ON THE SOURCE CONDITIONS FOR HERRINGBONE STRUCTURE IN TYPE II SOLAR RADIO BURSTS

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Abstract. We investigate the correlation of the occurrence of the herringbone phenomenon in type II solar radio bursts with various flare properties. We show that herringbone is strongly correlated with the intensity of the type II burst: whereas about 21% of all type II bursts show herringbone, about 60% of the most intense bursts contain herringbone. This fact can explain most of the correlations between herringbone and other properties such as intense type III bursts, type IV emission, and high type II starting frequencies. We also show that when this is taken into account, there is no need to postulate two classes of type II burst in order to explain why there appears to be a difference in herringbone occurrence between the set of type II bursts associated with the leading edges of coronal mass ejections, and those not so associated. We argue that the data are consistent with the idea that all coronal type II bursts are due to blast waves from flares.

1. Introduction

The phenomenon of herringbone emission was identified by Roberts (1959) as groups of fast-drift bursts seeming to emanate from the drifting bands of type-II solar radio bursts. Since that time, work on this phenomenon has been sporadic, in part due to its apparent similarity to the well-studied type III burst.

Recently, Cairns and Robinson (1987) have carried out a thorough study of the properties of herringbone emission based on the data available from observations at the Culgoora solar radio observatory. They have discussed properties such as drift rates, spectral profiles, exciter velocities, brightness temperatures and the polarization of individual bursts, and the correlation of herringbone occurrence with type-II properties and other flare-related phenomena. Amongst other results, they show that there are significant differences herringbone and type III bursts.

In this short note, we wish to expand the discussion of two points related to the herringbone phenomenon. Using essentially the same data which formed the basis of the Cairns and Robinson (hereafter CR) study, we first show that of all the available properties which might be correlated with the occurrence of herringbone in a type II burst, the strongest correlation is with the intensity of the type II burst, and that this relationship can explain of the other correlations found. We also discuss the correlation
of HB occurrence with the duration of type II bursts, and the possible implications of this correlation.

Secondly, CR discuss the question of the possible correlation of herringbone with coronal mass ejections (CMEs) using as a framework the view that there are two classes of type II shocks: one which is driven by the CME ('piston' shock), and another which is a blast wave resulting from a flare explosion. The whole question of the relationship of CMEs to associated flares and type II bursts is a matter of great interest, and many people now believe that the evidence for type II bursts driven by CMEs is weak. Rather, all type II bursts may be due to flare explosions. However, CR find a statistical difference in the incidence of herringbone between one group of candidate 'piston' events and another group of 'blast-wave' events. In Section 3 we argue that when one takes into account the intensity correlation of herringbone occurrence, the apparent difference can be explained without requiring the existence of two classes of type II bursts.

2. Correlation of HB Occurrence with Intensity

The Culgoora catalogue (Robinson et al., 1983) which forms the basis for the CR study and our results has recently been inserted into a computer database and studied in detail by Cane and Reames (1988a, b). The catalogue summarizes the morphological characteristics of all type II bursts detected by the observatory from 1968 to 1981. Our purpose here is to demonstrate that there is an important correlation between the intensity of the type II burst and the occurrence of HB.

While it has no significant effect on the outcome (see below), we will differ slightly from CR in our event selection. The column of the Culgoora catalogue which describes the morphology of a type II burst allows for a number of classifications, including complex, saturated, and herringbone. The description of 'complex' is 'profusion of structure and banding; difficult to classify'. Based on our inspection of the dynamic spectra of a number of 'complex' bursts which could well have been classified as containing herringbone, we believe that many of the 'complex' bursts do contain herringbone, even where they are not so marked in the catalogue. Here we regard them as herringbone events; this may, therefore, include some events which do not include herringbone. Our results (Table I, discussed below) obtained by including the complex events may be compared with the results of CR to see the effect of their inclusion. It turns out that the statistics are not greatly changed, since inclusion of the complex events adds only 18 events to the 95 already classified as containing herringbone. Based on our results, we believe that many of the saturated (and, therefore, intense) events also probably contain herringbone, but we do not include those events.

We will state our most important result at the outset. CR confirm the early result of Roberts (1959) that about 21% of all type II bursts contain herringbone structure. In our sample, the figure is 23% (note that, as CR remark, for weaker events it is often more difficult to tell whether an event has HB or not). However, on analyzing the occurrence rate in different intensity classes, a striking result is obtained. The Culgoora
catalogue lists an intensity class for each burst on a scale of 0 to 3, with 3 the strongest intensity class. We find that for intensity classes 0, 1, 2, and 3 the fractions of type II bursts which exhibit HB structure are 0%, 11%, 26%, and 65%, respectively. When complex bursts are not automatically assumed to have herringbone, the fraction of class 3 events with HB is 59%. If we exclude entirely those events in the catalogue which are characterized as either saturated, complex or borderline alone, indicating that probably it was not possible to detect any structure on the dynamic spectrum, the fraction of intensity class 3 events with HB is 63%.

We believe that many of the other correlations between HB occurrence and the properties of flares can be explained by this result. To demonstrate this, we present in Table I the associations of various phenomena with type II bursts listed in the Culgoora catalogue, together with soft X-ray data obtained from Solar Geophysical Data (an X-ray intensity of M5 corresponds to an intensity of $5 \times 10^{-5}$ W m$^{-2}$). We separate type II bursts into two groups according to whether or not they contain herringbone, and in addition we show the same associations for intense (i.e., intensity class 2 or 3) events. We note that the results for the non-HB and HB groups in this table are essentially a repetition of the associations discussed by CR, differing only slightly due to our inclusion of complex events. Comparison of our Table I with CR's Table IV indicates that this does not change any of the associations significantly.

The properties of the HB-associated type II bursts which appear significantly different from those of non-HB-associated type II bursts are: (i) the higher association with intense type III bursts; (ii) the higher association with type IV emission; and (iii) the higher starting frequencies. However, one also sees from Table I that 79% of type II bursts with HB structure are intense, and that the association of HB with other

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**TABLE I**

The association of type II bursts with and without herringbone structure with various phenomena

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Non-HB (420 events) (%)</th>
<th>HB (123 events) (%)</th>
<th>Intense type II (265 events) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type III</td>
<td>≤ 1</td>
<td>70</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>≥ 2</td>
<td>30</td>
<td>43</td>
</tr>
<tr>
<td>Type IV</td>
<td>No</td>
<td>75</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>25</td>
<td>48</td>
</tr>
<tr>
<td>Type II</td>
<td>≤ 1</td>
<td>60</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>≥ 2</td>
<td>40</td>
<td>79</td>
</tr>
<tr>
<td>Starting</td>
<td>≥ 60 MHz</td>
<td>49</td>
<td>69</td>
</tr>
<tr>
<td>frequency</td>
<td>&lt; 60 MHz</td>
<td>51</td>
<td>31</td>
</tr>
<tr>
<td>Soft X-ray</td>
<td>≤ M5</td>
<td>75</td>
<td>62</td>
</tr>
<tr>
<td>intensity</td>
<td>&gt; M5</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>Soft X-ray</td>
<td>≤ 2 hr</td>
<td>86</td>
<td>82</td>
</tr>
<tr>
<td>duration</td>
<td>&gt; 2 hr</td>
<td>14</td>
<td>18</td>
</tr>
</tbody>
</table>
phenomena are essentially the same as those of intense type II bursts with the same phenomena, given in the last column of Table I, independent of HB structure. Thus it seems to us that all of the correlations of HB with other phenomena in Table I can be explained if one assumes that the determining factor is simply the intensity of the type II burst.

There is one other property of the type II burst which may also be important, and whose influence is difficult to separate from that of intensity. This is the duration of the type II burst. The fraction of type II bursts with HB increases with the duration of the burst. For intense type II bursts with durations longer than 19 minutes, 45% have HB structure. If this effect is included in the starting frequency statistic one finds that 67% of long-lasting (duration > 19 minutes), intense type II bursts have starting frequencies greater than 59 MHz. This fraction is comparable to the 69% obtained in Table I for type II bursts with HB structure.

Since type II duration is also well correlated with type II intensity, it is not clear to us which of the two is more closely associated with the occurrence of herringbone. The physics implied by the two correlations could be quite different. A correlation with duration probably implies that herringbone is a locally determined phenomenon: that is, all type II bursts are intrinsically capable of producing herringbone, but only do so if they encounter a region in which the conditions (magnetic geometry, plasma parameters) are right. If regions in which these (unknown) conditions are met are randomly distributed in the corona, the chance that a type II shock encounters them depends on the total volume of the corona it passes through during its lifetime and, hence, its duration. CR cite another result which they also argue implies that occurrence of herringbone is triggered at least in part by the local conditions in the corona: this is the fact that HB tends to occur in tight groups, localized in time and, hence, in space. One can imagine that local effects could control the production of HB in at least two ways: either by facilitating the production of type-II-like streams of electrons; or, if energetic electrons are continuously produced, the local conditions could control their access to field lines on which they can travel the distances implies by the HB frequency drifts. The available evidence does not allow us to choose between these possibilities.

There is one argument which suggests that intensity and not duration may be the dominant factor in HB occurrence. We have shown that herringbone is most likely to be detected when a type II burst is intense, and it might, therefore, be thought that the detection of HB is a sensitivity effect. However, CR find that herringbone, when present, is often more intense than the accompanying type-II emission and, therefore, HB ought to be more easily detectable than the type-II emission. Thus it seems more likely that herringbone production is subject to some sort of threshold effect, i.e., the conditions required for the production of the electron streams presumed to be producing the HB are more likely to be satisfied by a strong burst than by a weak one. In all probability, as CR also conclude, the most plausible situation is a combination of the two dependencies.
3. Herringbone, Type IIs and CMEs

Here we address the relationship of the herringbone phenomenon to coronal mass ejections. CR find significant differences in HB occurrence between events in which the type II appears to be driven by a CME, and those events in which the type II is clearly not driven by a CME. Since on the face of it this result may seem to be evidence for two classes of type II bursts, we discuss it further here and show that their statistics are not incompatible with the view that there is only one type of coronal type II burst.

There have been several lines of work suggesting that type II bursts are not driven by CMEs (e.g., Wagner and MacQueen, 1983; Cane and Reames, 1988a). If one extends the time profile of a type II burst on a dynamic spectrum back to the solar surface, the start time of the shock wave generally agrees well with the impulsive phase of the flare. Another argument that we mention here is that type II bursts have never been seen to precede an associated flare. It is now established that CMEs can start moving well before (e.g., 30 min before) an associated flare (e.g., Wagner and MacQueen, 1983; Harrison, 1986; and the summary of the 1988 SEIIM workshop by Joselyn, 1988). Since the time taken by a type II disturbance to propagate to the height at which it is first observed as a radio burst (assumed to be the height in the corona at which the type II disturbance is travelling faster than the local Alfvén speed and can, therefore, form a fast-mode shock) is typically only several minutes at the known velocities of type II shocks, it seems to us that the only way one can explain the lack of type IIs preceding flares is to assume that CMEs do not drive type IIs. Instead, we assume that all type IIs are due to blast waves from flares.

CR analyze two aspects of the relationship of HB to CMEs. Firstly, they compare the occurrence frequency of herringbone in two sets of type II bursts from the work of Sheeley et al. (1984). One set is of 44 events occurring in association with CMEs, while the other is of 18 events not accompanied by a CME. They find a slightly higher occurrence rate for HB amongst the second set (28%) than amongst the first (16%), but note that this result is not highly statistically significant. Therefore, we believe that it is not inconsistent with the existence of only one class of coronal type II bursts. We discuss this further below.

Secondly, CR consider a subset of those events for which Robinson and Stewart (1985) were able to derive height-time plots for the type II burst and compare them with the motion of the CME as observed by the Solwind coronagraph on P78–1. Of the 7 type II events which both showed herringbone and were associated with a CME, 4 were found to be in a group clearly not coincident with the leading edge of the CME (i.e., by hypothesis, blast waves), and none were in the group in which the type II burst was coincident with the leading edge of the CME (and thus presumed to be piston-driven). By contrast, in the whole set of 33 events from Sheeley et al. (1984) for which Robinson and Stewart (1985) could derive height-time plots, 11 were not at the leading edge of the CME, 9 were uncertain and 13 were at the leading edge of the CME. Therefore, CR conclude that there appears to be a statistically significant difference between the occurrence frequency of HB in bursts associated with blast waves and those driven by
CMEs (they do, however, caution that this result should be regarded as tentative due to possible selection effects in Sheeley et al.'s sample).

We argue that this result can also be influenced by the correlation of HB occurrence with intensity. Specifically, we will test whether the incidence of herringbone in the different sets of events is consistent with that in the whole population of type II bursts given the distribution of intensities within each of those groups, and then test whether the intensity distributions are also consistent with the groups being drawn at random from a single population of type II bursts. Thus, the first question that must be asked is whether the difference in HB occurrence between the 'piston' candidates and the 'blast wave' candidates can be explained by the correlation with intensity, or whether the correlation of herringbone with blast wave candidates is independent of that result.

The answer is that intensity does appear to be relevant. The distribution of all type II bursts among intensity classes is roughly 2 : 9 : 7 : 4 in classes 0, 1, 2, and 3, respectively (Cane and Reames, 1988b). The 13 'piston' candidates are distributed as 6 class 1, 6 class 2, and 1 class 3. They are thus slightly under-represented in class 3 events compared to the expected distribution of 0.8 class 0, 5.5 class 1, 4.3 class 2, and 2.5 class 3. The remaining 29 events from Sheeley et al.'s list which are present in the Culgoora catalogue are distributed as 10 class 1, 11 class 2, and 8 class 3 (compared with the expected distribution of 1.7, 12.0, 9.6, and 5.6). Of these, the 11 events which are clearly not associated with a CME and are, therefore, regarded as likely 'blast-wave candidates' are distributed as 4 class 1, 4 class 2, and 3 class 3 (R. Robinson, private communication; predicted distribution 0.7, 4.6, 3.7, 2.1). Thus the group of 29 non-piston candidates in Robinson and Stewart's study is clearly relatively rich in intense events compared to the 'piston' candidates. In fact, however, all three of these groups contain fewer herringbone events than would be predicted by the distribution found in Section 2: with its intensity distribution, the set of 'piston' candidates should contain 2.2 herringbone events (compared to 0); the group of 29 'non-piston' candidates should contain 8.1 (compared to 6 out of the 29); and the subset of 11 'blast-wave' candidates contains 3 herringbone events when 3.4 would be expected. The chi-square measure for a distribution in which no cases of HB are found when 2.2 are expected is 2.2; in 14% of all distributions with one degree of freedom is the chi-square measure 2.2 or greater. The lack of HB events in the 'piston'-type IIIs would, therefore, not normally be regarded as statistically significant. The chi-square measure for the HB occurrence in the group of 29 candidates is only 0.5, and for the 'blast-wave' group it is only 0.05. Thus the latter two groups are very close to the expected incidence of herringbone, based on its incidence in different intensity classes for all type II bursts.

Therefore, if there is a statistically significant difference between the 'piston' candidates and the 'blast-wave' candidates, it lies in their different distributions of intensity. CR's finding appears to say that the 'blast-wave' candidates are on average more intense than 'piston' candidates. This is not true, however, of another set of 'blast-wave' candidates: this is the group of 19 type II bursts found by Sheeley et al. (1983) when no CME was present. We can find 17 of these in the Culgoora catalogue, and they are distributed as 1 class 0, 7 class 1, 8 class 2, and 1 class 3 (expected distribution 1.0, 7.0,
5.6, 3.3). This distribution is very similar to the set of 'piston' candidates. This group also may appear to support CR's correlation, in that there are 4 occurrences of HB when only 2.5 are expected. However, the chi-square measure for this outcome is also small.

The remaining question is whether the intensity distributions in these groups are consistent with them being drawn from one population of type II bursts. We note firstly that the sample of Sheeley et al. (1983) from which the groups were identified was not randomly selected in any sense, as Sheeley et al. (1983) emphasized, and so we should not expect that the whole sample will reflect the intensity distribution of all type II bursts. For example, it is well known that type II bursts in events where CMEs are also detected tend to be more intense than average. However, the four groups all appear to have intensity distributions close to those expected if they were randomly chose from a single population. Using the distributions and the expected distributions given above, we find that the chi-square measure for the group of 13 'piston' events is 2.43; that for the 29 'non-piston' candidates in CME events is 2.95; for the 11 'blast-wave' candidates it is 1.1; and for the 17 non-CME-event 'blast waves' it is 2.60. For a distribution with three degrees of freedom, 39% of all distributions will have a chi-square measure in excess of 3.0. If we remove intensity class 0 from consideration, the chi-square measures for the first three groups all drop considerably.

In summary, we have shown the following: both the 'piston' and the 'blast-wave' candidates discussed by Cairns and Robinson (1987) are deficient in herringbone, compared to the expected incidence based on their intensity distributions. However, neither is deficient to a statistically significant extent (the most extreme is the lack of HB in the 'piston' group; 14% of distributions randomly drawn from the type II population would show a lack of HB this extreme or worse). Since the distributions of intensity are consistent with them being randomly drawn from one population of type II events, the apparent difference between them is not statistically significant.

Clearly our result is not proof that there is no statistical difference between the two groups, but we argue strongly that the apparent effect in CR’s sample is not evidence for two classes of type II burst. A larger sample is needed in order to resolve this question clearly.

4. Conclusions

We have demonstrated that the strongest observational factor which determines whether or not herringbone is seen in a type II burst is the intensity of the type II. This factor can explain most of the correlations of herringbone occurrence with other flare properties, since these associations are found to be almost identical to those of intense type II bursts. We believe that there is no need to postulate the existence of two classes of type II events based on differences in these associations.

We have also argued that the apparent differences in herringbone occurrence between two sets of events which have been associated with piston-driven shocks and blast waves, respectively, can be explained by the above effect, because of the presence of slightly more intense events in one set than in the other. Thus we believe that the
differences are also consistent with the existence of only one class of coronal type II burst.

Finally, we note that neither of these points throws any light on the many other important issues concerning herringbone emission raised by Cairns and Robinson (1987), such as the differences between herringbone and type III emission and the absence of correlation between individual components of the fundamental and harmonic herringbone bands.

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References