formula MDS obtained plausible values of the coronal magnetic field from the observed polarization of the second harmonic, the present results imply fields which are stronger by a factor of 3 to 4. For example, a typical polarization at 100 MHz would now imply \( B \approx 10 \text{G} \) rather than the value \( B \approx 3 \text{G} \) obtained in MDS. Although these higher fields are not impossible, they seem highly implausible. In particular, they are much stronger than that implied by other estimates of the coronal magnetic field (Dulk and McLean 1978).

It is not clear how this inconsistency between the values of \( B \) might be resolved. One possibility is that the head-on approximation is not valid. Indeed Melrose and Stenhouse (1979) found that use of the head-on approximation can lead to substantial quantitative errors for \( \omega_p/k' c \) of order unity. However, the general case is much more complicated than the head-on approximation because of the more complicated dependence on the angles between \( k' \), \( k'' \) and the magnetic field, and also because the Langmuir waves cannot be regarded as longitudinal. Also, preliminary calculation indicates that terms of higher order than included here, i.e. of order \( k/k' \), could substantially affect the polarization.

One of us (D.B.M.) would like to thank Dr E. Ya. Zlotnik for valuable discussions. Part of this work was supported by NASA under grant NSG 7287 to the University of Colorado.

**Spectral Observations**

Culgoora radio spectrograms of four of the six Type II bursts containing herringbone structure are reproduced in Figure 1. The fifth example is shown in Figure 1(c) of Riddle and Sheridan (1971) and the sixth in Plate 3(b) of Weiss (1963). The simplest example is (d) of Figure 1. Note the spiky herringbone features on the low-frequency side of both the fundamental and the second-harmonic bands of the Type II burst. Note also — a common characteristic of herringbones, yet to be explained — that the fundamental component is less diffuse than the second harmonic herringbone. This effect is also noticeable in example (c) of Figure 1 near 01°20' and in (b) near 03°10'. In the latter example the herringbone spikes

**Solar**

**Radio Evidence for Electron Acceleration by Transverse Shock Waves in Herringbone Type II Solar Bursts**

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**Introduction**

Perhaps the most direct evidence to date for shock wave acceleration of electrons in the solar corona is provided by radio observations of Type II bursts containing herringbone structure (Roberts 1959). On spectral records the herringbones appear to resemble miniature forward and reverse drift Type III bursts extending above and below the Type II backbone.

Further evidence for the similar nature of Type III bursts and herringbones has come from polarization observations (Stewart 1966; Suzuki et al. 1979). The herringbones, like Type III bursts, are strongly polarized while normal Type II bursts are not. This result is consistent with the picture of fast electrons being accelerated in the turbulent shock of the Type II burst with some electrons escaping along ordered field lines to produce herringbone features (Wild et al. 1963). Both Weiss (1963 — personal communication) and Wild (1964) pointed out that the unusually slow drift rates of Type II bursts containing herringbone structure can be explained if the shock waves propagate more or less transverse to open magnetic field lines in the corona thus allowing the electrons to escape along the field lines and produce the herringbone features. Here we describe six Type II bursts containing herringbone structure in which the tangential source motions observed are consistent with Weiss (1963 — personal communication) and Wild (1964) models. We note however that the high source brightness temperatures and second harmonic polarization of the herringbones are difficult to reconcile with existing theoretical interpretations.

**Figure 1. Examples of Type II bursts containing herringbone structure**

Recorded by the Culgoora radio spectograph. Sections of the records where herringbones are clearly visible in both the fundamental and second-harmonic bands are indicated by the letters HB.
have forward and reverse slopes on the low-frequency and high-frequency sides respectively of the Type II backbone, like the classic example described by Roberts (1959). Another beautiful example with extended herringbone features is shown in Plate 3(b) of Weiss (1963). The remaining two examples, (a) of Figure 1 and Figure 1(c) of Riddle and Sheridan (1971), are more complex Type II bursts. Occasionally herringbone features can be distinguished but most of the Type II appears as bursty continuum, sometimes saturating the spectrograph film records. A close examination of both spectrograms and heliograms allows one to distinguish the herringbone sources. Some of the bursty continuum is probably unresolved herringbones.

**Source Observations**

Figure 2(a)-(d) summarize the Culgoora radioheliograph observations of the positions and the tangential motions of the various sources in the four herringbone Type II bursts of Figures 1(a)-(d). The remaining two events are described by Riddle and Sheridan (1971) and Weiss (1963). From Figure 2 we see that the herringbone source displacement at 80 and 160 MHz is considerable and that the movement is away from the radial direction (see A of Fig. 2a, A and B of Fig. 2b, B and C of Fig. 2c and A of Fig. 2d). In contrast, the Type III burst and continuum source positions are located close to the radial direction above the flare region. The measurements refer to second-harmonic herringbone sources. Similar large source displacements and tangential motions are observed for the herringbone sources in the remaining two events (see sources D, E and F of Fig. 3 of Riddle and Sheridan (1971), and Plate 3b of Weiss (1963)). The herringbone source properties are summarized in Table 1. The very large tangential displacements (0.5 to 1.0 R⊙) and speeds (560 to 2000 km s⁻¹) and the wide separation of the herringbone sources indicate that the disturbance causing the herringbone structure in Type II bursts travels over wide angles and has a substantial velocity component parallel to the plasma level. Herringbones only occur in discrete regions of the corona, not all over the wide front of the Type II disturbance (see Fig. 2c).

Finally we note that the radioheliograph observations for the event of 1978 May 7 (Figs. 1a and 2a) give exceptionally high brightness temperatures for the broadband features in the Type II burst of ~10¹³ K at 43 MHz and ~10¹² K at 80 MHz (Duncan *et al.* 1979). In the light of the present results that large source movements can be observed for Type II bursts with herringbone structure it would appear that these very high brightness temperatures may refer to the herringbone source and not to a possible moving Type IV source, as Duncan *et al.* (1979) previously suggested.

**Discussion**

The simplest interpretation for tangential source motion in Type II bursts containing herringbone features is to assume that the Type II disturbance travels across a radial magnetic field (Weiss 1963 — personal communication; Wild 1964). This interpretation does not exclude the possibility that the initiating disturbance travels along magnetic field lines elsewhere in the corona. For example, there is evidence from radio observations of Type II bursts at the solar limb that the initiating disturbance is guided along curved magnetic field lines from a distant flare site behind the solar limb (Smerd 1970; Dulk *et al.* 1971; McLean and Nelson 1977). However, the fast forward and reverse drift rates of the herringbone bursts require the magnetic field lines to be more or less radially directed in the vicinity of the radio source region while the tangential source motions observed require the Type II disturbance to travel perpendicular to these field lines. The question has often been raised why Type II radio emission (including in this instance herringbone bursts) only occurs within discrete regions of the corona and not along the total path of the m.h.d. disturbance (e.g. see Fig. 2c). The most obvious explanation is that the m.h.d. disturbance only becomes a shock wave, and thus able to accelerate electrons to produce radio emission, within discrete regions of the corona (Uchida 1968). Such regions might occur, for example, near the axes of coronal streamers where the Alfvén speeds are low and where the magnetic field lines are more or less radially...
Table I

Source Properties of Spectral Type II Bursts Containing Herringbone Structure

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Time (UT)</th>
<th>Source</th>
<th>Freq. (MHz)</th>
<th>Circular polarization (%)</th>
<th>Tangential speed (km s⁻¹)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1978 May 7</td>
<td>03°31′-48″</td>
<td>A</td>
<td>80</td>
<td>10 R</td>
<td>700</td>
<td>Second harmonic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>160</td>
<td>5 R</td>
<td>560</td>
<td>See Figures 1(a) and 2(a)</td>
</tr>
<tr>
<td>2</td>
<td>1978 Apr. 18</td>
<td>01°19′-23″</td>
<td>A</td>
<td>80</td>
<td>20 L</td>
<td>1700</td>
<td>Second harmonics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>80</td>
<td>20 L</td>
<td>1700</td>
<td>See Figures 1(b) and 2(b)</td>
</tr>
<tr>
<td>3</td>
<td>1978 May 11</td>
<td>03°01″</td>
<td>A</td>
<td>80</td>
<td></td>
<td></td>
<td>Second harmonics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>80</td>
<td>10 L</td>
<td>850</td>
<td>See Figures 1(c) and 2(c)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>80</td>
<td>20 L</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1979 Oct. 18</td>
<td>04°03′-06″</td>
<td>A</td>
<td>80</td>
<td>10 R</td>
<td>1000</td>
<td>Second harmonic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>See Figures 1(d) and 2(d)</td>
</tr>
<tr>
<td>5</td>
<td>1971 Jan. 24</td>
<td>23°20′-46″</td>
<td>D</td>
<td>80</td>
<td>10-20 R</td>
<td>950</td>
<td>Second harmonics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E, F</td>
<td>80</td>
<td></td>
<td></td>
<td>See Figures 1(c) and 3 of Riddle and Sheridan (1971)</td>
</tr>
<tr>
<td>6</td>
<td>1961 Apr. 6</td>
<td>00°17′-22″</td>
<td></td>
<td>45-65</td>
<td></td>
<td>2000</td>
<td>See Plate 3(b) of Weiss (1963)</td>
</tr>
</tbody>
</table>

The authors wish to thank the staff of the Culgoora radio observatory for their assistance with these observations, Mrs J. Tuxford for assistance with the analysis and Dr D. J. McLean for helpful discussion.

directed (Uchida 1968; Wild and Smerd 1972). The Type II disturbance might propagate as a transverse shock wave along the axis of the streamer arcade and produce herringbone bursts as shown in Figure 3. These explanations must remain speculative until we have a more direct means of determining the coronal structure of the radio source regions.

If the Type II disturbance is a transverse fast-mode m.h.d. shock wave we would expect the Alfven speed at the 40 MHz level in the corona to be no greater than the observed tangential speeds ~ 500 to 2000 km s⁻¹. Another estimate of the Alfven speed can be obtained from the observed degree of circular polarization of the second-harmonic herringbone bursts. At 80 MHz the polarization ranges from 10% to 20% (Table 1). According to the theory of Melrose et al. (1978) the corresponding Alfven speed at the 40 MHz plasma level would be ~ 1000 to 2000 km s⁻¹. This estimate is in reasonable agreement with our observations. However, further theoretical work by Melrose and Dulk (1980) indicates that a correction factor ~ 3 should be applied to the above values, thus making this estimate of the Alfven speed prohibitively large. Another problem encountered in the theoretical interpretation of herringbone emission is the observed source brightness temperatures ~ 10¹³ K for the fundamental at 40 MHz and ~ 10¹² K for the harmonic at 80 MHz. If the herringbones result from Langmuir waves the latter must have extremely high brightness temperatures of > 10¹³ K. Brightness temperatures of ≥ 10¹¹ K are very difficult to explain with reasonable parameters for the Langmuir wave source model (Melrose 1974, 1977). Further observational and theoretical work on the herringbone structure in Type II bursts is required before we can hope to understand the acceleration mechanism of shock waves in the solar corona.