FINE STRUCTURES IN DECAMETRIC NOISE STORMS : POSSIBLE MECHANISMS

D.B. Melrose
School of Physics, University of Sydney, Sydney, NSW, Australia

Abstract

The properties and existing theories for three types of fine structure observed in solar decametric storms are reviewed. The types are stria bursts, including split pair bursts, triple bursts and type IIIb bursts, drift pair (DP) bursts and S bursts.

In discussing the interpretation of stria bursts emphasis is placed on their splitting in split pair and triple bursts. Existing theories involve either a frequency splitting of the spectrum Langmuir waves or a splitting induced in the conversion process to transverse waves due to coalescence with low frequency turbulence. Neither accounts naturally for triple bursts. An alternative suggestion is made here: the Langmuir waves may be split due to coalescence with low frequency turbulence so that conversion to transverse waves becomes possible through coalescence with a second low frequency wave. This mechanism can account qualitatively for the observed splitting. Lower hybrid turbulence is favoured but there are unresolved kinematic difficulties, and the exciting agency for the turbulence is not identified. The Langmuir waves are assumed to be generated by a type III stream.

It is suggested that the two traces in a DP are due to two rays from a single source (the echo hypothesis) which is within an overdense flux tube inside a conical coronal duct. The model leads naturally to two parallel emerging rays, one reflected from the near side of the duct and the other from the far side of the duct. It is suggested that S bursts are due to an analogous process with the rays escaping directly, i.e. without reflection from the sides of the duct. In both cases fundamental plasma emission is assumed. The exciting agency for DPs and S bursts is not identified.

1. Introduction

There are three well defined types of fine structure in metric (rather decametric) noise storms. In order of their classification they are drift pair bursts (DPs), stria bursts and S bursts. DPs were first identified by Roberts (1958) and are characterized by two traces on a dynamic spectrum separated by 1 to 2 seconds and drifting at a characteristic rate, usually in the reverse sense, i.e. from lower to higher frequencies. Stria bursts were identified by Ellis and McCulloch (1966, 1967) and were given their current name by de la Noe and Boischot (1972). Individual stria are narrow band and are either non-drifting or

Proceedings of the 4th CESRA WORKSHOP ON "SOLAR NOISE STORMS"
Editors: A. O. Benz and P. Zlobec
Osservatorio Astronomico di Trieste .
pp. 182-218 1983.

S bursts in Section 7. A possible alternative model for the source region of DPs and S bursts is developed in Section 8.

2. Stria Bursts and Type IIIb Bursts

The following summary of the properties of stria bursts and of type IIIb bursts is based on earlier summaries by Ellis and McCulloch (1967), de la Noe and Boischot (1972), Møller Pedersen (1974), Baselyan et al. (1974a,b), de la Noë (1975), McCulloch and Ellis (1977), Elgarøy (1977) and Fomichev and Chertok (1977).

1. *Appearance*

Stria bursts are defined by their appearance on a dynamic spectrum: they are narrow non-drifting or slowly drifting bands persisting for at most several seconds. The stria tend to form doublets (split pair bursts) or triplets (triple bursts) with characteristic frequency separations comparable with the bandwidth of individual stria, some examples are shown in Figure 1.

2. *Occurrence*

Stria bursts are most common around 30 MHz, and have been observed from $\lesssim$ 100 MHz to the lowest frequency ($\cong$ 10 MHz) observable from the ground. They can occur in any decametric storm

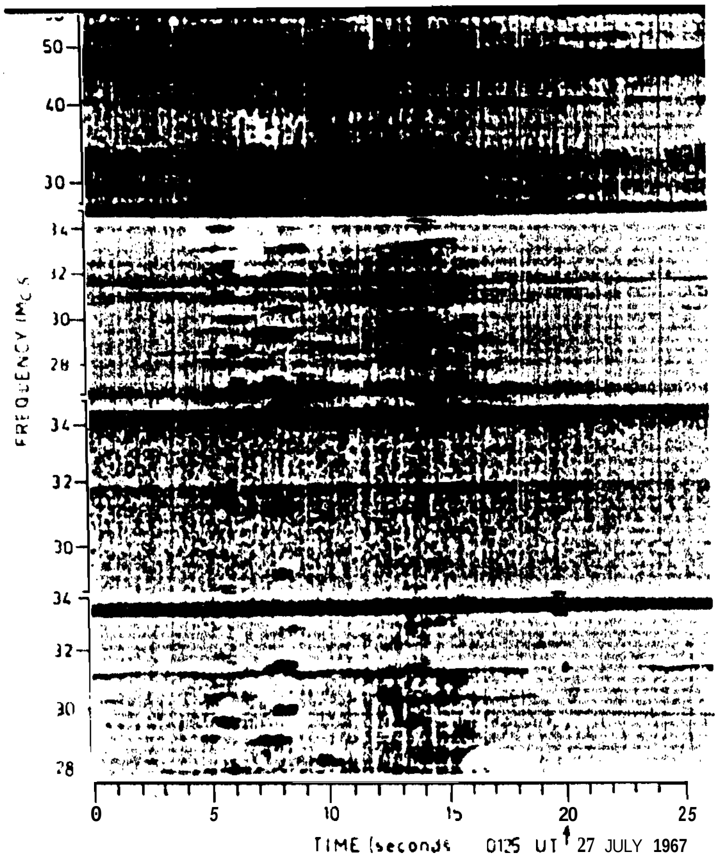

Fig. 1. Examples of stria bursts (with a type IIIb envelope) observed at Hobart. Note that frequency increases along the ordinate, contrary to the more usual solar convention. (courtesy of G.R.A. Ellis)

8. Type *IIIb Bursts*

The stria bursts often form chains whose envelope is characteristic of type III bursts, and which are called type IIIb bursts (Figure 2). Within a type IIIb envelope the individual stria may include singlets, douglets and triplets, and although there is usually a dominant sense of polarization not all stria bursts need be polarized in the same sense. The polarization of type IIIb is characteristic of that of normal fundamental type III bursts (Dulk and Suzuki 1980).

9. *Association with Type III Bursts*

Type IIIb bursts are associated with normal type III bursts. de la Noe (1974) suggested that the type IIIb burst is a precursor of the normal type III burst, with a somewhat larger (by a factor ≅ 2) drift rate. Baselyan et al. (1974b) presented statistical evidence for the type IIIb bursts being fundamental components of normal second harmonic type III bursts. This latter suggestion is favoured by a clear example of a U burst (Figure 3) and by evidence from polarization studies (Suzuki and Sheridan 1977, Dulk and Suzuki 1980). Type

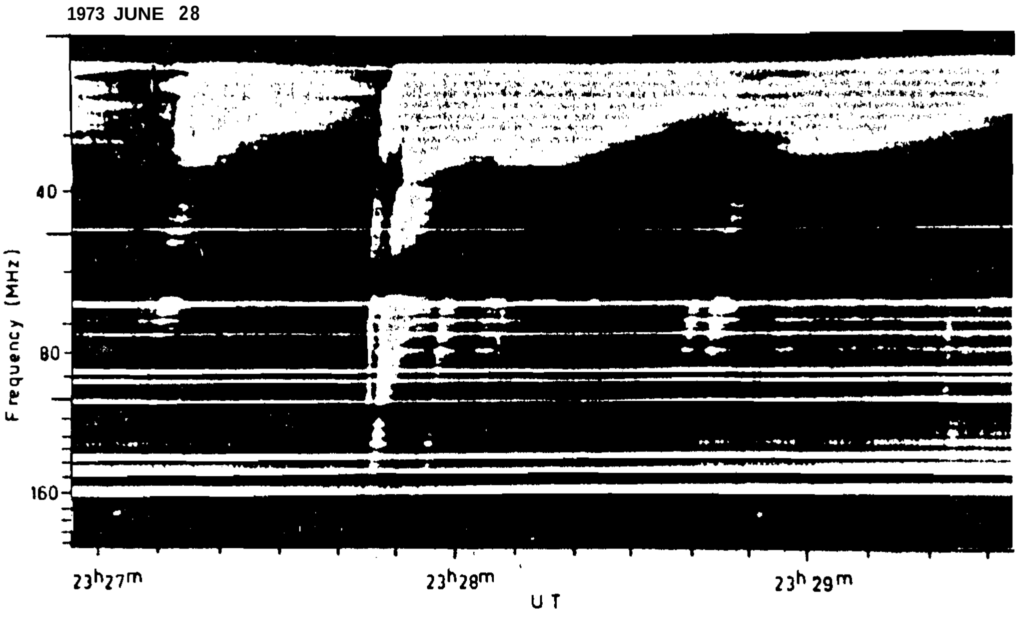

Fig. 2. An example of type IIIb bursts observed at Culgoora; the individual stria and not well resolved.

3. The Splitting of Stria Bursts

The most obvious feature of stria bursts is the frequency splitting in drift pair and triple bursts. For any theory to be convincing it must account for this splitting.

One can conceive of four types of explanation for the splitting. (We assume fundamental plasma emission, as implied by the data on type IIIb bursts.) These are in terms of (a) a frequency splitting of the Langmuir spectrum, (b) a frequency splitting during the conversion process into transverse waves, (c) a frequency splitting during the escape of the transverse waves, and (d) a source substructure which involves two or three localized regions with plasma frequencies differing by the observed frequency separations. Possibilities (a) and (b) seem more likely than (c) or (d), although the latter should not be dismissed out of hand (Melrose and Sy 1971). Here we concentrate on possibilities (a) and (b).

Splitting of the Langmuir Spectrum

Two types of splitting of the Langmuir spectrum have been suggested in the literature and a third is discussed in Section 4 below. The background idea is that if the Langmuir waves, with frequency

$$\omega_L(\underset{\sim}{k}_L) \cong \omega_p + \frac{3}{2}\frac{k_L^2 V_e^2}{\omega_p} + \frac{\Omega_e^2 \sin^2\theta_L}{2\omega_p}, \tag{3.1}$$

are split into two or three bands, then provided any change in frequency on conversion into transverse waves is negligible, the resulting spectrum of the escaping radiation will exhibit the same frequency splitting.

Following Tidman, Birmingham and Stainer (1966), Ellis and McCulloch (1967) suggested that the Langmuir spectrum could be split into a component near the plasma frequency ($\omega_L \quad \omega_p$) and another near the upper hybrid frequency ($\omega_L \cong (\omega_p^2 + \Omega_e^2)^{\frac{1}{2}} \approx \omega_p + \Omega_e^2/2\omega_p$). From (3.1) this requires a spectrum concentrated in angle θ_L arbund parallel ($\theta_L \cong 0$) and perpendicular ($\theta_L \cong \pi/2$) propagation respectively. To account for a triple splitting Ellis and McCulloch (1967) suggested $\omega \cong \omega_p$, $\omega_p + \Omega_e^2/2\omega_p$ and $\omega_p + \Omega_e^2/2\omega_p + \omega_{LH}$, where ω_{LH} is the lower hybrid frequency. However they did not discuss in detail how this third component might arise. We shall return to this point below.

The frequency splitting in this theory then corresponds to $\Delta f/f \approx \omega_B/\omega_p \approx (n_b/n_e)^{1/3}$, implying $n_b/n_e \approx 3 \times 10^{-8}$. Smith and de la Noë argued convincingly that $n_b/n_e \approx 3 \times 10^{-8}$ is an otherwise plausible value..

This theory can account for many of the qualitative and semi-quantitative features of stria bursts. However the general idea that a single stria (or split pair or triple burst) is due to a single large amplitude phase coherent wave is problematical in view of the relatively large size of the source region, and yet it seems essential to the theory that phase coherence be maintained over the entire source region. Using Smith and de la Noe's estimates the source region has dimensions $\approx 3 \times 10^5\lambda \times (10^7\lambda)^2$ where $\lambda = v/f_p$ (≈ 3 m) is the wavelength of the Langmuir waves. They estimated that saturation occurs in ≈ 10 growth times corresponding to propagation distance $\approx 10^3\lambda$ for the stream and this is much less than $3 \times 10^5\lambda$. No suggestion was made as to how phase coherence could be maintained over 10^7 wavelengths in the perpendicular direction. It may be possible to revise the theory by assuming that the actual source consists of many subsources of volume $\approx (10^3\lambda)^3$, but then Smith and de la Noe's argument for localized emission, to produce the striations, would become inapplicable. Other criticisms of Smith and de la Noe's (1976) theory have been made by Baselyan, Zinichev and Rapoport (1977).

Splitting in the Conversion Process

Melrose and Sy (1971) and Yip (1973) proposed that the splitting occurs during the conversion process which they attributed to coalescence with ion sound waves. The coalescence can occur either through an up conversion (+ sign) or a down conversion (- sign) leading to

$$\omega_t(\mathbf{k}_t) = \omega_L(\mathbf{k}_L) \pm \omega_s(\mathbf{k}_s) , \tag{3.4a}$$

$$\mathbf{k}_t = \mathbf{k}_L \pm \mathbf{k}_s , \tag{3.4b}$$

where t, L and s refer to the transverse, Langmuir and ion sound waves respectively. We have $k_t \ll k_L$ and hence require $k_s \approx k_L$ to satisfy (3.4b). Furthermore the ion sound waves must be nearly antiparallel to the Langmuir wave in an up conversion and nearly parallel to the Langmuir wave in a down conversion.

Coalescence with Lower Hybrid Waves

One possible alternative mechanism is a modified version of that proposed by Melrose and Sy (1971) with the ion sound waves replaced by lower hybrid waves. The splitting is then given by

$$\frac{\delta f}{f} = \frac{\omega_{LH}}{\omega_p} \cong \frac{1}{43}\frac{\Omega_e}{\omega_p} . \tag{4.1}$$

As argued by Ellis and McCulloch (1967) a frequency separation $\cong \omega_{LH}$ can account satisfactorily for the observed splitting.

With this suggestion one could account for the central element in triple bursts in terms of coalescence with ion sound waves. The ion sound waves would induce a splitting, but according to (3.5) with $v_\phi \cong 20\ V_e$ this may not be detectable because it is of order of the bandwidth of the stria burst. In this way one could account for three traces with equal frequency separations of the order of that observed. This splitting has also been proposed by Zaitsev (1977).

Although this mechanism overcomes the obvious difficulties with some of the other proposed mechanisms, it is not entirely satisfactory. The requirement that two separate distributions of low frequency waves be present places a severe demand on any possible mechanism for the generation of such turbulence. Furthermore the only low frequency waves which can contribute to the emission are those with $\underset{\sim}{k}_S = \pm \underset{\sim}{k}_L$, where $\underset{\sim}{k}_S$ refers to either the lower hybrid or the ion sound waves. Thus the only relevant low frequency waves have a specific wavenumber determined by $k_S\lambda_{De} \cong V_e/v_\phi \cong 0.3$, where λ_{De} is the electron Debye length. Moreover, if the Langmuir waves are highly directional, as expected for a stream, then the low frequency waves must be nearly parallel or antiparallel to this direction. This is particularly unfavourable for lower hybrid waves if, as seems likely, the Langmuir waves are directed preferentially along the magnetic field. For these reasons the alternative splitting mechanism discussed below seems more favourable.

The Twofold Coalescence Process

One of the unsatisfactory features of the foregoing mechanism is that only a very small part of the spectrum of low frequency turbulence can be involved. Suppose we have a relatively broad spectrum of low favouring one hemisphere, the processes uu and dd will be suppressed relative to the processes ud and du. In this case one would expect an unsplit stria burst at $\omega \cong \omega_L$.

Further Discussion

Let us suppose that this twofold coalescence process applies and explore its implications further. The first question which arises is whether the relevant waves are ion sound or lower hybrid waves.

For ion sound waves we have a dispersion relation

$$\omega_s(\underset{\sim}{k}_s) \cong k_s v_s , \tag{4.3}$$

with $v_s = V_e/43$. Ignoring the magnetic field, i.e. neglecting the final term in (3.1), one finds that processes uu and ud lead to transverse waves with frequencies

$$\omega_{1,2} = \omega_p + (k_L^2/k_0 + k_s \pm \sqrt{k_L^2 + k_0k_s})\, v_s \tag{4.4a}$$

and the processes du and dd lead to

$$\omega_{3,4} = \omega_p + (k_L^2/k_0 - k_s \pm \sqrt{k_L^2 - k_0k_s})\, v_s , \tag{4.4b}$$

with

$$k_0 \simeq 2\omega_p v_s/3V_e^2 . \tag{4.5}$$

In (4.4a,b) the initial coalescence is with a sound wave with wavenumber k_s and the second coalescence is with $k_{s'} = \sqrt{k_L^2 \pm k_0k_s}$. For plausible values ($k_L \cong 3\omega_p/c$, $V_e \cong 10^{-2}c$) k_0/k_L is less than and of order unity.

In this case there are four frequencies, but ω_4 does not exist for $k_s > k_L^2/k_0 - k_0$, and ω_3 does not exist for $k_s > k_L^2/k_0$. In the case k_s k_L^2/k_0 we could hope to account for split pair bursts. The frequency separation would be given by

$$\frac{\delta f}{f} = \frac{\omega_1 - \omega_2}{\omega_p} = \frac{\sqrt{k_L^2 + k_0k_s}}{\omega_p}\, v_s . \tag{4.6}$$

This is of the same order as the splitting (3.5), which is too small for interpretation of the splitting. The situation is somewhat less favourable when one examines the kinematics in more detail. The intermediate Langmuir wave (L') must satisfy

$$k_{L'}^2 = k_L^2 \pm \frac{\omega_{LH}\, k_0}{v_s}\,, \qquad \underset{\sim}{k}_{L'} = \underset{\sim}{k}_L \pm \underset{\sim}{k}_T\,, \qquad (4.9a,b)$$

and the final transverse wave must have effectively negligible $\underset{\sim}{k}$, requiring

$$\underset{\sim}{k}_{L'} \pm \underset{\sim}{k}_{T'} = 0\,. \qquad (4.10)$$

These conditions cannot be satisfied for $\underset{\sim}{k}_L$ parallel to the magnetic field and $\underset{\sim}{k}_T$ and $\underset{\sim}{k}_{T'}$ perpendicular to **it**. They effectively require $\underset{\sim}{k}_T$ and $\underset{\sim}{k}_{T'}$ to be at moderate angles to the magnetic field and to be of order k_L in magnitude. The kinematics requires further detailed investigation before the foregoing favourable features are accepted as valid.

In conclusion the double coalescence process offers a variety of possibilities, and **it** seems likely that all the observed features of single, double and triple stria bursts can be explained in terms of **it** with the low frequency waves being near the lower hybrid resonance. However unresolved difficulties with this proposed mechanism remain. Furthermore these ideas relating to the splitting of stria bursts have yet to be combined with a model for type IIIb bursts, e.g. such as that proposed by Takakura and Yousef (1975). By implication the stria emanate only from regions where appropriate low frequency turbulence is present, and a model is required to account for the localized excitation of this turbulence.

5. Drift Pair Bursts

The following summary of the properties of drift pair (DP) bursts is based on studies reported by Roberts (1958), Ellis (1969), de la Noe and Møller Pedersen (1971), Møller-Pedersen, Smith and Mangeney (1978) and Suzuki and Gary (1979).

1. *Appearance*

On a dynamic spectrum DPs appear as two narrow parallel traces over a frequency range from as small as the bandwidth to ≅ 10 MHz. In a particular storm there can be preferential frequencies at which DPs start or stop.

7. *Polarization*

Both elements of DPs are polarized in the same sense (Shastry 1972, Suzuki and Gary 1972) and this sense is that of the type I-III storm itself. The degree of polarization (up to ≅ 50%) is consistent with that of fundamental type III bursts in the same storm. In one storm Suzuki and Gary (1979) found the earlier trace more highly polarized than the later trace in reverse DPs, and the later trace more polarized in forward DPs.

8. *Size, Position and Brightness Temperature*

Radioheliograph data show that all bursts from a particular storm overlap in position and that the two elements of DPs came from about the same position (Stewart 1977, de la Noe and Gergely 1977, Suzuki and Gary 1979). In a particular storm observed at 43 MHz Suzuki and Gary (1979) found that the size of DPs was 120-160 (arc)', with brightness temperatures from 2×10^9 K to 2×10^{10} K, similar to those of type III bursts in the same storm; however they noted that the duration of DPs is shorter than the integration time of the instrument and that the true brightness temperatures should be higher than the measured values.

9. *Association with Type III Bursts*

Other bursts most commonly associated with DPs are storm type III bursts. Besides the general association there is an indication of a causal connection between DPs and type III bursts. Definite associations were observed for 10% of DPs by Roberts (1978), 48% by de la Noe and Møller Pedersen (1971) and 37% by Suzuki and Gary (1979). (The differences are partly instrumental.) An example of an association is shown in Figure 5.

10. *Variants*

Besides the forward and reverse forms of DPs, several other variants have been reported. Ellis (1969) observed hook bursts which appear to be a pair of DPs with opposite drift rates with the later one starting at the stopping frequency of the earlier one. Møller-Pedersen, The only more recent theory for DPs is that by Møller-Pedersen, Smith and Mangency (1978, hereinafter MPSM) whose basic assumptions were radically different from those underlying Roberts' suggestions. MPSM assumed that the source of DPs lies inside a coronal streamer, that the splitting is due to two correlated sources, specifically two MHD shock waves, and that the drift rate is due to the exciting agencies propagating along density gradients perpendicular to the axis of the streamer. Other details of the model include (i) the trigger is a magnetosonic soliton which penetrates the streamer and excites two shock waves one propagating towards and the other away from the axis of the streamer, (ii) these shock waves generate ion sound turbulence which causes the generation of Langmuir turbulence through turbulent bremsstrahlung but only in the outer regions of the streamer where the plasma β is small, (iii) the time separation between the two traces of the DP is attributed to the delay involved in the inward propagating shock crossing the axis of the streamer and entering the low-β region on its far side, (iv) the emission is fundamental plasma emission with the bandwidth determined by that of the Langmuir waves, $\Delta f/f \cong 3(k_L \lambda_{De})^2/2 \cong 1.5 \times 10^{-2}$.

In Section 8 below an attempt is made to formulate an alternative model which retains Roberts' echo hypothesis and MPSM's assumption of fundamental emission from a locally overdense structure. However, before introducing any new ideas it is appropriate to discuss these existing ideas and criticisms of them.

The Pairing

There seems to be only two possible explanations for the observed pairing in DPs: two different ray paths from a single source, or two correlated sources. The former is Roberts' echo hypothesis, and the model of MPSM contains an example of the latter.

In discussing his echo hypothesis Roberts (1958) assumed that the two rays were a direct and a reflected ray. Using calculations of Jaeger and Westfold (1950) for a radio wave propagation in a spherically symmetric corona, Roberts noted that the time delay would be of the order of a few seconds for a source at the second harmonic of the plasma frequency. Criticisms of this suggestion include (i) that the reflected of DPs, and MPSM suggested that it involved MHD shock waves. From a more general viewpoint, we can hope to identify the exciting agency by its speed: type III exciters are electron streams with speed $\cong c/3$ and type II exciters are MHD shock waves with speeds $\cong c/100$. To estimate the speed of the exciter we divide the drift rate df/dt by $|\mathrm{grad}\ f_p|$, which involves the density gradient. There are two possibilities: either the density gradient is that of the average corona (as in type II and type III bursts) or it is associated with a specific coronal structure. Let us discuss these two possibilities separately.

If the relevant density gradient is that of the average corona then the speeds of the exciters of DPs are of order $c/10$. The specific nature of DPs suggests a specific type of exciter, and one would hope to identify this speed with some characteristic speed and thus identify the exciter. However, $c/10$ corresponds to no obvious speed. It is too fast for an MHD shock wave, e.g. it would require a Mach number greater than about ten. It is also too fast for an electrostatic shock wave which shockspropagate at less than about the thermal speed of electrons. The only shock like structure which propagates nearly fast enough is a whistler soliton (Tidman and Krall 1971, p. *63;* Kuijpers 1975) which propagates at $\frac{1}{2} v_{Ae} < v < v_{Ae}/\sqrt{2}$, with $v_{Ae} = 43\ v_A$. Alternatively the exciting agency could be a stream of electrons with velocity $\cong c/10$ corresponding to energies of a few keV. The association with type III bursts favours this syggestion. However, the narrow traces and apparent lack of dispersion of the exciting agency argue against it.

On the other hand, if the density gradient is associated with some specific coronal structure then the inferred speed of the exciter is less than $c/10$ by a factor equal to the ratio of the actual density gradient to the mean gradient in the corona. For a density gradient 10 to 30 times the mean gradient the inferred speed would be of order the Alfvén speed as in the model of MPSM.

The model developed in Section 8 is not strongly dependent on which of these two cases applies, however the former case was specifically in mind. The reason that the drift rate is interpreted in terms of the average density gradient relates to S bursts. It seems possible that S bursts are a variant of DPs with essentially the same drift rate.

sometimes with the same drift rate and sometimes with a drift rate decreasing with time. No periodicities or systematic pairings are observed. Sometimes two or more S-bursts appear to diverge from a point on the dynamic spectrum, and a single S burst may break up into two or more distinct bursts.

2. *Occurrence*

S bursts are relatively infrequent in decametric storms. They probably have higher frequency counterparts, e.g. the fast drift storm bursts at ≅ 200 MHz reported by Elgarøy (1961) and bursts at ≅ 100 MHz reported by Chernov (1974). S bursts are most commonly associated with DPs.

3. *Bandwidth*

Besides the absence of pairing and the predominance of forward drifts, the main feature distinguishing S-bursts from DPs is their narrow bandwidth, typically $30\ \mathrm{kHz} \lesssim \Delta f \lesssim 200\ \mathrm{kHz}$ at $f \cong 30$ MHz.

4. *Duration*

The duration of S bursts at fixed frequency is typically $\Delta t \lesssim 0.1\mathrm{s}$, with $\Delta t \lesssim 20$ ms for some bursts.

5. *Drift* Rate

The drift rate of S bursts is similar to that of DPs. Individual bursts and S bursts in general extend over a broader frequency band than DPs, and over the range $30 \lesssim f(\mathrm{MHz}) \lesssim 150$ the drift rate is given by the empirical formula

$$\frac{df}{dt} = -af^b\ \mathrm{MHz\ s^{-1}}$$

with

$$a = (6.5 \pm 0.5) \times 10^{-3}, \qquad b = 1.6 \pm 0.6 .$$

6. *Polarization*

S bursts are partially circularly polarized in the same sense as the background storm.

7. *Intensity*

The maximum intensity observed for S bursts corresponds to a flux frequency drift. It may be that in some storms the negative drifting bursts are often paired and classed as DPs while in other storms they are unpaired or multiple and are classed as S bursts. McConnell (1981, 1982) argued that the drift rates of S bursts are systematically greater than those of DPs in the same storm; however, the difference is very small and the similarity in drift rates seems the more notable feature. In summary, there seems no good reason to regard S bursts as unrelated to DPs.

Before discussing the interpretation of both DPs and S bursts, there is one feature of S bursts which calls for particular attention: their very narrow traces.

Interpretation of Fine Traces

Although there is no detailed theory for S bursts, McConnell (1981) has discussed several aspects of their interpretation. The most notable feature requiring interpretation is the narrowness of the traces. On a dynamic spectrum the bandwidth Δf and duration Δt at fixed frequency for a drifting burst are related by

$$\Delta f = \left|\frac{df}{dt}\right| \Delta t \,. \tag{7.1}$$

All effects which contribute to the bandwidth of the radiation or to the persistence time at fixed frequency contribute to the thickness of the trace, and a very narrow trace implies limits of all such processes. McConnell listed three contributions to the bandwidth and four to the persistence time. The spread Δf_n in plasma frequencies in the source, the bandwidth Δf_L of the Langmuir waves and the bandwidth Δf_C imposed during the conversion from Langmuir waves to transverse waves contribute to Δf, and the time Δt_E for the exciter to move through the plasma level, the light travel time Δt_t through the source along the line of sight, the broadening Δt_{MP} due to multipath propagation and the decay time Δt_D of the Langmuir waves all contribute to Δt. Consider a source of thickness d with a density gradient $|\text{grad}\, n_e| = n_e/L_N$, an exciter of speed v and length L, and Langmuir waves in a range Δv_ϕ about phase speed v_ϕ. Then we have context by **Kuijpers** (1981).

Alternative Interpretation of the Narrow Bandwidth

A conceivable interpretation of S bursts involves a stream of electrons with $v \lesssim 0.1\,c$ propagating in the quasilinear relaxed state as discussed in detail by **Grognard** (1982) and envisaged for type **III** bursts by Zaitsev, Mityakov and Rapoport (1972). However, any theory of this kind implies $\Delta f_L/f$ very much larger than the observed value of $\Delta f/f$. Other sources of Langmuir waves, e.g. turbulent bremsstrahlung as envisaged by MPSM give even larger value of $\Delta f_L/f$. One might conclude the restrictions imposed by condition $\Delta f_L <$ Af are so severe as to be unacceptable, and some way of relaxing this requirement should be sought.

It does not appear to have been pointed out that **it** is possible for fundamental plasma emission to have a bandwidth considerably less than the bandwidth of the Langmuir waves. (During induced scattering the bandwidth can be reduced somewhat, but this is a relatively small effect.) Consider transverse waves close to the plasma frequency in a scatter-free corona. Waves with different frequencies **emerge** at different angles. Let + be the angle between the emerging ray path and the direction of the negative density gradient, assumed constant. Then one has

$$\sin\psi = \mu \cong \left(\frac{2(f - f_p)}{f_p}\right)^{\frac{1}{2}} . \qquad (7.5)$$

A range of frequencies Δf in the source then corresponds to a range of angles $\Delta\psi$ given by

$$\Delta\psi \cong \left(\frac{2\Delta f}{f_p}\right)^{\frac{1}{2}} , \qquad (7.6)$$

which for $\Delta f/f_p \cong 3 \times 10^{-4}$ correspond to $\Delta\psi$ of order one degree. That is two rays separated by $\Delta f/f \cong 3 \times 10^{-4}$ emerge along ray paths separated by $\Delta\psi \cong 1^{o}$. Put another way, **if** scattering produces a range $\Delta\psi \lesssim 1^{o}$ of emerging ray paths for monochromatic radiation from a single point in the corona, then a fixed distance observer sees only radiation in a range of frequencies $\Delta f/f \cong 3 \times 10^{-4}$.

Provided the escape of radiation from an S burst source is nearly favourable configurations. More importantly for the formulation of a model, hypothesis B more or less forces one to conclude that the exciting agency propagates along a density gradient similar to that of the average corona. This makes a model in which the drift is due to an exciting agency propagating into or out of a coronal streamer, as in MPSM, difficult to maintain. Thus we imagine an exciting agency moving along a roughly radial overdense structure at a speed $\cong c/10$. However it might be remarked that the arguments against an exciting agency propagating into a streamer are not compelling. Many of the features of the model below are unchanged for an exciting agency propagating in this alternative way.

Source Model for DPs

With these remarks in mind we now seek to identify a source structure which could produce the observed splitting of DPs. To limit speculation let us confine ourselves to structures which have already been suggested in the literature. We start by outlining some of these proposed structures.

There is radio evidence for overdense structures overlying active regions (Axisa et al. 1971, Dulk and Sheridan 1974). Hoang, Poquérusse and Steinberg (1977) suggested that these form a conical structure which surrounds the active region. From STEREO data at 169 MHz they estimated the half angle α of the cone to be $\alpha \approx 6^{\circ}$ from the directivity of the fundamental component. Others (e.g. Mercier 1975, Dulk, Melrose and Suzuki 1979) have argued that the field lines diverge rapidly, which would suggest a larger cone angle at lower frequencies. A value $\alpha \cong 30^{\circ}$ was suggested by Dulk et al.

There is evidence for isolated overdense structures overlying active regions. Individual loops can be observed directly in X-rays and in the EUV, e.g. as discussed by Stewart and Vorpahl (1977) and Stewart (1977). Bougeret and Steinberg (1977), in discussing the directivity of Type I emission, invoked a forest of overdense fibers; they also envisaged nested flux loops extending high over the active region.

The model for DPs introduced here is illustrated in Figure 8. The source is an overdense isolated flux tube inside a conical duct.

rays are at an angle ψ_0 to the axis of the flux tube with

$$|\cos\psi_0| \quad < \quad \mu/\mu_0 \qquad\qquad (8.1$$

where μ is the refractive index at the point of emission and μ_0 is the refractive index in the duct just outside the flux tube. The value of $\mu \ll 1$ is determined by the details of the emission process, and the value of $\mu_0 = (1 - f_{p0}^2/f^2)^{\frac{1}{2}}$ is determined by the ratio of the plasma frequency at the point of emission ($\cong f$) to the plasma frequency f_{p0} in the duct just outside the flux tube. As they propagate across the duct the angle ψ between the ray direction decreases due to two effects. The first is refraction: Snell's law requires

$$\mu \sin \psi \quad = \quad \mu_0 \sin \psi_0 \qquad\qquad (8.2)$$

which implies that ψ decreases as the plasma frequency decreases and hence μ increases. The second is an abrupt decrease by 2α on reflection from the edge of the duct. Let subscript R denote the reflection point. Then the reflected ray immediately after reflection is at an angle ψ_R determined by

$$\psi_R \quad = \quad \arcsin\left(\frac{\mu_0 \sin \psi_0}{\mu_R}\right) - 2\alpha \;. \qquad\qquad (8.3)$$

The value of ψ at infinity is then

$$\sin \psi_\infty \quad = \quad \mu_R \sin \psi_R \;. \qquad\qquad (8.4)$$

In this special case the emerging rays are parallel to the axis of the duct ($\psi_\infty = 0$) only for $\psi_R = 0$, which according to (8.3) requires $\mu_0 \sin \psi_0 = \mu_R \sin 2\alpha$. For $\psi_0 \cong 90^0$, $\mu_R \cong 1$ and $\alpha \cong 30^0$, this requires $\mu_0 \cong \sqrt{3}/2$, implying $f_{p0} = \frac{1}{2}f$. Consider an observer whose line of sight is at a small angle $\delta\psi$ to the axis of the duct. Two rays reach him, one from the near side of the duct due to $\psi_\infty = \delta\psi$ and the other from the far side due to $\psi_\infty = -\delta\psi$. Using (8.3) with $\psi_0 \cong 90^0$ and $\mu_R \cong 1$, these two rays would have slightly different frequencies separated by δf with $\delta f/f \cong 2\mu_0\,\delta\psi$.

i.e. for $\mu_0 < \tan \alpha$ (which is a necessary but not a sufficient condition). Thus the relatively density enhancement in the flux tube should be modest. For $\alpha = 30^0$ we require the density enhancement to be by a factor $< (3/2)^{\frac{1}{2}}$.

Thus it seems possible to attribute S bursts to the same phenomenon occurring in only slightly overdense flux tubes close to the far wall of the duct.

Difficulties

The model envisaged here for DPs has several unsatisfactory features. First, the two emerging rays would be expected to be separated by about the distance across the duct, whereas observations indicated that the two rays emanate from the same region (de la Noë and Gergely 1977, Suzuki and Gary 1979). Second, the separation between the two traces should increase with decreasing frequency, whereas observations indicate that the time delay is roughly independent of frequency. These difficulties are in addition to those mentioned above, namely the absence of a plausible exciting agency at $\cong c/10$ and the difficulty in accounting for the very narrow traces observed, especially in S bursts. Further ideas on the interpretation of DPs and S bursts are required.

9. Conclusions

Several new ideas have been introduced here for the interpretation of fine structures in metric noise storms. Specifically the double coalescence process involving lower hybrid waves (Section 4) appears capable of accounting for the fine structure in stria bursts, and the model introduced in Section 8 appears capable of accounting for many features of drift pair bursts and S bursts. However, even granted that these suggestions are accepted, many problems remain unsolved and even unaddressed.

In the Introduction a stated objective is to identify (a) the exciting agency, (b) the details of the emission mechanism and (c) the coronal structures required for each fine structure. Let us now consider each of these for stria - type IIIb bursts and drift pair - S bursts.

References:

Axisa, F., Avignon, Y., Martres, M.J., Pick, M., and Simon, P.: 1971, Solar Phys., 19, 110.

Baselyan, L.L., Goucharov, N.Yu., Zaitsev, V.V., Zinichev, V.A., Rapoport, V.O., and Tsybko, Ya.G.: 1974a&b, Solar Phys., 39, 213 & 223.

Bazelyan, L.L., Zinichev, V.A., and Rapoport, V.O.: 1977, Izv. Vyssh. Uchebn. Zaved. Radiofizika, 20, 1399.

Bhonsle, R.V., Sawant, H.S., and Degaonkar, S.S.: 1979, Space Sci. Rev., 24, 259.

Bougeret, J.L., and Steinberg, J.L.: 1977, Astron. Astrophys., 61, 777.

Briggs, R.J.: 1964, Electron-Stream Interaction with Plasmas, M.I.T. Press (Cambridge Mass.)

Chernov, G.P.: 1974, Soviet. Astron. AJ, 17, 788.

de la Noe, J.: 1974, Solar Phys., 37, 225.

de la Noe, J.: 1975, Astron. Astrophys. 43, 201.

de la Noe, J., and Boichot, A.: 1972, Astron. Astrophys., 20, 55.

de la Noe, J., and Gergely, T.H.: 1977, Solar Phys., 55, 195.

de la Noe, J., and Møller Pedersen, B.: 1971, Astron. Astrophys., 12, 371.

Dulk, G.A., Melrose, D.B., and Suzuki, S.: 1979, Proc. Astron. Soc. Australia, 3, 375.

Dulk, G.A., and Sheridan, K.V.: 1974, Solar Phys., 36, 191.

Dulk, G.A., and Suzuki, S.: 1980, Astron. Astrophys., 88, 203.

Duncan, R.A.: 1979, Solar Phys., 63, 389.

Elgarøy, Ø.: 1961, Astrophys. Norv., 7, 123.

Elgarøy, Ø.: 1977, Solar Noise Storms, Pergamon Press (Oxford)

Ellis, G.R.A.: 1969, Aust. J. Phys., 22, 177.

Ellis, G.R.A., and McCulloch, P.M.: 1966, Nature 211, 1070.

Ellis, G.R.A., and McCullocy, P.M.: 1967, Aust. J. Phys., 20, 583.

Fomichev, V.V., and Chertok, I.M.: 1977, Izv. Vyssh. Uchebn. Zaved. Radiofizika, 20, 1255.

Gergely, T.E., 1982, these Proceedings.

Grognard, R.J.-M.: 1982, Solar Phys., (in press).

Hoang, S., Poquérusse, M., and Steinberg, J.L.: 1977, Astron. Astrophys., 56, 283.

Takakura, T., and Shibahashi, H.: 1976, Solar Phys., 46, 323.

Takakura, T., and Yousef, S.: 1975, Solar Phys., 40, 421.

Tidman, D.A., Birmingham, T.J., and Stainer, H.M.: 1966, Astrophys. J., 146, 207.

Tidman, D.A., and Krall, N.A.: 1971, Shock Waves in Collisionless Plasmas, Wiley-Interscience (New York).

Tsytovich, V.N.: 1970, Nonlinear Effects in Plasma, Plenum Press (New York).

Yip, W.K.: 1973, Solar Phys., 30, 513.

Zaitsev, V.V.: 1977, Izv. Vyssh. Uchebn. Zaved. Radiofizika, 20, 1379.

Zaitsev, V.V., Mityakov, N.A., and Rapoport, V.O.: 1972, Solar Phys., 24, 44.

slowly drifting. The stria often occur in doublets called split pair bursts or triplets called triple bursts. Stria tend to be grouped in chains whose envelopes have the appearance of type III bursts and are called type IIIb bursts. S bursts were identified as fast drift storm bursts by Ellis (1969) and were renamed by McConnell (1980, 1982). Their drift rate is similar to that of DPs from which they differ in having a narrower bandwidth and absence of a characteristic pairing and in other statistical properties.

As already mentioned these fine structures appear in decametric storms. They are almost always accompanied by storm type III bursts and often by type I emission at higher frequencies. They are quite distinct from the fine structures observed at decimetric wavelengths in type IV bursts, i.e. the decimentric zoo of zebra, fiber, tadpole and other bursts as reviewed by Kuijpers (1980) and Slottje (1981), for example. The properties of fine structures in decametric storms have been reviewed by Bhonsle et al. (1979), and are discussed by Gergely (1982) and Sawant (1982) in these Proceedings. Also, Fomichev and Chertok (1977) have reviewed the properties of other fine structures observed between the decimetric and decametric bands.

Although some details of the fine structures vary from one storm to another, many of the characteristics are well defined and quite specific. This suggests that they are generated by specific types of exciting agency and/or in specific coronal structures. In this paper I review the relevant observational properties and existing theories, and attempt to identify (a) the exciting agency, (b) the details of the emission mechanism (all are most likely fundamental plasma emission) and (c) the coronal structures required. Although a number of new ideas concerning the interpretations will be introduced, no attempt at a detailed comprehensive theory is made. A few problems may be solved but many more remain unsolved.

In Section 2 the properties of stria bursts are reviewed and the existing theories for their splitting are summarized in Section 3. An alternative theory for the splitting is introduced and discussed in Section 4. The properties of drift pair bursts are summarized in Section 5, existing theories for DPs in Section 6 and the properties of and are more common for storms over active centres near the solar limb.

3. *Bandwidth*

The bandwidth Δf of individual stria bursts can vary from 15 kHz to 100 kHz, implying $5 \times 10^{-4} \lesssim \Delta f/f \lesssim 3 \times 10^{-2}$. The bandwidth for unpaired stria bursts is somewhat larger (by a factor ≅ 1.5) than for the elements of doublets or triplets.

4. *Splitting*

The typical splitting δf between the elements in a split pair burst or a triple burst is of order 100 kHz at f ≅ 30 MHz and appears to increase slightly with increasing f. de la Noe (1975) suggested that in triple bursts the central element appears to define an axis of symmetry; however unpublished observations by McConnell (Honours Thesis, University of Tasmania, 1977) show an asymmetry with the splitting between the upper and middle traces being larger than that between the middle and lower traces in ten out of sixteen samples. Split pair bursts appear to correspond to triple bursts with the lowest frequency element absent.

5. *Duration*

Individual stria bursts persist for as short as the resolution time (usually a few tens of milliseconds) up to a few seconds. In split pair bursts the higher frequency element usually lasts the longer and in triple bursts the central element usually lasts the longest.

6. *Drift Rate*

Individual stria may drift from higher to lower frequencies at a rate up to ≅ − 250 kHz s^{-1}. The mean is ≅ − 150 kHz s^{-1}. Some stria have a negligible (undetectable) drift rate, and this seems to be more common in split pair and triple bursts.

7. *Polarization*

The stria bursts are usually circularly polarized and the degree of polarization can be anywhere from zero to 100%. The elements in a split pair or triple burst have the same sense, but not necessarily the same degree of polarization.

IIIb bursts are of comparable average brightness to other type III bursts in the same storm, indicating that the individual stria bursts are brighter than normal type III emission (Smith and de la Noe 1976).

10. *Variants*

A number of variants of stria bursts have been reported. Diffuse stria bursts (Baselyan et al. 1974a, de la Noë 1975, McCulloch and Ellis 1977) have broader (factor ≅ 2) bandwidths and frequency separations than normal stria bursts. They also last longer (up to ≅ 10 s) and are less polarized. They often appear as tails on normal stria bursts. The suggestion (Baselyan et al. 1974b) that chains of diffuse stria bursts might be a new class (type IIId) of second harmonid type III bursts associated with normal fundamental type III bursts has not been supported by subsequent authors (de la Noë 1975, Suzuki and Sheridan 1977, Dulk and Suzuki 1980). Fork bursts (Baselyan et al. 1974a, McCulloch and Ellis 1977) are triple bursts in which the central element precedes the other two elements; reverse fork bursts in which the central element follows the other two have also been observed. Other fine structures reported by Baselyan et al. (1974a) are reviewed by Bhonsle et al. (1979). It must be remarked that some particular fine structures may be peculiar to one specific storm.

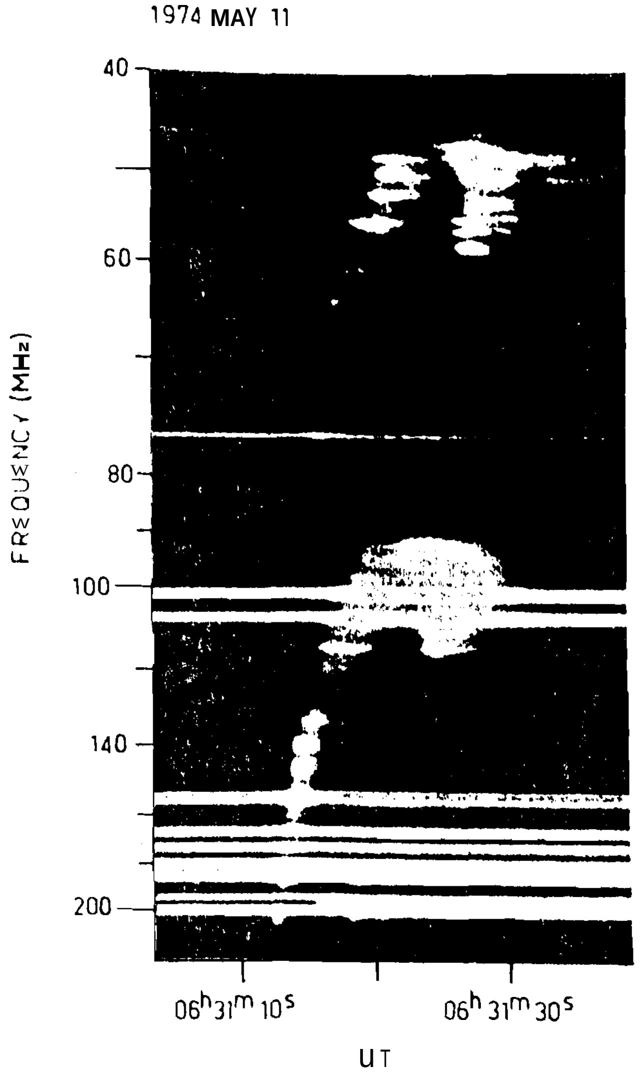

Fig. 3. The U burst reported ty Stewart (1977) as implying fundamental emission for type IIIb bursts.

From a semiquantitative viewpoint the most favourable feature of this suggestion is that the observed splitting is plausibly of the order of the lower hybrid frequency ($\omega_{LH} = \Omega_e/43$ here). For example, a splitting $\delta f \cong 100$ kHz at $f \cong 30$ MHz with $\delta f/f = \omega_{LH}/\omega_p$ would correspond to a ratio $\Omega_e/\omega_p \cong 1/8$ of the electron cyclotron frequency to the plasma frequency.

Criticisms of the mechanism include the following:-

(a) there is no basis for expecting the Langmuir spectrum to be concentrated at $\omega \cong \omega_p$ and $\omega_2 \cong \omega_p + \Omega_e^2/2\omega_p$,

(b) the frequency $\omega_p + \Omega_e^2/2\omega_p + \omega_{LH}$ is not a natural frequency of the plasma and

(c) the splitting between the lower two and upper two frequencies is unequal.

Nevertheless, in a modified form (Section 4) this theory remains one of the most favourable theories.

A detailed theory based on splitting of the Langmuir spectrum was developed by Smith and de la Noë (1976). In their case it was assumed that the Langmuir waves are generated in what they called a strong-beam interaction and others have called the hydrodynamic (Shapiro 1963, Tsytovich 1970, p. 183) or reactive (Briggs 1964, Melrose 1980a, p. 125) stage or version of the two-stream instability. This requires that the spread Δv in electron velocity v satisfy $\Delta v/v < (n_b/n_e)^{1/3}$ where n_b is the number density of the beam. The growth of the Langmuir waves then produces a large amplitude phase coherent wave, and the growth is limited by trapping of electrons in the potential wells associated with the wave. The trapped electrons oscillate with a bounce frequency

$$\omega_B = \left(\frac{e\, E_L k_L}{m_e}\right)^{\frac{1}{2}}, \tag{3.2}$$

where E_L is the electric amplitude of the wave and k_L is its wavenumber. Frequency modulation of the initial wave at $\omega = \omega_L$ then leads to sidebands at $\omega = \omega_L + \omega_B$. Smith and de la Noe argued that the process saturates at an amplitude corresponding to

$$\frac{\omega_B}{\omega_p} \cong \left(\frac{n_b}{n_e}\right)^{1/3} . \tag{3.3}$$

The frequency splitting could produce a split pair at $\omega_t = \omega_L \pm \omega_s$, corresponding to

$$\frac{\delta f}{f} = \frac{2\omega_s}{\omega_L} \cong \frac{2k_s v_s}{\omega_p} \cong \frac{2}{43}\frac{V_e}{v_\phi} \tag{3.5}$$

where $v_\phi = \omega_p/k_L$ is the phase speed of the Langmuir wave. However, to produce a triple burst one would need to invoke emission at w ω_L, e.g. due to induced scattering off ions, and then the splitting would be half that implied by (3.5), i.e. $\delta f/f \cong V_e/43v_\phi$.

If we assume $v_\phi \cong c/3$, as one would expect for a type III stream, then (3.5) implies $\delta f/f \quad V_e/7c$ which corresponds to $\delta f/f \quad 5 \times 10^{-3}$ for $T_e \cong 10^6$ K. This splitting is smaller than that observed, and the difficulty is exacerbated if one deletes the factor of two in (3.5). To overcome this difficulty Melrose and Sy (1971) and Yip (1973) suggested that the Langmuir waves are generated by an electron stream propagating at a speed corresponding to that implied by the drift rate of individual stria bursts. The subsequent recognition that stria bursts are part of type IIIb bursts suggests strongly that the exciting agency of the Langmuir waves is a stream of electrons with $v \cong c/3$. The splitting due to ion sound turbulence is then too small to account for the observed splitting.

. Another unsatisfactory feature of the mechanism is that it is difficult to account plausibly for triple bursts. It is true that one could invoke induced scattering off ions, as suggested above, but there is no reason to expect it to produce a line of comparable intensity to the other two. More important, one would expect a split pair burst to correspond to a triple burst with the central element missing, rather than the lowest frequency element as the observational data indicate.

4. Alternative Splitting Mechanisms for Stria Bursts

Here we propose two alternative splitting mechanisms for stria bursts. One is a fairly obvious modification of that suggested by Melrose and Sy (1971); it overcomes one but not the other of the difficulties just discussed with that earlier theory. The other mechanism seems highly favourable at first sight. Although it remains favourable, on closer examination some less appealing details emerge.

frequency turbulence, which may be ion sound, lower hybrid, ion cyclotron or some other form. For a wide range of $\underset{\sim}{k}$-values, coalescence of the initial Langmuir waves to form secondary Langmuir waves is possible. Again both up conversions and down conversions may occur, and hence we have secondary Langmuir waves with frequencies

$$\omega_{L'}(\underset{\sim}{k}_{L'}) = \omega_L(\underset{\sim}{k}) \pm \omega_T(\underset{\sim}{k}_T) \tag{4.2a}$$

$$\underset{\sim}{k}_{L'} = \underset{\sim}{k}_L \pm \underset{\sim}{k}_T , \tag{4.2b}$$

where T stands for low frequency turbulence.

The secondary Langmuir waves may produce transverse waves (with $k_t << k_L$) by coalescing with a second low frequency wave with $k_{T'} = |\underset{\sim}{k}_T \pm \underset{\sim}{k}_L|$. Assuming $k_T >> k_L$, for the sake of discussion, this requires $k_{T'} \cong k_T$ and hence $\omega_{T'} \cong \omega_T$. There are four possibilities. Denoting up and down conversion by u and d respectively, these four possibilitiesareuu, ud, du, dd. They lead to four possible final frequencies, $\omega_L \pm \omega_T \pm \omega_{T'}$, which reduce to three frequencies $\omega_L + 2\omega_T$, ω_L and $\omega_L - 2$ for $\omega_{T'} \cong \omega_T$.

A notable feature of this alternative mechanism is that a broad spectrum of the low frequency turbulence can contribute to **it**. In particular, lower hybrid waves propagating at an oblique angle to the magnetic field can contribute for parallel Langmuir waves.

Another attractive feature of the mechanism is that **it** appears capable of accounting naturally for single stria, split pair and triple bursts. As already discussed **a** triple burst may result when all four processes uu, ud, du and dd are allowed for $k_{T'} \cong k_T >> k_L$. However the final process dd is allowed only for $\omega_T + \omega_{T'} < \omega_L - \omega_p$, because otherwise **it** would lead to a frequency below the plasma frequency where transverse waves do not exist. In this case the lowest frequency element would be missing leaving a split pair burst. Inspection of the coalescence conditions for the processes uu and dd shows that they require $\underset{\sim}{k}_{T'} \cong - \underset{\sim}{k}_T$ for $k_T >> k_L >> k_t$, while the processes ud and du requires $\underset{\sim}{k}_{T'}$ $\underset{\sim}{k}_T$. Hence **if** the low frequency turbulence is anisotropic strongly favouring one direction, or more generally with wave angles

$k_s \cong k_L$. Assuming $k_s >> k_L^2/k_0$, we can account for a sufficiently large bf. However, the bandwidth of the lines cannot plausibly be less than $\Delta\omega \cong k_s v_s$, and for large k_s the bandwidth would exceed the frequency separation. Thus we have either $k_s \cong k_L$, when the frequency separation is too small, or $k_s >> k_L$ when the bnadwidth is too large. We also encounter difficulty in explaining the frequency separation in triple bursts. One has $\omega_1 - \omega_2 \neq \omega_2 - \omega_3$ in general, and hence even when a triplet is allowed $(k_s < k_0^2/k_L)$ one would not expect the spacings between the elements to be equal.

For lower hybrid waves the dispersion relation is not of the form (4.3) and the kinematics are significantly different than for ion sound waves. For $k_T \leq \Omega_e/V_e$ the frequency of lower hybrid waves is given approximately by cold plasma theory, with $\omega_{LH} \cong \Omega_e/43$ for $|\cos\theta| \lesssim 1/43$. At somewhat higher frequencies the relevant resonance is in the whistler mode at $\omega \cong \Omega_e|\cos\theta|$. For $k \geq \Omega_e/V_e$ a broader range of angles of propagation is allowed.

If the splitting is due to lower hybrid waves then we have

$$\frac{\delta f}{f} \cong \frac{2\omega_{LH}}{\omega_p} \cong \frac{2}{43}\,\frac{\Omega_e}{\omega_p} . \tag{4.7}$$

With a bandwidth $\Delta\omega \cong \omega_{LH}$ for these waves, the separation δf would be about twice the bandwidth Δf for stria ,bursts, as observed. The observed splitting gives $\delta f/f \cong 1/300$ and hence requires $\Omega_e/\omega_p \cong 1/14$. For example at $\omega_p/2\pi = 30$ MHz this implies a magnetic field $B \cong 0.7$ G, which is a reasonable value. For triple bursts to be possible the lowest frequency trace must be above the plasma frequency, and this requires

$$\frac{2}{43}\,\frac{\Omega_e}{\omega_p} < \frac{3}{2}\left(\frac{V_e}{v_\phi}\right)^2 . \tag{4.8}$$

For $v_\phi \cong c/3 \cong 30\, V_e$, (4.8) requires $\Omega_e/\omega_p \lesssim 1/30$. It is only for a slower stream or a hotter corona, say for $v_\phi \cong 20\, V_e$, that triple bursts could be observed.

This semiquantitative discussion suggests that the double coalescence involving lower hybrid waves offers a highly favourable starting at about the same frequency and separated in time by 1 to 2 seconds. They drift at a characteristic rate more commonly from lower to higher frequencies (reverse DPs) and sometimes from higher to lower frequencies (forward DPs). Some examples are shown in Figure 4.

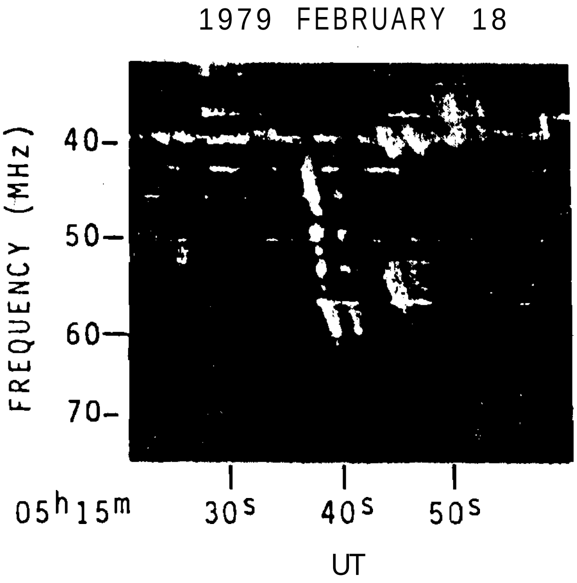
1979 FEBRUARY 18

Fig. 4. An example of a reverse DP in which the second trace is clearly shifted in time but not in frequency from the first trace (from Suzuki and Gary 1979).

2. *Occurrence*

DPs occur in decametric noise storms. They are restricted to frequencies $\lesssim 80$ MHz and are most common near the lowest frequencies observed ($\cong$ 25 MHz). These occur preferentially in storms near the central meridian (Møller Pedersen 1974).

3. *Drift Rate*

In individual storms the drift rate of DPs falls in a narrow range, and the mean value varies from storm to storm. Both reverse and forward DPs have about the same magnitude of the drift rate. At $f \cong 30$ MHz the drift rate is typically in the range 2 to 8 MHz s^{-1} which is about ten times that of type II bursts and about a third that of type III bursts at the same frequency.

4. The *Separation*

The characteristic time separation of 1 to 2 seconds is the most notable feature of DPs. The separation is at least predominantly in time rather than frequency, as illustrated in Figure 4.

5. *Bandwidth*

The instantaneous bandwidth Δf varies from 0.2 MHz to 2 MHz with a mean around 0.5 MHz for DPs at $f \cong 30$ MHz.

6. *Duration*

Individual traces of a DP persist from 0.5 to 4 seconds and extend

Fig. 5. An example of a forward DP superimposed on a faint type III burst (de la Noe and Moller Pedersen 1971).

Smith and Mangeney (1978) distinguished between sharp DPs with bandwidths $\Delta f \lesssim 0.4$ MHz, and diffuse DPs with $\Delta f \cong 1$ MHz. Ellis (1969) noted cases of DPs with a third faint trace midway between the other two, and de la Noe and Møller-Pedersen (1971) reported single traces which have properties otherwise typical of an element of a DP.

6. Existing Interpretations for Drift Pair Bursts

In the first discussion of DPs Roberts (1958) made several suggestions concerning their interpretation. He concentrated on two points: the time separation and the prevalence of reverse drifts. His suggestion for the time separation is that it is due to an echo, with the later trace being an echo of the earlier trace. For the reverse drifts he noted two possibilities: an exciting agency either propagating inwards towards higher densities, or propagating outwards and encountering a "hill" in the electron density. Much of the subsequent discussion of the interpretation of DPs has involved criticism of various aspects of Roberts' suggestions.

ray should be broadened due to coronal scattering (Riddle 1974), (ii) that the delay should increase with frequency, (iii) that the later (reflected) trace should lie closer to the central meridian than the earlier trace (Stewart 1977, de la Noe and Gergely 1977) and (iv) that the polarization is inconsistent with second harmonic plasma emission. Howevsr, all these criticisms apply to the specific form of the echo suggested by Roberts, and do not necessarily rule out any model based on an echo.

The pairing mechanism suggested by MPSM is also open to criticism. It is true that there are two correlated sources, but it is not obvious that a distant observer would see two traces. Emission at the fundamental is strongly refracted into the direction of decreasing electron density. In the coronal streamer model this implies strong refraction towards the direction perpendicular to the axis of the streamer. Hence one would expect radiation confined to a small range of angles about $\psi = \pi/2$, where ψ is the angle between the emerging ray and the streamer axis. Further refractions and/or reflections are required to account for two parallel rays being directed towards the Earth. A further criticism is that one might expect the two rays to be oppositely polarized if they are both due to o-mode emission (Suzuki and Gary 1979). (Suzuki and Gary remarked on mode conversion as the more distant ray crosses the axis of the streamer, but it is not possible for this ray to propagate back towards the axis of the streamer because of the increasing density gradient in this direction.)

The view adopted here is that the echo hypothesis seems more plausible than two correlated sources. One is then left with the problem of identifying a source structure which allows two parallel rays to emerge with a relative time delay of 1 to 2 seconds. A single source inside an overdense structure like that envisaged by MPSM and emitting at the fundamental can lead to radiation escaping nearly perpendicular to the axis of the structure, and subsequent refraction and/or reflection might lead to two emerging parallel rays. This idea is outlined further in Section 8 below.

The Exciting Agency

Roberts (1958) made no specific suggestion for the exciting agency

The frequency range over which S bursts extend is larger than can plausibly be explained by a locally overdense region, and the inferred small size of S burst sources (≅ (1800 km)^3 from estimates below) would have to be ever smaller by a factor 10^3 to 30^3 creating difficulties similar to that in a model for type I bursts (Melrose 1980b).

7. S Bursts

Ellis (1969) identified a class of fine structure bursts which he called fast drift storm bursts by analogy with a variant of type I emission reported by Elgarøy (1961). McConnell (1980, 1981, 1982) made a systematic study of these bursts and renamed them S bursts by analogy with a class of Jovian bursts. The following summary is based on McConnell's (1981) thesis.

1. *Appearance*

On a dynamic spectrum S bursts form a fine trace drifting usually from higher to lower frequencies at about the same rate as drift pairs (Figure 6). They often occur in groups of up to several per second,

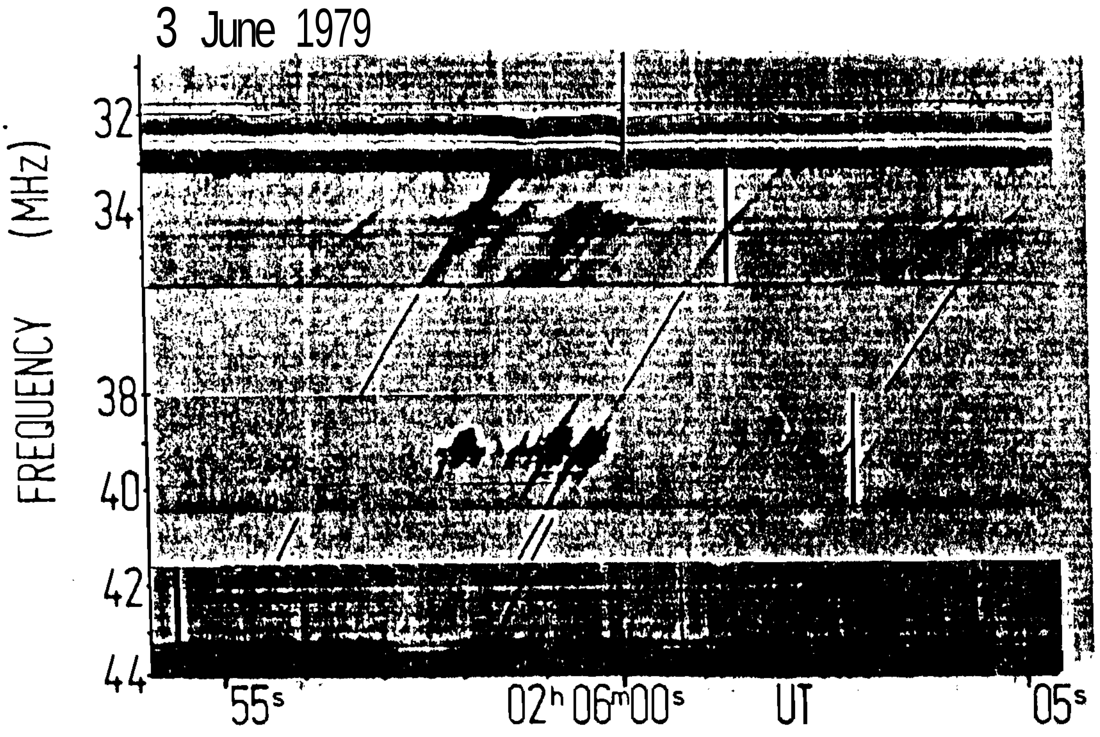

Fig. 6. An example of a sequence of S bursts (McConnell 1982).

density 5×10^{-21} W m^{-2} Hz^{-1} at f ≅ 40 MHz. No heliograph data are available on the sizes (due to the persistence time of the bursts at fixed frequency being much shorter than the integration time of the heliograph).

8. *Fringes*

One to two percent of S bursts observed in one storm (2-3 June 1979) showed fine structure in the form of fringes (McConnell and Ellis 1980), i.e. the narrow trace is broken into fringes rather like a type IIIb burst on a different scale (Figure 7). The fringes had a narrow bandwidth $\Delta f/f$ 3×10^{-4} and a characteristic frequency separation varying from 6f ≅ 60 kHz at f ≅ 30 MHz to 6f ≅ 500 kHz at f ≅ 150 MHz.

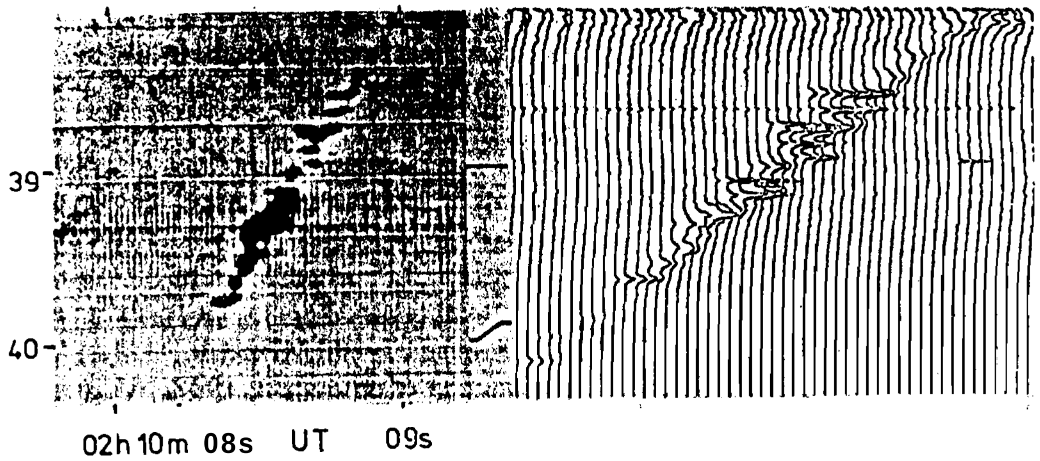

Fig. 7. Fringes in S bursts (McConnell and Ellis 1981).

Are S Bursts a Variant of DPs?

We assume below that S bursts are variants of DPs. The main argument for this is their common drift-rate and their association in the same storms. Another argument, which however requires further investigation from an observational viewpoint, is that there appears to be a range of variants from ordinary DPs to S bursts. For example, Roberts (1958) referred to negative drift bursts which included a high proportion of single bursts and some triple bursts, and MPSM referred to sharp DPs, i.e. narrowbanded and featureless, which drift over a much larger frequency range than diffuse DPs, almost always with a forward

$$\frac{\Delta f_n}{f} = \frac{d}{2L_N}, \qquad \frac{\Delta f_L}{L} = \frac{3}{2}\left(\frac{V_e}{v_\phi}\right)^2 \frac{\Delta v_\phi}{v_\phi}, \tag{7.2a,b}$$

$$\Delta t_E = \frac{L}{v}, \qquad \Delta t_t = \frac{d}{\mu c}, \tag{7.2c,d}$$

with $\mu = (1 - f_p^2/f^2)^{\frac{1}{2}}$.

McConnell (1981) showed that S bursts were consistent with a constant velocity exciter moving through a 1 × **Newkirk** (1961) corona emitting at the fundamental plasma frequency with a speed v in the range

$$0.07 \lesssim v/c \lesssim 0.10 . \tag{7.3}$$

With this interpretation he found that the limits on the size of the source region are consistent with a roughly spherical source with **linear** dimensions $\lesssim$ 1800 km. Imagining the exciter to be a stream of electrons with velocity dispersion Δv, McConnell argued that the fact that the source size is maintained over a propagation distance ≅ 10^5 km implies

$$\frac{\Delta v}{v} \cong 0.015 . \tag{7.4}$$

It-might be remarked that in order to explain the smallest bandwidths observed in fringes one requires $\Delta f_L/f \lesssim 3 \times 10^{-4}$, which with **(7.2b)**, with $v = v_\phi$ and $\Delta v = \Delta v_\phi$, and (7.3) is **compatible** with the very small value of $\Delta v/v$ implied by (7.4). Such an extremely monoenergetic stream is similar to that required by Smith and de la **Noë** (1976) in their theory for stria bursts.

Amongst the other contributions to the thickness of the traces, the decay time of the Langmuir waves seems to require an explanation. A persistence time less than 0.1 is incompatible with collisional damping. The Langmuir waves could be reabsorbed by the stream, as in some theories for type **III** bursts, **e.g.** Magelssen and **Smith (1977)**, Takakura and Shibahashi (19**76)**, **Grognard** (1982). **Al**ternatively the conversion process could involve low frequency turbulence with a decay time much shorter than that of the Langmuir waves so that the latter is not relevant; a suggestion along these lines was made in a somewhat different scatter-free, the observed bandwidth Δf can be much less than Δf_L. It is then not necessarily inconsistent to assume that the exciting agency is a stream of electrons with a moderate velocity spread. The underlying reason for this is simply that refraction can cause different frequencies emitted at a single point to emerge along different ray paths only one of which may intersect the observer.

8. Towards an Alternative Model for Drift Pair Bursts

In attempting to formulate an alternative model (e.g. to that of MPSM) for DPs we will proceed as far as possible by drawing inferences from the data and relying on existing ideas concerning possible coronal structures. However there are two particular assumptions which are only partly justified by rational argument and which are made partly from personal preference. We regard these two assumptions as working hypotheses:-

A. The two traces of a DP are from a single source and are due to two rays emerging along different paths (echo hypothesis).

B. S bursts are variants of DPs; their exciting agencies are similar and the differences in their properties are due to differences in the structure and/or location of the source.

There are two inferences we can draw from the most recent observational data (Suzuki and Gary 1979). First, the polarization implies fundamental plasma emission. Second, the overlapping positions of the apparent sources suggests that the source is in a coronal duct of the form invoked to account for several properties of type III bursts (Duncan 1979, Poquérusse and Bougeret 1981).

Clearly the echo hypothesis is incompatible with fundamental plasma emission unless the source is in a locally overdense region. Only then can rays escape in different directions and propagate over ray paths separated by distances of order a light second ($\approxeq$ 0.4 $R_\odot$). Thus we are forced by hypothesis A to assume that the source is in a locally overdense structure within a coronal duct.

Our working hypothesis B requires that the source model be capable of allowing the rays to escape directly, i.e. without reflection, for

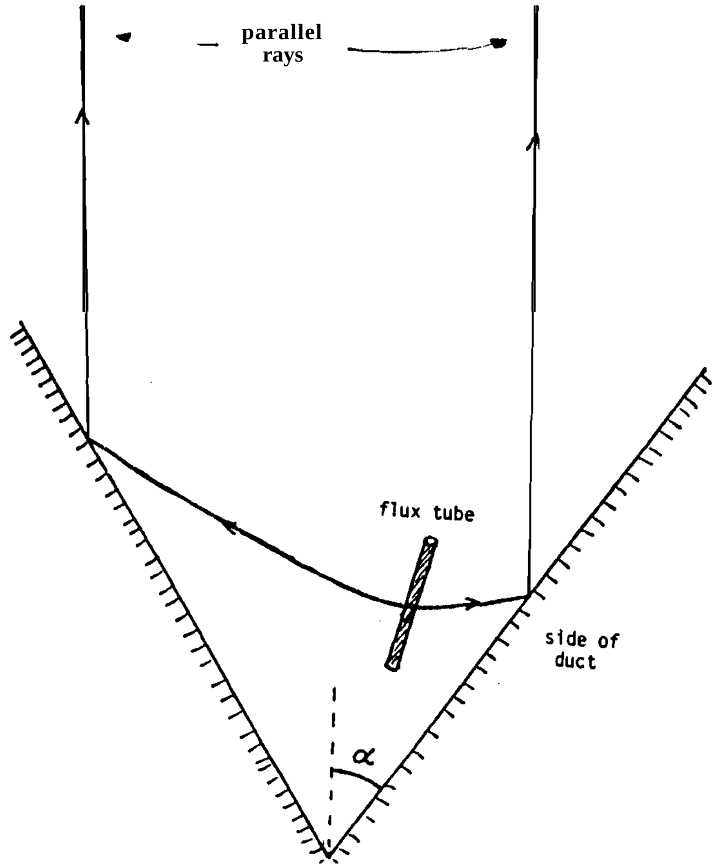

Fig. 8. Idealized model for the source region in a relatively overdense flux tube inside an underdense duct bordered by conical walls. Schematic ray paths for emerging parallel rays are indicated.

Fundamental plasma radiation is assumed to be generated over the cross section of the flux tube by an exciter which moves up (forward DP) or down (reverse DP) the flux tube. At any given height there is a range of plasma frequencies across the flux tube and hence a range of frequencies is emitted from each height.

Escape of Two Parallel Rays

The essential requirements for this model to account for the basic properties of DPs is that it produce two parallel rays over a small range of angles relative to the axis of the conical duct, with a delay of 1 to 2 seconds between these rays. To see how this might occur let us start by considering a flux tube at the centre of the duct with its axis parallel to that of the duct.

Radiation is generated over a range of frequencies at any given height in the flux tube and is refracted strongly towards the normal to the flux tube as it escapes. Just outside the flux tube the emerging

The important effects in this simple model are (i) the source (flux tube) produces a range of frequencies at any given point with all the rays at large angles ($\psi_0 \cong 90^\circ$) to the axis of the duct, (ii) the ray angle is reduced by both refraction and reflection off the walls of the duct, (iii) the rays escaping in any given direction include one from the near side and one from the far side of the duct at slightly different frequencies. None of these effects is altered in any essential way when the flux tube is not at the centre of the duct or when its axis is at a modest angle $< a$ to the axis of the duct.

There are two contributions to the time delay between the two rays. One is due to the flux tube being off centre leading to ray paths of different lengths to the reflection points on either side of the duct. The other is due to the difference in the path lengths from the observer to the near and to the far reflection point. Each of these leads to a delay which is a fraction of the light propagation time across the duct. A light travel time of several seconds is consistent with the observed sizes of DP sources. Indeed provided that the rays emerging from opposite sides of the flux tube are both reflected from the walls of the duct one would expect two parallel emerging rays. The larger the tilt of the axis of the flux tube to the axis of the duct, and the larger the viewing angle relative to the axis of the duct, the larger the frequency separation between the two rays. It is tempting to identify the frequency differences sometimes reported (e.g. Ellis 1969) between the two traces to be due to this effect. In general however this frequency difference would be small, e.g. $\delta f/f \cong 0.1 - 0.2$ for angles $\cong 10^\circ$ between the two axes or between the line of sight and the axis of the duct.

S Bursts

We have already suggested that the broader bandwidths of DPs compared with S bursts is due to the rays for DPs experiencing reflections. By implication an S burst would correspond to the same phenomenon as a DP observed without reflection. For example, consider a flux tube near the far wall of the duct and with its axis nearly parallel to the wall. Then rays emerge into the duct at an angle ψ_0 ■ $90^\circ - a$ to the axis of the duct. These rays can escape without reflection provided we have

$$\psi_\infty = \text{arc}\,\sin(\mu_0 \cos \alpha) < \alpha \,, \qquad (8.5)$$

For stria - type IIIb bursts the two exciting agencies are required: one for the Langmuir waves and one for the lower hybrid waves. We have assumed implicitly that the Langmuir waves are generated by a type III electron stream, and that the level of these waves is too low to produce observable emission except when the regions of lower hybrid turbulence are encountered. The source of the lower hybrid waves is evidently some pre-existing coronal structure which is subject to an instability producing the waves. Thus in the case of stria - type IIIb bursts we have identified the emission mechanism and partly identified the existing agency, but we have not identified the coronal structures required to produce the stria.

For drift pair - S bursts we have concentrated on the coronal structure. The exciting agency is problematical. Its speed is not any of the characteristic speeds in the corona. A stream of electrons of energy a few keV or a whistler wave soliton seem the only possible interpretations. Assuming the former and setting aside the problem of how these electrons might be accelerated or injected into the flux tube, an important question remains unanswered: why does the stream appear not to disperse? The extremely narrow bandwidth of S bursts can be partly explained as suggested in Section 7, but even with that explanation the short duration of the bursts remains a mystery. The alternative of a whistlersoliton raises even more unsolved problems. Also we have not discussed the details of the emission mechanism for drift pair - S bursts. Perhaps the emission mechanism involves low frequency waves, as for stria - type IIIb bursts, and that the short duration is characteristic of the persistence time of the low frequency waves. However this is mere speculation: neither the exciting agency nor the details of the emission mechanism have been identified adequately for drift pair - S bursts.

In conclusion, the highly specific character of fine structure required highly specific interpretations which may shed light on more general problems in solar radiophysics. Clearly it is desirable to develop and explore the ideas introduced here in further detail in the hope that they will lead not only to a better understanding of the fine structures themselves but lead to a deeper understanding of plasma emission and of coronal physics.

Jaeger, J.C., and Westfold, K.C.: 1950, Australian J. Sci. Res., A3, 376.

Kuijpers, J.: 1975, Solar Phys., 44, 173.

Kuijpers, J.: 1980, in M.R. Kundu and T.E. Gergely (eds) Radio Physics of the Sun, D. Reidel (Dordrecht) p. 341.

Kuijpers, J.: 1981, Astron. Astrophys., 103, 331.

Magelssen, G.R., and Smith, D.F.: 1977, Solar Phys., 55, 221.

McConnell, D.: 1980, Proc. Astron. Soc. Australia, 4, 64.

McConnell, D.: 1981, dissertation, University of Tasmania.

McConnell, D.: 1982, Solar Phys., 78, 253.

McConnell, D., and Ellis, G.R.A.: 1981, Solar Phys., 69, 161.

McCulloch, P.M., and Ellis, G.R.A.: 1977, Izv. Vyssh. Uchebn. Zaved. Radiofizika, 20, 1413.

McLean, D.J.: 1969, Proc. Astron. Soc. Australia, 1, 188.

Melrose, D.B.: 1980a, Plasma Astrophysics, Gordon and Breach (New York).

Melrose, D.B.: 1980b, Solar Phys., 67, 357.

Melrose, D.B. and Sy, W.: 1971, Proc. Astron. Soc. Australia, 2, 56.

Mercier, C.: 1975, Solar Phys., 45, 169.

Møller Pedersen, B.: 1974, Astron. Astrophys., 37, 163.

Møller Pedersen, B., Smith, R.A., and Mangeney, A.: 1978, Astron. Astrophys., 70, 801.

Newkirk, G.: 1961, Astrophys. J., 135, 983.

Poquérusse, M., and Bougeret, J.L.: 1981, Astron. Astrophys., 97, 36.

Riddle, A.C.: 1974, Solar Phys., 35, 153.

Roberts, J.A.: 1958, Aust. J. Phys., 11, 215.

Sawant, H.S.: 1982, these Proceedings.

Shapiro, V.D.: 1963, Soviet Phys. JETP, 17, 416.

Shastry, Ch.V.: 1972, Astrophys. Lett., 11, 47.

Slottje, C.: 1981 Atlas of Fine Structures of Dynamic Spectra of Solar Type IV-dm and Some Type II Radio Bursts, the Astronomical Institute at Utrecht.

Smith, R.A., and de la Noe, J.: 1976, Astrophys. J., 207, 605.

Stewart, R.T.: 1977, Izv. Vyssh. Uchebn. Zaved. Radiofizika, 20, 1338.

Stewart, R.T., and Vorpahl, J.: 1977, Solar.Phys., 55, 111.

Suzuki, S., and Gary, D.E.: 1979, Proc. Astron. Soc. Australia, 3, 379.

Suzuki, S., and Sheridan, K.V.: 1977, Izv. Vyssh. Uchebn. Zaved. Radiofizika, 20, 1432.