DECAY TIME OF TYPE III SOLAR BURSTS OBSERVED AT KILOMETRIC WAVELENGTHS

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Abstract. Type III bursts were observed between 3.5 MHz and 50 kHz by the University of Michigan radio astronomy experiment aboard the OGO-5 satellite.

Decay times were measured and then combined with published data ranging up to about 200 MHz. The observed decay times increase with decreasing frequency but at a rate considerably slower than that expected from electron-proton Coulomb collisions. At 50 kHz values differ by about a factor of 100. Using Hartle and Sturrock's solar wind model, Coulomb collisional frequencies were computed and compared with the apparent collisional frequencies deduced from the observations. It was found that the ratio of observed to computed values varies with heliocentric distance according to an inverse 0.71 power. This is similar to an ad hoc function used by Wolff, Brandt, and Southwick to increase the electron-proton collisional energy exchange and make the solar wind theory agree with the measurements of electron and proton temperature near the Earth. These results may provide a clue about the nature of the non-collisional plasma wave damping process responsible for the short duration of type III bursts.

1. Introduction

The temperature of the solar corona has been determined near the Sun from optical observations using different methods (Newkirk, 1967). Measurements near the Earth indicated that the temperatures of electrons and protons in the solar wind are different. This led to the formulation of two-fluid theoretical models (Hartle and Sturrock, 1968; Cuperman and Harten, 1971; Wolff *et al.*, 1971).

Hartle and Sturrock's model considered only Coulomb collisions in the proton-electron energy exchange process, and the predicted proton temperature at the Earth orbit was considerably lower than that observed. To remove this discrepancy Nishida (1969) introduced an ad hoc 'collisionless' proton-electron interaction leading to an effective collision frequency. 10 times larger than the Coulomb collision frequency. This concept was further developed by Cuperman and Harten (1971), and by Wolff *et al.* (1971).

A method used to study the temperature of the solar corona is based on the observation of type III solar bursts. According to the local plasma hypothesis (Wild, 1950) these bursts are produced by the passage through the corona of streams of fast charged particles ejected by the Sun. Throughout the corona they excite plasma oscillations that couple into electromagnetic waves at the fundamental and second harmonic of the plasma frequency. Jaeger and Westfold (1949) found that plasma oscillations set up by a pulsed excitation in a homogeneous ionized medium decay with time, due to Coulomb collisions, according to an exponential law $\exp(-\nu t)$. ν is the proton-electron collision frequency given by:

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$$\nu = 42NT^{-3/2},\ \mathrm{s}^{-1} \tag{1}$$

where N = electron density, cm^{-3} and T = electron kinetic temperature, K.

A measurable quantity in a type III burst profile is the time it takes the radiation to decrease from the maximum to $1/e$ of it. This has been defined as the decay time that, for the collisional case, can be written as:

$$\tau_c = \frac{1}{\nu},\ \mathrm{s}. \tag{2}$$

Boischot *et al.* (1960) used Equation (1) in the frequency range from 15 to 30 MHz assuming the local plasma hypothesis and computed temperatures in general agreement with those obtained from optical observations. Malville (1962) using a similar formula also obtained good agreement at 25 MHz. Boischot (1967) found that the temperatures obtained from observations at 36, 18 and 8 MHz decreased with frequency, as expected from collisional damping. The first measurements from an artificial Earth satellite reported by Hartz (1964) also showed this decreasing trend with frequency between 10 and 2 MHz. Slysh's value at 0.985 MHz was consistent with this trend (Slysh, 1967). Hartz (1969) pointed out that the temperatures obtained in the range from 9 to 0.7 MHz were "substantially below those expected for the solar wind." Further studies of type III bursts at lower frequencies have confirmed this disagreement (Alexander *et al.*, 1969; Haddock and Graedel, 1970).

In a recent theoretical paper, Zaitsev *et al.* (1972) propose that Landau damping in the tail of the exciter stream is responsible for the observed decay time of type III bursts. They found that their theory seems to fit experimental burst profiles at hectometric wavelengths.

To investigate this problem we measured the decay times of the type III bursts observed between 3.5 and 0.05 MHz by the radiometer that the University of Michigan has aboard the Orbital Geophysical Observatory-5 (OGO-5). Combining our observations with other published values we obtained a simple formula to express decay time as a function of frequency. Comparison of the observations with collisional decay times computed from theoretical solar wind models shows conclusively that the simple collisional damping hypothesis cannot explain the decay time of type III bursts.

We derived an approximate relationship for the discrepancy ratio of the observed to the computed decay times as a function of distance from the Sun. This relationship is derived from radio data in a continuous range of distances between the Sun and the Earth's orbit. It is shown that this empirical relationship is practically identical to the one that solar wind theoreticians have invoked to fit the temperature measurements made near 1 AU.

2. The Observations

The data are the same that were analyzed in two previous papers (Alvarez and Haddock, 1973, and Haddock and Alvarez, 1973). They consist in observations at 3.5, 1.8, 0.9, 0.6, 0.35, 0.20, 0.10 and 0.05 MHz with a time resolution of 9s. We selected the type III bursts that drifted down to or below 0.35 MHz. Between March 1968 and February 1970 we observed 79 of these bursts. Our results are based on 64 of them whose data were available at the time of analysis. Because of the selection criterion and because of sensitivity limitations the radio events were necessarily very strong. This frequently resulted in receiver saturation during high signal levels. Most of the observed events were formed by a large number of bursts which resulted in a blended, complex time profile. Saturation and blending introduce problems in measuring time profile characteristics. Furthermore there are two more effects. First, the duration of the radio bursts increases with decreasing frequency which causes further blending of the bursts. Second, it is difficult to distinguish between the fundamental emission produced at a coronal level with a plasma frequency *f*, from the second harmonic emission produced at the coronal level with a plasma frequency *f*/2 which has been designated the *half-frequency harmonic* (Haddock and Alvarez, 1973).

3. Data Analysis

In spite of the above difficulties it was decided to estimate grossly the decay times. The smoothed time profiles were measured independently of the complexity of the event and regardless of whether the decay was exponential or not. Results of our ex-

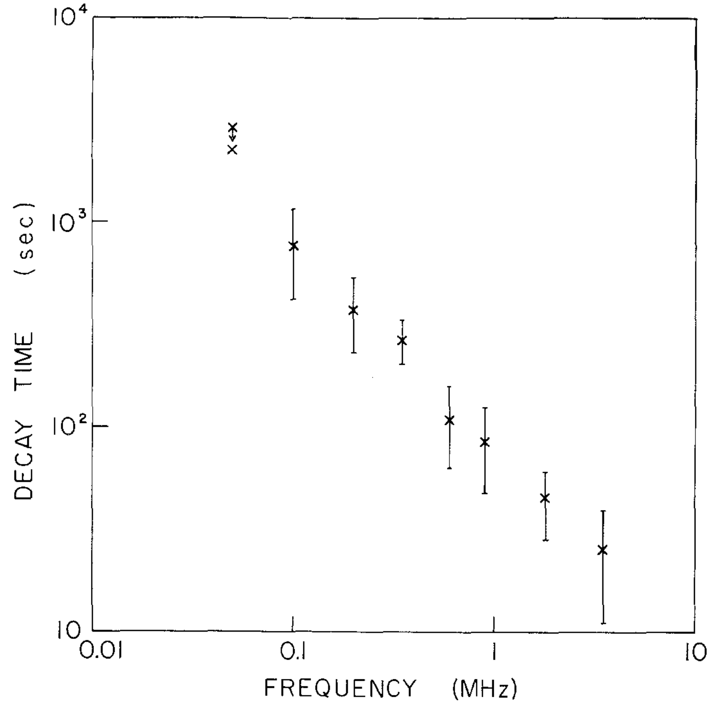

Fig. 1. Decay times of type III bursts observed by OGO-5.

periment aboard the IMP-6 satellite in the same frequency range seem to indicate that the decay is approximately exponential in the absence of saturation. No attempt was made to separate the fundamental from the half-frequency harmonic emission. Therefore our measurements are *upper limits* to the actual decay times of individual bursts. Figure 1 shows the measured decay times. The symbol x represents the average value with its one-σ error bars. The number of bursts used at each frequency between 0.2 MHz and 3.5 MHz ranges from 25 to 64; 12 bursts were used at 0.1 MHz and 2 at 0.05 MHz. At 0.05 MHz we have used the data of the radio burst that occurred on 6 April, 1971, at 0915 UT, observed by OGO-5 but not included in previous analyses. Note that in spite of the rough upper limit measurements the decay times follow an almost power-law trend of increase with decreasing frequency.

In Figure 2 we have collected published decay time data for type III bursts. Note that the observations fall approximately on a straight line, except for a few points. The most deviant points, by Boischot *et al.* (1960), were considered erroneously high by Kundu (1965, p. 329).

A least-square linear fit to the log-log plot of the data in Figure 2 gives the relation:

$$\tau f^{0.95} = 10^{7.71} \tag{3}$$

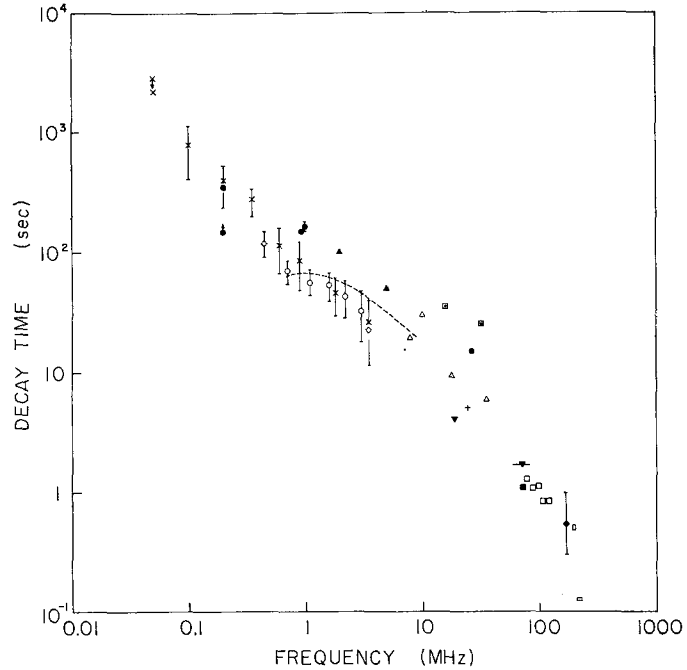

Fig. 2. Decay times of type III bursts. The key to the authors is: ×, this paper; ●, Slysh (1967); △, Boischot (1967); ⊡, Boischot *et al.* (1960); ◇, Haddock and Graedel (1970); ▭, Elgaroy and Rodberg (1963); □, Wild (1950); ⊙, Riihimaa (1963); +, Malville (1962); ○, Alexander *et al.* (1969); ■, Williams (1948); ◆, Bougeret *et al.* (1970); ▯, de Jager and Van't Veer (1957); ▼, Payne-Scott (1949); ▲, Hartz (1964); ----, Hartz (1969).

where τ is in seconds and f in Hz. This is in remarkable agreement with a similar relation $\tau f = 10^8$ obtained by Wild (1950), observing only between frequencies of 80 and 120 MHz. This equation implies that it takes 10^8 cycles of the plasma wave for damping to $1/e$ to occur, independently of frequency or plasma density.*

4. Discussion of the Results

The collisional decay times τ_c derived from some theoretical solar wind models were calculated using Equations (2) and (1), and are presented in Figure 3 along with the line fitted to the measured decay times, τ. The exponents in Equation (3) have been rounded off and the frequency expressed in MHz.

The increasing disagreement with diminishing frequency is obvious, at 0.1 MHz the discrepancy is greater than an order of magnitude. At 1 AU the Whang *et al.* model gives $\tau_c \approx 21$ hr and Hartle and Sturrock's model gives even longer time.

It is interesting to note that the variation of τ_c with frequency is similar in the three theoretical models even though the Pneuman and Kopp model is for a coronal streamer.

Figure 3 illustrates graphically the inappropriateness of using Equation (1) to compute burst decay times or, alternatively, to derive coronal temperatures. One poor

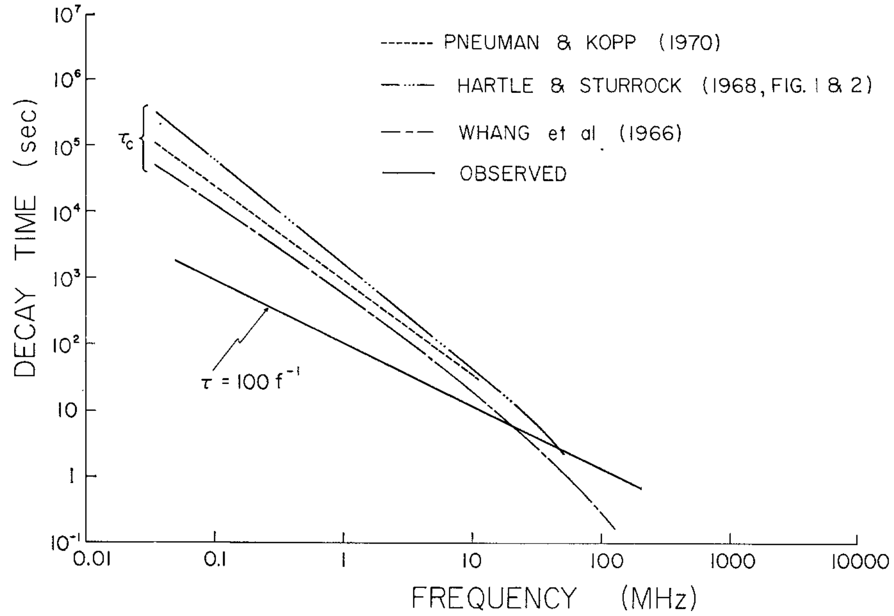

Fig. 3. Decay times observed and those calculated from theoretical models assuming Coulomb collisions.

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* R. N. Bracewell pointed this out in the discussion of a preliminary report of our results at the URSI meeting in fall 1971 at UCLA (Alvarez and Haddock, 1971).

assumption used in the application of that equation is that the distribution of the solar wind electron velocities is Maxwellian. In fact, the velocity distribution functions of protons and electrons in the solar wind is not Maxwellian (Hundhausen, 1968, 1970). A simple consideration will indicate that the decay of plasma oscillations by proton-electron collisions may not have a chance to play an important role. Using Equation (1) at 1 AU, with $N=5\ \mathrm{cm}^{-3}$ and $T=10^5\,\mathrm{K}$, for example, it is found that an electron collides with a proton once every 1.5×10^5 s, or 1.74 days! During this time the solar wind, at 350 km s^{-1}, travels 0.3 AU and the plasma waves are swept away to lower densities and consequently lower plasma frequencies. The observed decay times are sufficiently short to prevent this solar wind velocity effect from being significant in our analysis. For example, at the observing frequency of 50 kHz the -6 dB points of our receiver bandpass are at 55 and 45 kHz. Under typical conditions the time taken by the material of the solar wind to go through plasma levels corresponding to the bandpass limits is several times longer than the observed decay times.

In Figure 3 we can draw approximately a straight line through the low-frequency portion ($10> f >0.05$, MHz) of the curve derived from the Hartle and Sturrock's model. Its equation is $\tau_c=10^{12.71}f^{-1.58}$, where τ_c is in seconds and f in Hz. Denoting by τ the observed decay time given by Equation (3), we can express the discrepancy between theory and observation in the following functional form:

$$\frac{\tau_c}{\tau}=10^{5.00}f^{-0.63}. \tag{4}$$

To express this equation in terms of heliocentric distance we have accepted the local plasma hypothesis and, for consistency, the electron density model of Hartle and Sturrock. The plasma frequency equation is

$$f=9\times10^3 j\sqrt{N},\ \mathrm{Hz}, \tag{5}$$

where N is in cm^{-3}, $j=1$ for the fundamental of the plasma frequency and $j=2$ for its second harmonic. The distances corresponding to the frequency range of $10\gtrsim f\gtrsim$ $\gtrsim0.05$ MHz, considered as fundamental, range between about 10 and 150 $R_\odot$. In this range Hartle and Sturrock's model (1968, Figure 1) can be approximated by:

$$N=10^{6.33}r^{-2.25}\ \mathrm{cm}^{-3} \tag{6}$$

where r is in solar radii. Using Equations (5) and (6) Equation (4) can be written as:

$$\frac{\tau_c}{\tau}=\alpha r^{0.71},\quad \begin{array}{l}\text{for}\quad j=1,\alpha=3.3\quad\text{and}\\ \text{for}\quad j=2,\alpha=2.1.\end{array} \tag{7}$$

To increase the deduced proton temperature near the Earth orbit, Cuperman and Harten (1971) introduced an enhanced noncollisional coupling between the protons and the electrons. This was done by taking, ad hoc, an effective collision frequency 30 times larger than the classical Coulomb collision frequency at 1 AU. A later and more comprehensive solar wind model by Wolff *et al.* (1971) expanded this concept by introducing a distance-dependent coefficient to increase the collisional energy exchange between electrons and protons. Wolff *et al.* define an effective collision frequency by assuming that the electron mean free path is proportional to the reciprocal of the distance from the Sun raised to an arbitrary power. This power was chosen so as to give the best agreement between the theory and the observations at 1 AU, particularly of the proton temperature. In terms of our notation their relationship can be written as:

$$\frac{\tau_c}{\tau_{\text{eff}}} = r^{0.73}, \tag{8}$$

where τ_{eff} is the reciprocal of their effective collision frequency.

Considering the uncertainties in the measurements of temperatures, in our determination of decay times and in the least square fit we believe that the similarity between Equations (7) and (8) suggests that they represent the same unknown phenomenon. The comparison of Equation (7) deduced from Hartle and Sturrock's model with Equation (8) from Wolff *et al.* is valid because Wolff *et al.* model reduces practically to Hartle and Sturrock's when no non-collisional energy exchanged is considered.

5. Conclusions

We have shown conclusively the failure of the pure collisional damping hypothesis to account for the decay rate of type III bursts. Our results are consistent with deductions made from models obtained by solar wind theoreticians independently and by completely different means. Both results are quantitative and complement each other because theirs is based on data from near the Earth and ours is based on data in a continuous range in distance between the Sun and the Earth. The cause of the phenomenon whose effects have been discussed is at present unknown.

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