THE BRIGHTNESS TEMPERATURES OF SOLAR TYPE III BURSTS

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Abstract. There is a characteristic maximum brightness temperature $T_B \approx 10^{15}$ K for type III solar radio bursts in the solar wind. The suggestion is explored that the maximum observed values of T_B may be attributed to saturation of the processes involved in the plasma emission. The processes leading to fundamental and second harmonic emission saturate when T_B is approximately equal to the effective temperature T_L of the Langmuir waves. The expected maximum value of T_B is estimated for this saturation model in two ways: from the growth rate for the beam instability, and from the maximum amplitude of the observed Langmuir turbulence. The agreement with the observed values is satisfactory in view of the uncertainties in the estimates (a) of the intrinsic brightness temperature from the observed brightness temperature, (b) of the actual growth rate of the beam instability, which must be driven by local, transient features (that are unobservable using available instruments) in the electron distribution, and (c) in the **k**-space volume filled by the Langmuir waves, and this is consistent with the observational data on two well-studied events at the orbit of the Earth and with statistical data for events over a range of radial distances from the Sun.

1. Introduction

The brightness temperature T_B is an important indicator of whether observed emission is classified as (i) thermal, (ii) nonthermal and incoherent, or (iii) coherent. For thermal emission one has $T_B \leq T$, where T is the temperature of the radiating particles, and for nonthermal incoherent emission one has $T_B \lesssim \varepsilon$ where ε is a typical energy of the radiating particles. A higher brightness temperature ($T_B \gg \varepsilon$) indicates that the emission process is coherent. Examples of coherent emission in astrophysics include: 'astronomical masers' which are interstellar or circumstellar clouds in molecular lines, notably of OH and of H_2O; 'plasma emission' from the solar corona and the interplanetary medium, notably in type III solar radio bursts; cyclotron maser emission from the planets, notably the Earth's AKR and Jupiter's DAM, and analogous emission from the Sun in microwave 'spike' bursts, and from some flare stars; and the radio emission from pulsars. A satisfactory theory for a coherent emission process should be capable of accounting not only for the qualitative features of the observed emission but also for the observed values of T_B. Coherent emission requires a 'pump' for maser emission or, equivalently, a driving mechanism for an instability of some form. One should be able to estimate the maximum value of T_B from the condition that the instability saturates. Saturation of molecular line masers has been invoked with some success for astronomical masers (e.g., Elitzur, 1982), but the detailed processes involved are not relevant for saturation in the other examples cited. Ideas on saturation of cyclotron masers (Melrose and Dulk, 1982) provide plausible estimates for the maximum values of T_B observed for the planetary and solar emissions. The question addressed in the present paper

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concerns the possible interpretation of the observed values of T_B for type III bursts due to saturation of plasma emission.

Most sources of plasma emission and if cyclotron maser emission are sporadic, with the emission involving individual bursts that are not always resolved from one another. These bursts can have a range of brightness temperatures T_B; nevertheless for each source one can usually identify a characteristic maximum value of T_B. A semi-quantitative theory of the coherent emission process should account at least for the characteristic maximum values of T_B. For cyclotron masers the condition for saturation is that the energy density in the waves (whose properties are predicted by the maser theory) approach the free energy available to drive the instability (Melrose and Dulk, 1982). Plasma emission is a multistage process and the maximum value of T_B results when each stage saturates.

One way of estimating the saturation value of T_B is based on an assumed knowledge of the distribution function of the particles that drive the instability. In the cases where the particle distributions can be measured directly (the Earth's AKR and type III bursts in the interplanetary medium), the measured distributions do appear to be weakly unstable to the respective instabilities, as simple theory requires. However, the time-scales over which particle distributions can be measured are much longer than the time-scales required for the relevant instability to saturate. This presents a serious difficulty because the actual features in the distribution that drive the instability cannot survive for much longer than several growth times for the instability and, hence, all measured particle distributions must be essentially of the relaxed distributions. The measured distribution may be marginally unstable, as appears to be the case, but the important features driving the instability are necessarily washed out over the relatively long time-scale for measurement of the distribution. Thus use of the measured distributions may lead to a serious underestimate of the maximum value of T_B to be expected. This point has been discussed (a) for cyclotron maser emission from the Sun by Melrose and Dulk (1984) and by Winglee, Dulk, and Pritchett (1988), (b) for cyclotron maser emission from the planets by Melrose (1986), and (c) for type III bursts by Melrose and Goldman (1987). A realistic estimate of the expected maximum value of T_B must rely on some indirect argument for the transient features in the distribution of particles that actually drives the instability.

For plasma emission there is an independent alternative way of predicting the expected maximum value of T_B from observational, *in situ* data. The measured electric amplitudes of the Langmuir waves allow one to calculate their energy density W_L and from this one may estimate their effective temperature T_L. As argued below, saturation of the emission process occurs for $T_B = T_L$. However, one requires a knowledge of the $\mathbf{k}$-space volume filled by the Langmuir waves to infer T_L from W_L. This $\mathbf{k}$-space volume can be inferred only by indirect argument and is quite uncertain.

Thus both methods for predicting the maximum value of T_B from the available observational data (on the electron distribution and on the Langmuir waves, respectively) are subject to considerable uncertainty. These uncertainties are compounded by another uncertainty in relating the intrinsic brightness temperature T_{Bi}

at the source of the observed value T_{Bo}. Scattering of the radiation off coronal density fluctuations increases the apparent size of the source, and the apparent brightness temperature is reduced from the intrinsic value at the source by the same factor as the apparent area is increased from the intrinsic area. This factor can be very large for fundamental sources due to the following effect, whose implications have only been recognized recently (Melrose and Dulk, 1988). In the absence of scattering, refraction causes a source to have an apparent area that is smaller than its intrinsic area by a factor $\approx \mu^2$, where μ is the refractive index at the source. Thus, for a fundamental source to have an apparent area comparable to its actual area, scattering must have increased its apparent area by a factor $\approx \mu^{-2}$, which is $\gtrsim 10^2$ for $\mu \lesssim 10^{-1}$. It follows that the observed values of T_{Bo} are likely to be less than the intrinsic values T_{Bi} by a factor of at least 10^2.

In Section 2 relevant data relating to the brightness temperatures of type III bursts are reviewed briefly, and the model used here in their interpretation in terms of saturated processes is summarized in Section 3. An indirect argument that enables one to estimate the actual growth rate for the Langmuir waves in a type III event is given in Section 4. The expected maximum values of T_B are compared with the observed values in Section 5, the conditions for saturation are discussed in Section 6 and the conclusions are summarized in Section 7.

2. Observed Brightness Temperatures of Type III Bursts

An estimate of the brightness temperature of a source requires a knowledge of the specific intensity of the radiation, that is, of the flux density and also of the angular size of the emitting region. The size of a source in the solar corona can be measured directly with a radioheliograph. However, radioheliographs have been available only at several specific frequencies, and reliable estimates of T_B are available only at some of these frequencies, specifically 169, 80, and 43 MHz. Bursts in the interplanetary medium are very large, and can be resolved through modulation of the signal received by a dipole on a rotating spacecraft. An uncertainty arises in connection with the possibility that a source consists of several unresolved bright spots; then the actual brightness temperature of the spots (which is the relevant to interpret theoretically) is higher than the average brightness temperature measured. Uncertainties associated with such unresolved structures in the source are reduced by considering only the brightest bursts. A theory for saturation of the coherent emission process must be capable of accounting at least for the brightest bursts observed.

Observational data on the brightness temperatures of type III bursts in the solar corona have been reviewed by Suzuki and Dulk (1985), cf. also Suzuki and Gary (1979) and Dulk, Suzuki, and Sheridan (1984), and data on the brightness temperatures of bursts in the interplanetary medium have been presented by Dulk, Steinberg, and Hoang (1984) and Steinberg *et al.* (1984). The average brightness temperatures have been plotted by Dulk, Steinberg, and Hoang (1984). The average value of T_B varies with frequency, having a maximum of $\approx 10^{14}$ K at a few megahertz. The highest brightness temperatures are about a factor of ten greater than the average values. Several representative points are shown in Figure 1, which illustrates how the maximum value varies with frequency. The highest brightness temperatures ($\gtrsim 10^{15}$ K) appear to occur in the range 1–10 MHz (perhaps closer to 1 MHz than to 10 MHz; G. A. Dulk, private communi-

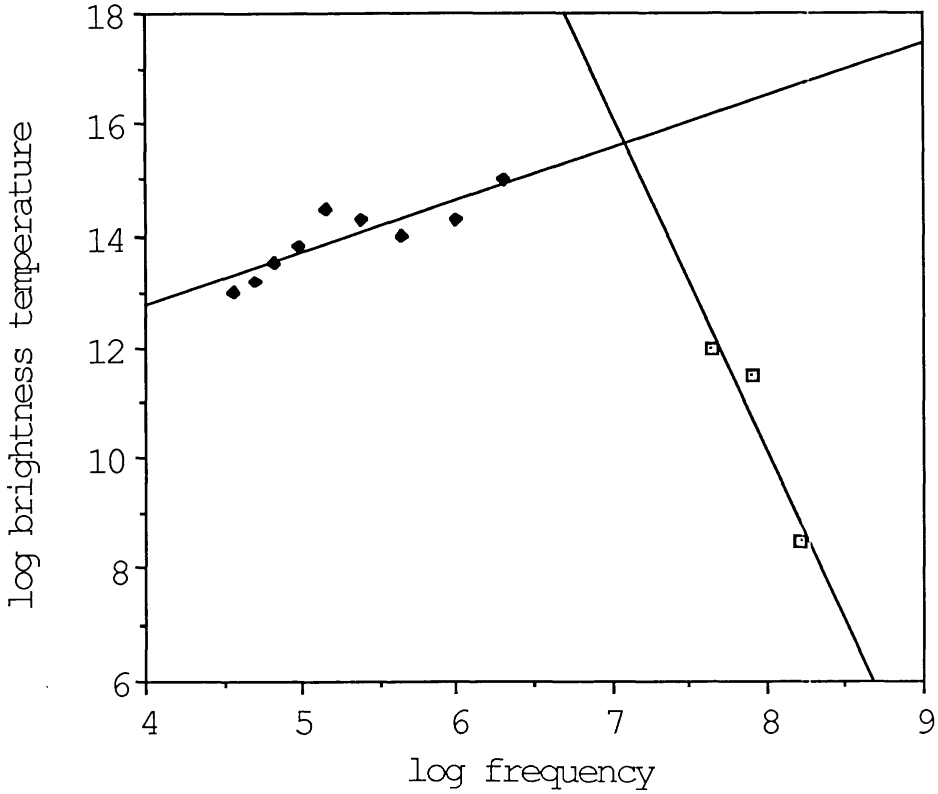

Fig. 1. The log of the maximum brightness temperature T_B in kelvins is plotted as a function of the log of the frequency of observation f in hertz. Straight lines are drawn through the points corresponding to bursts in the corona ($f \gtrsim 10^7$ Hz) and in the interplanetary medium ($f \lesssim 10^6$ Hz).

cation) where there are few observations. The maximum brightness temperatures remain approximately constant or decrease slightly with decreasing frequency for bursts in the interplanetary medium.

It should be emphasized that the observed brightness temperatures T_{Bo} provide only a lower limit to the intrinsic brightness temperature T_{Bi} at the source, and it is T_{Bi} that must be explained by the theory. As remarked in the Introduction, the intrinsic brightness temperature at the source is expected to be mch larger than the apparent brightness temperature if the source is at the fundamental, as is the case for the relevant data in Figure 1 (Dulk, Suzuki, and Sheridan, 1984). T_{Bi} may be estimated from T_{Bo} by multiplying by an appropriate correction factor. This factor is poorly determined and is most probably $\gtrsim 10^2$. It follows that the intrinsic values that the theory needs to explain are $T_{Bi} \gtrsim 10^{17}$ K.

3. A Model for Type III Emission

'Plasma emission' is a multistage emission process involving generation of Langmuir waves and then emission of transverse waves at the fundamental $\omega \approx \omega_p$ and the second harmonic $\omega \approx 2\omega_p$ due to nonlinear processes in the plasma. In virtually all models for type III bursts the generation of the Langmuir waves is attributed to a beam instability, but there is a variety of different possibilities for the details of the conversion processes into transverse waves. Here it is assumed that these processes are dominated by the effect of low-frequency waves, e.g., ion sound waves. These waves can coalesce with the Langmuir waves to produce both the fundamental transverse waves and also the secondary Langmuir waves that are required for second harmonic emission. The possible role of ion sound waves has been discussed in the reviews by Melrose (1980a, b), and described in more detail by Melrose (1983). The model has been applied to type III bursts by Melrose, Dulk, and Cairns (1986), and to emission from the bow shock by Cairns and Melrose (1985) and Cairns (1988). The main arguments in favor of this model are (i) that it overcomes some serious difficulties with other models by enhancing the efficiency of generation of the transverse waves from the Langmuir waves, and (ii) that there is direct evidence for the presence of ion sound waves in the interplanetary medium most of the time (Gurnett *et al.*, 1979), and specifically in association with type III bursts in the interplanetary medium (Lin *et al.*, 1986).

The assumption that the conversion processes for Langmuir waves into transverse waves are dominated by the effect of ion sound waves greatly facilitates saturation of the processes. Melrose, Dulk, and Cairns (1986) discussed the conditions under which such saturation occurs, and found that only a modest level of ion sound waves is needed. As saturation is approached the wave actions tend to equalize (Melrose, 1980a, b), and the brightness (or effective) temperature is given by the product of the wave action and the wave frequency. This implies that at saturation the brightness temperature of the fundamental transverse waves should be equal to the effective temperature of the Langmuir waves. In principle this allows one to relate the observed brightness temperature T_B to the properties of the stream or to the observed level of the Langmuir turbulence.

The free energy density W_F in a beam of electrons that is available for the growth of the Langmuir waves has been estimated by Melrose, Dulk, and Cairns (1986) and by Melrose and Goldman (1987). The value adopted by Melrose and Goldman (1987) is

$$W_F \approx \tfrac{1}{2} m v_b^2 (\Delta v)^2 \, \frac{\partial f(v_\parallel)}{\partial v_\parallel} \,, \tag{1}$$

where v_b is the beam velocity, Δv is the spread in velocity, and $f(v_\parallel)$ is the one-dimensional distribution function, that is, the distribution function integrated over the perpendicular components of velocity. The free energy (1) may be written in terms of the growth rate γ for the beam instability:

$$W_F \approx \frac{\gamma}{\omega_p} \, \frac{n_e m (\Delta v)^2}{2\pi} \,, \tag{2}$$

with

$$\gamma = \frac{\pi \omega_p v_b^2}{n_e} \, \frac{\partial f(v_\parallel)}{\partial v_\parallel} \,. \tag{3}$$

Saturation of the beam instability occurs when the free energy has all been converted into energy in Langmuir waves. Let us assume that the Langmuir waves are confined to a range Δv_ϕ of phase speeds about a phase speed v_ϕ, and to a range $\Delta\Omega$ of solid angle about the beam axis. For simplicity, let us further assume that the level of waves is uniform within the volume of **k**-space defined by these ranges, and let this level be described by the effective temperature T_L. The energy density W_L in the Langmuir waves is then related to their effective temperature by

$$W_L = \left(\frac{\omega_p}{2\pi v_\phi}\right)^3 \left(\frac{\Delta v_\phi}{v_\phi}\right) \Delta\Omega T_L \,, \tag{4}$$

where Boltzmann's constant has been set equal to unity. When saturation of the conversion processes into transverse waves occurs, the resulting brightness temperatures are given by (Melrose, 1980a, b)

$$T_B = T_L \,. \tag{5}$$

There is a factor of two ($T_B = 2T_L$) for the second harmonic, but this is ignored in the following discussion which refers primarily to the fundamental. The implied value of T_B may then be determined from (1) or (2) and (4) by setting $W_L = W_F$. If we further assume $v_\phi = v_b$ and $\Delta v_\phi = \Delta v$, the resulting value is

$$T_B = \frac{\frac{1}{2} m v_b^2}{\pi\Delta\Omega} \frac{\gamma}{\omega_p} \frac{\Delta v}{v_b} n_e \left(\frac{2\pi v_b}{\omega_p}\right)^3 . \tag{6}$$

There is an alternative way of estimating the saturation value of $T_B = T_L$ from the observations. This involves using the observed value of the electric field $\mathbf{E}$ to estimate $W_L = \varepsilon_0 |\mathbf{E}|^2$ in place of $W_L = W_F$. This estimate gives

$$T_B = \frac{\varepsilon_0 |\mathbf{E}|^2_{\max}}{\Delta\Omega} \left(\frac{2\pi v_\phi}{\omega_p}\right)^3 \left(\frac{v_\phi}{\Delta v_\phi}\right) . \tag{7}$$

The maximum observed values of $|\mathbf{E}|_{\max}$ should be inserted in (7) to estimate the maximum value of T_B.

4. Estimation of the Growth Rate

Although observational data are available on the value of $\partial f(v_\parallel)/\partial v_\parallel$ for selected type III events (Lin *et al.*, 1986), these values cannot be used to estimate the growth rate γ in (6). The reason is that the time-scales for growth of the waves and saturation of the instability are much shorter than the time required to measure $\partial f(v_\parallel)/\partial v_\parallel$. As a consequence the measured distribution function must describe the relaxed value of $\partial f(v_\parallel)/\partial v_\parallel$, that is, the value after quasi-linear relaxation has occurred. The actual value of $\partial f(v_\parallel)/\partial v_\parallel$ that drives the instability cannot persist for long enough to be measured directly, and it must be inferred indirectly. The following arguments allow one to place a limit on the appropriate value of γ to insert in (6).

Melrose and Goldman (1987) argued that when the growth rate (3) is estimated for the observed distributions of electrons it is too small to overcome an effective damping rate due to the presence of density fluctuations. This effective damping is due to diffusion of the Langmuir waves in angle, i.e., scattering of Langmuir waves out of the range of solid angles where growth is effective. The diffusion coefficient D_θ was estimated by Muschietti, Goldman, and Newman (1985); for a relative level $\delta n/n$ of fluctuations at a wavenumber k_S they found

$$D_\theta = \frac{\pi}{12}\frac{\omega_p}{(k_L\lambda_D)^2}\frac{k_S}{k_L}\left(\frac{\delta n}{n}\right)^2, \tag{8}$$

where $k_L = \omega_p/v_b$ is the wavenumber of the Langmuir waves. Thus there is a threshold condition for growth of the Langmuir waves. To within a numerical factor (set equal to unity here) one requires

$$\gamma > D_\theta \tag{9}$$

in order for the beam instability to develop at all.

It follows that the growth rate must be much larger than implied by the measured value of $\partial f(v_\parallel)/\partial v_\parallel$. In order to infer the growth and, hence, the expected maximum value of T_B, one may proceed as follows. Estimate the value of D_θ from observations, and insert the resulting value into (6). This then provides a lower limit to the expected value of T_B when saturation occurs. Melrose and Goldman (1987) estimated $D_\theta \approx 10^2$ s.

The required large growth rate of Langmuir waves implies that there must be localized peaks in the velocity distribution, that is, sharp peaks in $f(v_\parallel)$ that arise in spatially-localized regions. It is appropriate to consider the likely properties of such peaks in order to infer the likely value of the solid angle $\Delta\Omega$ that appears in both (6) and (7). Such peaks can arise, perhaps in a quasi-periodic manner, due to fractionation of the electrons, that is, as a result of the faster electrons outpacing the slower electrons (Melrose and Goldman, 1987). A peak has a range Δv which becomes narrower as time evolves. In such a localized peak one has

$$\partial f(v_\parallel)/\partial v_\parallel \sim n_b/(\Delta v)^2\,, \tag{10}$$

where n_b is the number density in the beam. As Δv decreases due to the increasing fractionation, (10) implies that $\partial f(v_\parallel)/\partial v_\parallel$ increases and, hence, the growth rate increases. This continues until the threshold condition (9) is exceeded and the Langmuir waves grow. This model provides a natural explanation for the observed 'clumpy' or 'spiky' distribution of the Langmuir waves (Gurnett and Anderson, 1977; Gurnett *et al.*, 1978; Lin *et al.*, 1981).

The parameter $\Delta\Omega = \pi\delta\theta^2$ is the range of solid angles filled by the Langmuir waves, where $\delta\theta$ is the angle about the streaming direction to which the waves are confined. The parameter $\delta\theta$ cannot be predicted confidently from simple theory. One could estimate it from the observed angular spread in the electron streams, and this gives a value $\delta\theta \approx 25°$ (Lin *et al.*, 1981), although perhaps a smaller value may apply for the lower energy electrons (of a few keV) of relevance here. However, the measured anisotropy is not relevant for Langmuir waves generated by localized transient peaks in the distributions, as seemingly must be the case. It is likely that such localized peaks in the velocity distribution are highly collimated. Then the best estimate of $\delta\theta$ is the value $\approx \Delta v/v_b$ that applies for a stream with negligible angular spread. Melrose and Goldman (1987) argued on both observational and theoretical grounds that an enhancement of γ/ω_p by a factor $\gtrsim 10^2$ is required to account for the growth of the observed Langmuir waves. The postulated fine structures in the electron distribution that drive the instability should have small Δv and Melrose and Goldman suggested a value $\Delta v/v_b = 0.05$. The Langmuir waves generated by such fine structures would then be confined initially to a very small range of solid angles $\Delta\Omega \approx 10^{-4}$ to 10^{-3} sterad.

5. Interpretation of the Observed Brightness Temperatures

The foregoing model provides a quantitative means of estimating the maximum brightness temperature for type III bursts. In this section the predicted value (6) is evaluated using the data on type III events and compared with the observed values of T_B.

Comprehensive data sets for two type III events in the interplanetary medium have been presented by Lin *et al.* (1986). The values quoted for the event of 1979 March 11 correspond to:

$$n_e = 2 \times 10^6\ \mathrm{m}^{-3}, \qquad \omega_p/2\pi = 1.3 \times 10^4\ \mathrm{Hz}, \qquad v_b \approx 3.5 \times 10^7\ \mathrm{m\,s}^{-1},$$
$$\Delta v/v_b \approx 0.1\text{–}0.2, \qquad \partial f(v_\parallel)/\partial v_\parallel = 10^{-15}\ \mathrm{m}^{-5}\,\mathrm{s}^2, \tag{11}$$
$$|\mathbf{E}|_{\max} \approx 1\ \mathrm{mV\,m}^{-1},$$

where $|\mathbf{E}|_{\max}$ is the maximum value of the electric field strength in the Langmuir waves.

The first of the two alternative procedures for estimating T_B follows by inserting the parameters (11) into (6). For the event of 1979 March 11, this gives

$$\frac{\gamma}{\omega_p} = 2 \times 10^{-6}, \qquad \tfrac{1}{2}mv_b^2 = 3.6\ \mathrm{keV} = 4 \times 10^7\ \mathrm{K},$$
$$\frac{T_B}{\tfrac{1}{2}mv_b^2} \approx \frac{\gamma}{\omega_p}\,\frac{10^9}{\Delta\Omega}\,. \tag{12}$$

As anticipated, when the measured value of $\partial f(v_\parallel)/\partial v_\parallel$ is used in (6) and one estimated $\Delta\Omega = \pi\delta\theta^2$ with $\delta\theta = \Delta v/v_b$ given by (11), the implied maximum value of $T_B \approx 10^{12}$ to 10^{13} K from (12) is too low. That is, observed values of T_B are often well in excess of the predicted maximum. The enhancement that results when one sets $\gamma = D_\theta \approx 10^2$ s, as argued in the previous section, is by a factor $\gtrsim 10^3$. Then the estimated maximum value of T_B is $T_B \gtrsim 10^{15}$ to 10^{16} K. A further enhancement by a factor 10^2 results if one adopts the smaller value of $\Delta\Omega$ discussed in the previous section. The resulting estimate of T_B is poorly determined due to the uncertainties in these estimates. The most likely factor is 10^5 in excess of the initial estimate, that is, $T_B \approx 10^{17}$ to 10^{18} K.

The alternative way of estimating the maximum value of T_B involves inserting the maximum value $|\mathbf{E}|_{\max}$ from (11) into (7). Although the foregoing arguments suggest that the actual Langmuir waves are generated in a very small range of **k**-space, due to the small ranges of Δv and of $\delta\theta$ postulated, it seems unlikely that the observed waves would be confined to such a small range. A clump of Langmuir waves spreads quite quickly in coordinate space (Melrose and Goldman, 1987), and a spreading in **k**-space should also occur. As a plausible estimate let us set $v_\phi = v_b$ and $\Delta v_\phi = \Delta v$, and assume $\Delta\Omega \approx 10^{-1}$ sterad. The estimated value of the maximum brightness temperature is then $T_B \approx 10^{18}$ K.

These two estimates suggest that the intrinsic maximum value of T_B is plausibly in the range being 10^{17} to 10^{18} K.

The detailed estimates used here are for the 1979 March 11 event as reported by Lin *et al.* (1986). These authors also gave data for another event on 1979 February 8. The parameter that is most significantly different is $|\mathbf{E}|_{\max} \approx 0.15$ implying a value of W_L that is smaller by a factor 1.25×10^{-2} for this event compared with the event of 1979 March 11. A test for the ideas presented here is to compare the observed values of T_B for the two events: the theory implies that the ratio of the values of T_B at the orbit of the Earth should be about 1.25×10^{-2}, and this corresponds to frequencies of $f_{p\oplus} = 13$ kHz on 1979 March 11 and $f_{p\oplus} = 24$ kHz on 1979 February 8. In Figure 2 the values of T_B are compared for the two events as a function of radial distance from the Sun. The values pertain to the fundamental component, although the second harmonic was of comparable brightness (Dulk *et al.*, 1987). As expected the burst of 1979 February 8 is significantly weaker. These data are consistent with the ratio of the values of T_B for the two bursts at the orbit of the Earth being of order 10^{-2}.

The variation of the maximum value of T_B with frequency should also be explained by the theory. There are two observational features, cf. Figure 1, that require explanation: the sharp rise in T_B with decreasing frequency in the corona, and the slow variation of T_B with frequency in the solar wind. It is argued in the next section that the rise in T_B with decreasing frequency in the corona is associated with a rise towards the saturation level.

It is apparent from Figure 1 that T_B varies only slowly with decreasing frequency less than about 1 MHz. If the variation is modeled by $T_B \sim \omega_p^\alpha \sim r^{-\alpha}$, where r is radial distance from the Sun, then α is in the range $0 < \alpha < 1$. This variation should be implied by (6) or (7). The expected variation of T_B with ω_p or r from (6) can be estimated by assuming $\gamma = D_\theta$ and inserting (8) in (6). However, the density fluctuations are measured only near the orbit of the Earth (e.g., Celnikier, Muschietti, and Goldman, 1987), and the variation of the level of fluctuation with r is not known. Also, the variation of the parameter $\Delta\Omega$ in the model is poorly determined. All that one can conclude from (6) is that T_B should vary only slowly with frequency, and this is consistent with the observations.

There are data available on the variation of $\mathbf{E}_{\max}$ with r and these data in (7) imply how T_B should vary with r in the saturation model. For a set of 90 type III bursts observed with the Helios 1 and 2 spacecraft, Gurnett, Anderson, and Tokar

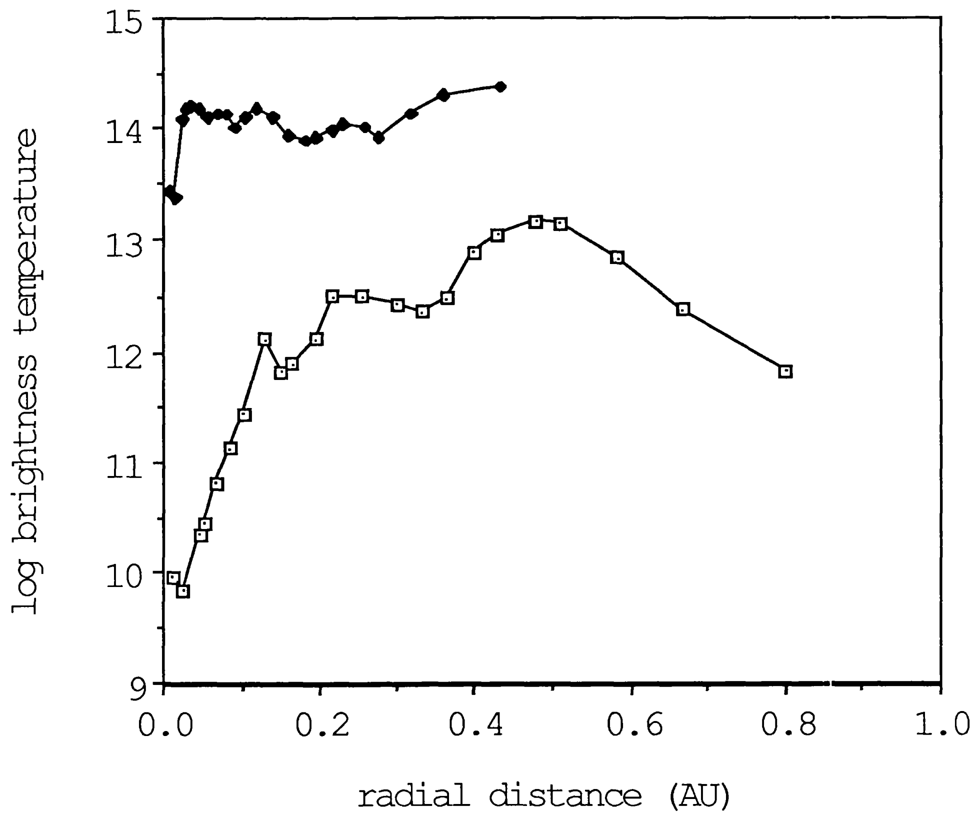

Fig. 2. The log of the brightness temperatures in kelvins is plotted as a function of radial distance for the type III bursts of 1979 March 11 (*upper*) and of 1979 February 8 (*lower*). (Note that the two low points on the left of the upper curve are lower limits.) The radial distance (in AU) is calculated as $f_{p\oplus}f$, where $f_{p\oplus}$ is the plasma frequency at the orbit of the Earth (13 and 24 kHz, respectively) and f is the frequency of observation. For both traces the rightmost point corresponds to the lowest observing frequency of 30 kHz, and the leftmost to 1980 kHz. Thedata, which are from the Meudon/Goddard experiment on ISEE-3, were provided by G. A. Dulk.

(1980) found $\mathbf{E}_{\max} \sim r^{\beta}$ with $\beta = 1.4 \pm 0.5$. Inserting this variation in (7) and assuming that the parameters, apart from $\omega_p \sim 1/r$, are slowly varying, the theory implies $T_B \sim e^{3-2\beta} \sim \omega_p^{2\beta-3}$. The agreement of this statistical prediction with the observed statistical variation of T_B in Figure 1 is excellent.

6. Conditions for Saturation

The theory for plasma emission adopted here invokes ion sound waves (or other appropriate low-frequency waves) in the plasma emission processes, and this allows the emission processes to be efficient enough to saturate. The predicted maximum value $T_B = T_L$ results when saturation occurs. However, in order for the saturation model to be relevant, all the stages in the plasma emission processes must in fact saturate. One can suggest several plausible reasons why the various stages might not saturate. These include the following:

(1) The growth rate for the beam instability with the observed distribution of electrons in type III events is quite slow, and unless it is enhanced, e.g., as discussed by Melrose

and Goldman (1987) and in Section 3 above, the Langmuir waves should not grow at all. The considerably enhanced growth rate is required, for the beam instability to saturate, and this enhancement requires localized, transient peaks in the velocity distribution.

(2) Granted that this first difficulty is overcome, as described in Section 3, and that growth of Langmuir waves occurs in isolated clumps, as observed (Gurnett and Anderson, 1977; Gurnett *et al.*, 1978), these clumps should expand relatively rapidly (Melrose and Goldman, 1987), causing their effective temperature T_L to decrease below the saturation value. The saturation value $T_B = T_L$ results only if the transverse waves are produced before the clumps expand significantly.

(3) The small sizes of the clumps of Langmuir waves provides a constraint on the condition that the generation of the fundamental transverse waves saturate (Melrose, Dulk, and Cairns, 1986); if this constraint is not satisfied then $T_B < T_L$ results. An interesting possible mechanism for facilitating saturation is localization of the fundamental transverse waves in the clumps of Langmuir waves (Melrose, 1989).

(4) For second harmonic emission it does not seem possible to account for saturation in one clump, it seems necessary to appeal to a second harmonic ray encountering many clumps of Langmuir waves before it saturates (Melrose, Dulk, and Cairns, 1986); the conditions for this to occur are quite restrictive.

(5) A related condition is a consequence of the transverse waves being generated only from the clumps of Langmuir waves: the observed type III sources must be composed of many unresolved clumps of emission. If the area obtained by summing the projected areas of these clumps does not fill the apparent area of the source, then the expected value of T_B is reduced from the maximum value by the ratio of these two areas.

The fact that the saturation model satisfactorily explains the value of T_B for type III bursts, at least for those at less than several megahertz, suggests that none of these possible difficulties with the model are important in practice.

It appears that saturation does not occur for type III bursts from the corona, that is for frequencies greater than about 10 MHz. This could be due to any of the reasons listed above or to a combination of them, and perhaps the most likely reason is (5). The evolution of a typical type III burst in corona suggests that the efficiency of the plasma emission processes increases with decreasing frequency and that saturation is not achieved until a relatively low frequency is reached. Type III streams do not begin to radiate significantly until they reach a height where the plasma frequency has decreased to ≈ 300 MHz, whereafter the brightness of radiation increases rapidly with decreasing frequency. The brightness of the fundamental, which becomes dominant below about 50 MHz (Suzuki and Dulk, 1985) and remains of major importance in the interplanetary medium (Dulk, Steinberg, and Hoang, 1984), increases faster than that of the second harmonic, which dominates initially.

There is another argument that suggests that the type III emission processes are more likely to saturate in the interplanetary medium than in the corona: individual bursts in type III groups propagating through the corona tend to maintain their identity until they reach the range 1–10 MHz where the electrons of individual streams start to overlap preceding and following streams. Thus a single type III event in the interplanetary medium corresponds to many type III acceleration events in the corona. It follows that a type III event in the interplanetary medium involves more electrons than a single event in the corona, by a factor ≈ 10 determined by the number of overlapping streams. The greater number of electrons suggests that saturation in the interplanetary medium is easier to achieve than in the corona.

7. Conclusions

(1) Although the observed brightness temperature T_{Bo} for type III bursts in the corona rises steeply with decreasing frequency, the value of T_{Bo} is remarkably constant for bursts in the solar wind. It is proposed here that the observed value of T_B and its variation with distance r from the Sun may be explained in terms of a model in which the plasma emission processes saturate.

(2) There is an uncertainty in the estimation of the intrinsic maximum brightness temperature T_{Bi} from the observed value of T_{Bo}. To estimate T_{Bi}, the observed maximum value ($T_{Bo} \approx 10^{15}$ K) needs to be scaled up considerably to take account of the large apparent sizes of fundamental sources, whose apparent areas in the absence of scattering should be smaller that their actual areas by a factor μ^2, where μ is the refractive index at the source (Melrose and Dulk, 1988). The scaling factor is probably of order 10^2, so that the theory needs to explain intrinsic values $T_{Bi} \approx 10^{17}$ K.

(3) There are two ways of using observational data to estimate the expected value of T_{Bi}. One involves using data on the electron distribution to estimate the growth rate γ for the Langmuir waves and inserting this in (6). However, the observed distribution must be a relaxed distribution from the viewpoint of the beam instability, and indirect arguments are needed to place limits on the actual growth rate, cf. Section 4. There is considerable uncertainty in the resulting estimate of T_B, but is compatible with a value $\approx 10^{17}$ K.

(4) The alternative way of using the observational data is to insert the observed value of the maximum electric field strength $\mathbf{E}_{\max}$ for the Langmuir waves into (7). There is an uncertainty in the **k**-space volume filled by the waves. Nevertheless, the observed values of $\mathbf{E}_{\max}$ imply a predicted value of T_B that is in satisfactory agreement with the inferred value of T_{Bi}.

(5) This second way of estimating T_B is in good agreement with two other observational features. First, for bursts at the orbit of the Earth it implies that T_B should be proportional to $\mathbf{E}_{\max}^2$, and this is consistent with the one example for which detailed data are available, cf. Figure 2.

(6) It appears that the emission does not saturate for bursts in the corona at higher frequencies ($\gg 2$ MHz) and this is consistent with other data on type III bursts in the corona.

Although the qualitative ideas on the plasma emission have changed relatively little since they were first proposed over 30 years ago by Ginzburg and Zheleznyakov (1958), there have been few successes in quantitative treatments of plasma emission. The discussion in the present paper provides a semi-quantitative explanation for the characteristic maximum observed values of T_B. The idea behind this model is simple, specifically that all relevant stages saturate, and this ignores many potential difficulties. Perhaps the most notable of the difficulties is the extremely inhomogeneous distribution ('clumpiness') of the Langmuir waves, which places severe constraints on the conditions for saturation. Another example of a successful semi-quantitative aspect of type III theory is the one-dimensional quasi-linear model (Gorgnard, 1984, 1985) for a beam as it propagates through the interplanetary medium. Despite the simplicity of the assumptions, including the neglect of the clumpiness of the Langmuir waves, this theory explains the measured distribution functions of type III electrons.

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