the shock thickness at Mercury where solar wind measurements are not available.

INTRODUCTION

Upstream whistlers have been recorded and studied at Mercury /1,2/, Venus /2-4/, Earth /5,6/ and Saturn /7/. These small amplitude ΔB/B < 0.1 waves are observed in the electron as well as in the ion foreshock /3/. Examples of these waves at different planets are shown in Figure 1. It has been established /2,3,6/ that these waves propagate upstream against the solar wind flow, obliquely to the background magnetic field and in the whistler mode. They are usually subject to strong negative Doppler shift which results in the observed mixed polarization dependent on the angle between the flow and the propagation direction of these waves /2,3/. The observed right-hand RH polarized upstream whistlers are characterized by a distinct break in the spectrum. Spectra of left-handed (LH) waves always have a pronounced peak and sharp cutoff at frequencies that are different at each planet /4/ and /6/. Examples of spectra of upstream whistlers at different planets are shown in Figure 2. As is seen in this figure the observed peak (or cutoff) frequency generally decreases for planets at larger heliocentric distances, but it does not depend linearly on the IMF magnitude. This is due to the fact that upstream whistlers are inherently broadband, subject to complicated negative Doppler shifting that results in mixed polarization observed in the spacecraft frame, and propagate with properties determined by their source located in the shock ramp and not solely determined by the upstream plasma properties as is the case for locally generated low frequency upstream waves /8/. In this paper we apply the fitting method we have used previously at Earth /6/ to compare the properties of the upstream whistlers at different planets and to show that the waves are propagating in a broad band. We also show that the lower frequency cutoff of these waves corresponds to a wavelength approximately equal to one proton inertial length which is the typical thickness of low beta shocks /9/.

AMPLITUDE VERSUS DISTANCE FROM THE SHOCK: A COMPARISON

As has been previously shown /6/ the upstream whistlers at Earth were found not to grow in the upstream region plasma at Earth but rather be subject to moderate Landau damping. In Figure 3 the wave amplitudes at different planets are shown as a function of distance from the shock along magnetic field line in kilometers. It is clearly seen that the amplitudes decrease approximately along the dashed line, a fit to the Mercury data only. This indicates that a similar damping process operates at all the planets studied here including Saturn, and implies that the amplitude (few nanoteslas) of the waves at the shock may be similar or differ no more than factor of 2 at each of the planets. For each planet we calculated average parallel group velocities for the cases shown in Figure 3 for each planet. At Mercury V∥ = 765 km/s at Venus V∥ = 760 km/s at Earth V∥ = 773 km/s and at Saturn V∥ = 635 km/s. Since the
1. Time series of components $B_x$, $B_y$, $B_z$ and total magnetic field strength $|B|$ at Mercury, Venus, Earth and Saturn expressed in the coordinate system equivalent to GSE. The high frequency small amplitude upstream whistlers are clearly seen.

Amplitudes of upstream whistlers at a given distance from the shock are also similar at different planets as shown in Figure 3, their Poynting flux (energy flux) at different planets expressed by $P = V \cdot \delta B^2 / 2 \mu_0$ is approximately the same. The plasma parameters necessary for calculations of group velocities were taken from references /2,3,6,7/.

**PLASMA FRAME SPECTRA: A COMPARISON**

The observed properties of upstream whistlers differ from planet to planet as seen in Table 1. In order to infer the plasma frame frequencies of these waves we use the fitting procedure described in /6/. This procedure is based on solving the power conservation equation simultaneously with the Doppler shift formula and the whistler dispersion relation assuming power law plasma frame spectra. The free parameters of the fit are the lower cutoff frequency, bandwidth and the slope of the spectrum. The results of the fit are shown in Figure 4. It is important to note that the observed high frequency cutoffs of left handed spectra (Mercury, Venus, Earth) constitute in fact lower frequency cutoffs of the spectra in the plasma frame. The physical interpretation of these cutoffs in terms of thickness of the wave source is discussed below.

It is clearly seen that the plasma frame frequencies of the broadband upstream whistlers range from 25 to at least 100 times the local proton gyro frequency, while the lower frequency cutoffs at each planet vary only from 28 to 38 $\Omega_p$ as indicated by the fit shown in Figure 4. If these waves are generated at the shock as indicated in /6/, their largest possible wavelength should not exceed the size of the unstable region namely thickness of the shock ramp. Therefore the wavelength corresponding to the lower cutoff of the frequency band in the plasma frame should yield an estimate of the effective shock thickness. Table 2 contains the results of a calculation of the cutoff wavelengths for different planets for the selected
2. Trace of the power spectral matrix as a function of spacecraft frame frequency of upstream whistlers at: a) Mercury, b) Venus, c) Earth, d) Saturn.

3. Dependence between upstream whistler wave amplitude and distance from the shock expressed in [km] for different planetary settings. The dashed line indicates fit to Mercury data only.

Cases showed in Figure 4. These cases, and corresponding plasma parameters necessary for calculations of the Alfven speed and proton inertial length, were taken from references /2,3,6,7/. As Table 2 indicates, in each case the cutoff wavelength is equal to about 1 local proton inertial length consistent with the results of the two spacecraft measurements /9/ of the ramp thickness at Earth for low beta shocks. We note that the cutoff wavelength expressed in local proton inertial length units, for the Saturn ($M_A = 20$) case is smaller than for all other cases where $M_A = 7-8$. This is consistent with findings of /9/. We also note that, in the case of Mercury due to a lack of simultaneous plasma and magnetic field data during the Mercury flybys $M_A$ was added to the set of free parameters of the fit. In this case the approximate

**TABLE 1**  Upstream Whistler Wave Properties

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Saturn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency* [Hz]</td>
<td>2.5-3.0</td>
<td>1.0-1.8</td>
<td>0.8-1.5</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Amp. Mean [nT]</td>
<td>1.3</td>
<td>0.8</td>
<td>0.3</td>
<td>0.02</td>
</tr>
<tr>
<td>Amp. Range [nT]</td>
<td>0.2-3.2</td>
<td>0.3-1.9</td>
<td>0.1-0.6</td>
<td>0.01-0.04</td>
</tr>
<tr>
<td>$\theta_{xk}$ [deg]</td>
<td>7-53</td>
<td>5-51</td>
<td>5-57</td>
<td>40-60</td>
</tr>
<tr>
<td>$\theta_{vk}$ [deg]</td>
<td>0-37</td>
<td>8-30</td>
<td>9-36</td>
<td>60-70</td>
</tr>
<tr>
<td>Polarization</td>
<td>left</td>
<td>left-right</td>
<td>left-right</td>
<td>right</td>
</tr>
<tr>
<td>Ellipticity</td>
<td>0.2-0.65</td>
<td>0.75-0.99</td>
<td>0.71-0.90</td>
<td>0.6</td>
</tr>
<tr>
<td>Distance*</td>
<td>0.3-16 $R_m$</td>
<td>0.1-4 $R_v$</td>
<td>0.1-5 $R_e$</td>
<td>0.5-2 $R_s$</td>
</tr>
</tbody>
</table>

* Spacecraft frame
+ To spacecraft from shock along magnetic field line
4. The observed spectra (filled circles), fitted spacecraft frame spectra (light shadowing) and modeled plasma frame spectra (dark shadowing) of upstream whistlers at Mercury, Venus, Earth and Saturn. See text for details.

"warm plasma" whistler dispersion relation was applied /10/. The $M_A=7$ obtained from the fitting procedure is consistent with the values obtained by Helios at similar heliocentric distance and with the estimates of /11/.

CONCLUSIONS

Upstream whistlers are observed at Mercury, Venus, Earth and Saturn. They propagate within a broad band of frequencies in the plasma frame from 20-100 $\Omega_p$. Their lower frequency cutoff corresponds to a wavelength equal to approximately one local proton inertial (which is a typical shock ramp thickness). The consistent damping in the upstream region and cutoff wavelengths support shock generation hypothesis of upstream whistlers.

TABLE 2 Cutoff wavelength of upstream whistlers

<table>
<thead>
<tr>
<th>Planet</th>
<th>$M_A$</th>
<th>$c/\omega_p$ [km]</th>
<th>$V_A$[km/s]</th>
<th>$\lambda_{\text{cutoff}} [c/\omega_p]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>7*</td>
<td>40*</td>
<td>76*</td>
<td>1.03</td>
</tr>
<tr>
<td>Venus</td>
<td>8</td>
<td>58</td>
<td>56</td>
<td>0.93</td>
</tr>
<tr>
<td>Earth</td>
<td>7</td>
<td>92</td>
<td>62</td>
<td>1.01</td>
</tr>
<tr>
<td>Saturn</td>
<td>20</td>
<td>953</td>
<td>22</td>
<td>0.78</td>
</tr>
</tbody>
</table>

c/\omega_p - local proton inertial length
$V_A$[km/s] - Alven speed
$\lambda_{\text{cutoff}} [c/\omega_p]$ - the wavelength of the upstream whistlers in [c/\omega_p] units corresponding to the cutoff frequency as indicated in Figure 4.
* inferred
ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration under research grant NAGW-2886.

REFERENCES


