Microwave bursts and the relative abundance of electrons and protons in cosmic rays from solar flares

E. I. Daibog, V. G. Stolpovskii, V. F. Mel'nikov, and T. S. Podstrigach

Scientific Research Institute of Nuclear Physics, Moscow State University; Scientific Research Radiophysics Institute, Gor'kii

(Submitted January 10, 1989; resubmitted June 26, 1989)

Pis'ma Astron. Zh. **15**, 991–1000 (November 1989)

The relation between the parameters of flare microwave bursts and the relative abundance of energetic electrons and protons (the *e/p* ratio) in solar cosmic rays is discussed. It is shown that a short (pulsed) microwave burst can be put into correspondence with a solar cosmic ray event with a higher *e/p* ratio. The variation of the *e/p* ratio for electrons and protons of different energies as a function of the burst length is due to the different lifetimes of these particles in flare arches of different sizes. The dynamics of energetic electrons and protons is discussed in terms of the regimes of pitch-angle diffusion occurring in extended and compact coronal arches.

The ratio of the abundance of electrons and protons (the e/p ratio) in streams of energetic particles accelerated in solar flares in a parameter that characterizes the conditions and mechanism of acceleration, as well as escape of particles into interplanetary space (see, for example, Refs. 1 and 2). Data on the e/p ratio in solar cosmic ray (SCR) events at different electron and proton energies, as well as estimates of the e/p ratio in the source on the sun from the hard x-ray and gamma-ray line emission, are given in Refs. 3-6. The e/p ratio is compared with the parameters of gamma-ray, x-ray, and microwave bursts in Refs. 6-8. The concept of pulsed and extended flares and of pulsed and extended SCR events is proposed in these papers. the e/p ratio is high in pulsed events and low in extended ones.

In the present paper the relation between the e/p ratio in SCRs and the effective length and exponential decay time of microwave bursts (μ-bursts) is analyzed with allowance for peculiarities of the dynamics of energetic electrons and protons in flare arches of different sizes.

INITIAL DATA

We considered 61 SCR events in which the time profiles of particle intensity had a nearly diffusive form and the maximum flux of protons with energies $E_p > 25$ MeV exceeded $I_p = 10^{-3}$ cm$^{-2}\cdot$sec$^{-1}\cdot$sr^{-1}. The data on particles were obtained in experiments on the Venera 11 and 14 automatic interplanetary stations and the Prognoz 5 and 6 earth satellites in 1977-1978 and 1981-1983 (Refs. 9-11). In 58 cases the SCR events were identified with western and central flares. In 54 cases we had data on radio bursts in the centimeter range obtained at the Zimenka Radio Astronomical Station of the Scientific Research Radiophysics Institute and at a worldwide network of stations.

The SCR events were characterized by the time of first arrival of electrons at the observing site (t_e) and by the maximum integrated fluxes of electrons with $E_e > 0.07$ and $E_e > 0.5$ MeV (I_e) and of protons with ep > 25 MeV (I_p). The microwave emission was represented by the frequency f_m of the spectral maximum, the emission flux $\int F dt$ at the frequency f_m, integrated over the burst, and the effective length of the burst, $T_\mu \equiv (\int F dt)/F_m$, where F_m is the maximum intensity.

RESULTS

The distribution of events with respect to the e/p ratio for electrons with $E_e > 0.07$ and $E_e > 0.5$ MeV is shown in Fig. 1. It was shown earlier[12] that pulsed bursts in thermal x-ray and μ-emission $T_{x_t} < 1$ h, $T_\mu < 5$ min) can be put into correspondence with SCR events in which the e/p ratio is considerably higher, on the average, than in SCR events associated with prolonged x_t- and μ-bursts ($T_{x_t} > 1$ h and $T_\mu > 5$ min, respectively). This difference may be seen in Fig. 1, where solid lines pertain to extended events and dashed lines to pulsed ones.

Such a distribution suggested that pulsed and extended events differ qualitatively in the mechanism and site of particle acceleration. In Refs. 7 and 13 pulsed events are associated with the so-called first phase of acceleration and extended events with the second phase. In this case the low e/p ratio in extended flares is explained by the fact that efficient acceleration of protons by the shock wave occurs high in the solar corona.

We think, however, that one need not exaggerate the role of proton acceleration at the shock wave in the formation of the e/p ratio in the source and in SCRs. Correlation studies indicate[10,14] that protons and moderately relativistic electrons and initially accelerated in the same process and, in addition, in the immediate vicinity of the source of flare μ-emission. In fact, it follows from Fig. 2 that the electron and proton flux are closely related

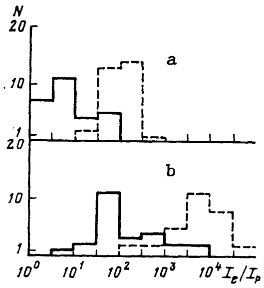

FIG. 1. Distribution of SCR events (N) with respect to the e/p ratio: a) for electrons with E > 0.5 MeV and protons with E > 25 MeV; b) for electrons with E > 0.07 MeV. The distribution for extended events is shown by solid lines and that for pulsed events by dashed lines.

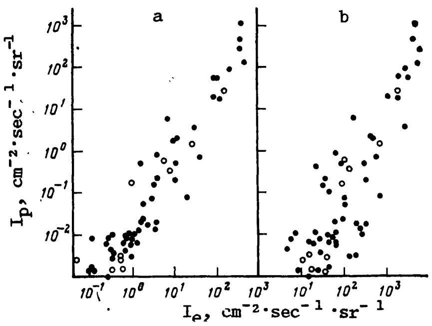

FIG. 2. Flux of protons with energies $E > 25$ MeV as a function of the electron flux: a) $E > 0.5$ MeV; b) $E > 0.07$ MeV. Light circles pertain to events for which a complete set of parameters of the microwave burst could not be obtained.

(correlation coefficient $r \simeq 0.9$). In addition, moderately relativistic electrons are closely related to the quantity $\phi\int F dt$ (see Fig. 3a, where $\phi \equiv (9/f_m)^2$ is a normalization factor that allows for the field strength in the radio source), which is a measure of the total number of electrons accelerated in the radio source. The proton flux is also closely related to $\phi\int F dt$ (Fig. 3b).

In Ref. 15 it was found that the fluences of nuclear and continuum ($E_\gamma > 300$ keV) gamma-ray emission correlate well and are proportional over a wide dynamic range. This can be taken as evidence that the number of accelerated protons with $E_p > 20$ MeV and of moderately relativistic electrons in a flare region are closely related and vary proportionally, regardless of the flare power and duration: $N_{tp} \propto N_{te}$. Together with the results given in Figs. 2 and 3, this means that, over a wide range of flare energy, the protons and electrons that generate electromagnetic raditiona in relatively narrow layers of the solar atmosphere and the energetic protons and electrons that escape into interplanetary space after the flare are accelerated in the same process.

We can therefore assume that the division of SCR events into pulsed and extended ones is not a reflection of a clear-cut distinction between the acceleration mechanisms in pulsed and extended flares.

e/p RATIO AND DYNAMICS OF PARTICLES IN A FLARE LOOP

For both pulsed and extended injection, it follows from the continuity equation

$$\frac{dN}{dt} = j - \frac{N(t)}{\tau_{esc}} - \frac{N(t)}{\tau_{loss}}$$

that the number of particles escaping from the trap, N_{esc}, is

$$N_{esc} \simeq N_t \frac{\tau_{loss}}{\tau_{esc}}, \quad \tau_{esc} \gg \tau_{loss}$$

$$N_{esc} \simeq N_t, \quad \tau_{esc} \ll \tau_{loss}.$$

Here j is the source function, τ_{esc} is the characteristic time of escape of particles from the trap, τ_{loss} is the characteristic time of energy loss and precipitation of particles into the bases of the magnetic arch due to scattering into the loss cone, and N_t is the total number of accelerated particles. Earlier it was found[12] that the coefficient of escape of accelerated electrons in flares accompanied by x-ray bursts is $\ll 1$. In Ref. 16 the proton escape coefficient in pulsed flares is also $\ll 1$. For these events it is natural to assume that $\tau_{esc} \ll \tau_{loss}$. In that case, the lifetime of particles in the trap is $T \simeq \tau_{loss}$ and, regardless of the escape mechanism (drift, diffusion, or destruction of the trap), the number N_{esc} of escaping particles must increase with an increase in their lifetime in the arch, $N_{esc} \simeq N_t T$, ultimately reaching the limit $N_{esc} \simeq N_t$ for $\tau_{esc} \ll \tau_{loss}$. Three such events with a very long duration of hard x-ray emission ($T_{xh} \gg 1000$ sec) were also cited in Ref. 16. For electrons such a limit is apparently satisfied in events unaccompanied by hard x rays.[17]

The particle lifetime depends, in turn, on the physical conditions in the trap (the size of the arch, the plasma density, the magnetic field, the turbulence level, etc.), as well as on the type of particle. In this connection the variation of the e/p ratio from event to event may be due to variation of the ratio of lifetimes of energetic electrons and protons as a function of the conditions in the arch:

$$\frac{N_{esc,e}}{N_{esc,p}} \propto \frac{T_e}{T_p}, \quad \frac{I_e}{I_p} \propto \frac{T_e}{T_p}. \tag{1}$$

The effective lifetime of energetic particles, $T = N/|N/dt|$, is determined by the ratio between the characteristic times of filling (T_D/σ) and emptying ($T_c = L/2v$) of the loss cone. Here T_D is the characteristic time of pitch-angle diffusion of the particles, which decreases with increasing turbulence level (whistlers for electrons, Alfvén waves for protons), $\sigma = B_{max}/B_{min}$ is the mirror ratio, L is the longitudinal size of the trap, and v is the particle velocity.

If $T_D/\sigma < L/2v$, a regime of moderate diffusion ensues in which the particle lifetime is $T = \sigma L/2v$. If $T_D/\sigma > L/2v$, then a regime of weak diffusion occurs in which $T \simeq T_D$.

Not only the diffusion regime but also the scattering agent can change upon variations in the parameters of the arch and the particle energy. When T_D is so long that it exceeds the time T_Q of

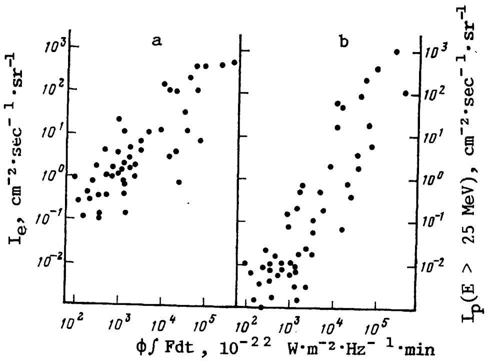

FIG. 3. Relation between the microwave flux integrated over the burst, $\phi\int F dt$ (ϕ is a normalization factor), the flux of electrons with $E > 0.5$ MeV (a), and protons with $E > 25$ Mev (b).

1989SvAL...15..432D

Coulomb losses, the effective lifetime is $T \simeq T_Q$. Under the usual conditions inside flare arches the condition $T_Q > \sigma L/2v$ is always satisfied for energetic particles, so Coulomb scattering into the loss cone occurs only in the weak diffusion regime. For electrons the energy losses due to Coulomb collisions are then of the same order of magnitude as those due to precipitation.

Let us see what the lifetimes of electrons and protons are in different diffusion regimes.

Electrons and protons have the minimum lifetime in the moderate diffusion regime. In this case T_e is close to T_p. For $\sigma \simeq 3$ and $L \simeq 10^9$, typical values for compact arches, we have $T_p \simeq 0.25$ sec. Electron precipitation in the moderate diffusion regime apparently can explain the results of stereoscopic observtions of pulsed flares, which imply that the regions of hard x-ray generation are located at the bases of magnetic arches. The existence of a moderate diffusion regime for protons is confirmed by the observation in certain pulsed flares of a close time correlation (down to $\Delta t \lesssim 1$ sec) between the profiles of hard x-ray and gamma-ray emission in lines.[18]

With an increase in electron energy and constant arch parameters, the regime of moderate diffusion from whistlers at moderately relativistic energies may be replaced by weak diffusion with $T \simeq T_D > \sigma L/2v$ owing to a decrease in the turbulence level. According to Refs. 19 and 20, the increment of whistler growth is

$$\alpha \propto \frac{\pi}{2} \frac{n_r(E)}{n_0 \sigma} \omega_B, \qquad (2)$$

where $n_r(R)$ is the density of fast electrons, ω_B is the gyrofrequency, and n_0 is the background plasma density. For a power-law distribution $n_r \propto E^{-\gamma}$, it follows from (2) that α decreases with increasing energy of resonant electrons. This effect is confirmed experimentally by the observation of a delay in the maxima of μ-bursts relative to the maxima of hard x-ray emission in pulsed flares.[13]

In pulsed flares the delays in the microwave and the nuclear gamma-ray emission relative to the hard x-ray emission are about the same[18] ($\Delta t \simeq$ 1 sec). This indicates that the lifetimes of energetic protons ($E_p \gtrsim 10$ MeV) and moderately relativistic electrons in pulsed flares are approximately equal.

The maximum possible lifetime of electrons and protons occurs when the turbulence level in the arch is low — in the regime where the main losses are due to Coulomb collisions. There are observations showing that this regime may occur in coronal arches. Cases are known when protons continue to enter interplanetary space for a fairly long time after a flare in an active region, which sugests prolonged confinement in traps.[21] In extended events, along with a delay relative to bursts of hard x-ray emission, μ-bursts are characterized by an exponential decay in intensity with a characteristic time of tens of seconds or even minutes.[13] Such a decay time indicates prolonged confinement of the moderately relativistic electrons in the vicinity of the radio source, which is impossible if well-developed turbulence is present.

The fact that in this regime, in contrast to moderate diffusion, the proton lifetime is considerably longer than the electron lifetime is important for our purposes. In fact, according to Ref. 22, the characteristic times of ionization energy losses by electrons and protons under coronal conditions are

$$\tau_{E_e} = \frac{2.1 \cdot 10^8}{n_0} E^{3/2} \ (E \text{ in keV}),\ E < 160 \text{ keV}, \qquad (3)$$

$$\tau_{E_e} = \frac{2.6 \cdot 10^9}{n_0} E \ (E \text{ in keV}),\ E > 160 \text{ keV}, \qquad (4)$$

$$\tau_{E_p} = \frac{1.3 \cdot 10^{11}}{n_0} E^{3/2} \ (E \text{ in meV}), \qquad (5)$$

respectively, where n_0 is the electron density of the background plasma in the arch. For a proton energy E_p = 25 MeV and an electron energy E_e = 500 keV we have $\tau_{E_e}/\tau_{E_p} \simeq 1/12$.

If we consider that, first, the trapped partices have power-law spectra and, second, collisional pitch-angle diffusion into the loss cone is important for electrons, in contrast to protons, then the characteristic lifetimes of the particles of a given energy due to losses in collisions, $T = N/|dN/dt|$, will be

$$T_{Qp} = \tau_{E_p}/(\gamma_p - 1), \text{ for protons}, \qquad (6)$$

$$T_{Qe} = \tau_{E_e}/(\gamma_e + 1), \text{for electrons}, \qquad (7)$$

where γ_p and γ_e are the exponents in the differential energy spectra of the protons and electrons.[23] From this we find that the ratio of proton and electron lifetimes

$$T_{Qp}/T_{Qe} = \tau_{E_p}(\gamma_e + 1)/\tau_{E_e}(\gamma_p - 1) \qquad (8)$$

turns out to be considerably larger than unity. For E_p = 25 MeV and E_e = 500 keV and the usual vlaues of γ_e and γ_p we have $T_{Q_p}/T_{Q_e} \simeq 20$.

In accordance with (1), the e/p ratio should decrease by the same factor (see Sec. 1). It should be noted that a similar decrease in the e/p ratio is observed in the transition from pulsed to extended events (Fig. 1a).

From (3)-(8) it follows that the spread of the e/p ratio should be even larger in the case of lower-energy electrons. In fact, T_p/T_e already increases 100-fold for an electron energy $E_e > 70$ keV. Observational data support this conclusion (see Fig. 1b).

On the whole, the spread of the e/p ratio should be even larger because cases are possible where the regime of moderate diffusion occurs for protons but not for electrons (i.e., the regime of Coulomb losses occurs in the limit) in the same flare loop. In such cases for protons with $E_p > 25$ MeV and electrons with $E_e > 500$ keV we have

$$(T_p/T_e)_{\max} = T_{Qp}/T_{Qe} \simeq 20,$$
$$(T_p/T_e)_{\min} = T_{Dp}/T_{Qe} = \sigma L\,(\gamma_e + 1)/2 v_p \tau_{E_e}.$$

For $n_0 = 10^{10}$ cm^{-3}, $\sigma = 3$, $L = 10^9$ cm, $v = 7 \cdot 10^9$ cm/sec, and $\gamma_e \approx 4$ we have $(T_p/T_e)_{\min} = 8.4 \cdot 10^{-3}$.

Such a situation is most likely for electrons of relativistic energies (see (2)). For protons with $E_p > 25$ MeV and relativistic electrons we have $(T_p/T_e)_{\max} \simeq 1$ but $(t_p/T_e)_{\min} \ll 1$.

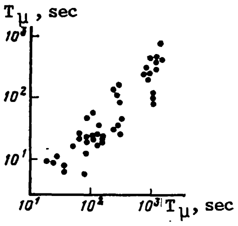

FIG. 4. Relation between the exponential decay time τ_μ and the effective duration $T_\mu = \int F dt/F_m$ of microwave bursts. F_m is the maximum intensity in the burst at the frequency f_m of the spectral maximum. Data were obtained for bursts recorded at the Zimenka Radio Astronomical Station of the Scientific Research Radiophysics Institute at the time of observations by the Venera 13 and 14 spacecraft.

e/p RATIO AND DURATION OF THE μ-BURST

The reason for the decrease in the e/p ratio with increasing duration of a μ-burst obviously consists in a change in the regime of electron and proton diffusion in flare arches.

This is indicated by the fact that the duration of microwave bursts correlates well with the exponential decay time of their intensity, which characterizes the lifetime of electrons in the flare loop ($r \approx 0.9$) (see Fig. 4). This correlation means that the conditions for particle confinement in flare arches becomes less favorable for shorter flares.

At the same time, observations show that the more extended flares are associated with larger flare loops.[7] It is well known from radio-interferometric measurements that the sources of prolonged μ-bursts lie high in the corona and are associated with high ($h \approx$ 10,000-50,000 km) coronal arches, observable in the soft x-ray range.[24] The exponential decay time for such bursts is also long and reaches several minutes. The sources of short μ-bursts are small ($h \approx$ 1000-10,000 km) and are associated with low flare loops.[13] The parameter of a loop that is related to the flare duration, therefore, is apparently its size. This relation holds for all diffusion regimes.

The relation between the duration of energy release and the size of the magnetic system was discussed theoretically by Somov.[25]

The time T_D of pitch-angle diffusion is also closely related to the size of the arch.[26,27] For stationary injection,[28,29] in particular,

$$T_{De,p} \propto \frac{n_{0L}V\nu}{\omega_{BL}I_{te,p}} = \frac{n_{0L}V\Delta t}{\omega_{BL}N_{te,p}}, \tag{9}$$

where $V \propto L^3$ is the volume of the arch, $I_{te,p}$ is the power of the source, $N_{te,p} = I_{te,p}\Delta t$ is the total number of electrons (protons) accelerated during the flare, n_{0L} and ω_{BL} are the background plasma density and the electron (proton) gyrofrequency at the top of the arch, and ν is the characteristic time of wave damping. Since estimates of I_t for pulsed flares (from gamma-ray line emission for protons and from hard x-ray emission for electrons) are usually considerably higher than those for extended flares,[13] from (9) it follows that T_D should depend very strongly on the arch size L. With a tenfold change in L (from $L \approx 10^9$ cm, typical of pulsed flares, to $L \approx 10^{10}$ cm, typical of extended flares, for example), T_D may increase by more than a factor of 10^3. Such considerable changes in T_D undoubtedly must result in a change in the diffusion regimes.

In addition, the threshold energy of the particles, above which coulomb losses predominate, decreases with increasing L. Thus, as L increases, the diffusion regimes succeed each other, resulting in an increase in the particle lifetimes in the trap.

CONCLUSION

Let us enumerate the results obtained in the present work.

1. The SCR events that are accompanied by short μ-bursts are characterized by high e/p ratios; extended μ-bursts accompany events with a low e/p ratio (these events are more proton-rich).

2. The difference between the average e/p ratios for pulsed and extended μ-bursts increases by an order of magnitude in going from moderately relativistic electron energies ($E > 500$ keV) to subrelativistic ones ($E > 70$ keV).

3. The effective duration of μ-bursts correlates well ($r = 0.9$) with and is related linearly to the characteristic time of exponential decay of the μ-burst intensity.

These results and theirm analysis enable us to conclude that the range of variation of the e/p ratio and its decrease in extended flares can be understood without resorting to the hypothesis of a secondary phase of particle acceleration high in the corona. It is sufficient to allow for the differences in the dynamics of electrons and protons in flare arches of different sizes.

Given the fact that the number of escaping particles is $N_{esc} \propto N_t T$, we can also understand the following results that have been obtained earlier:

the large variations of the e/p ratio from event to event for protons with $E > 30$ MeV and for electrons with $E > 3$ MeV and its anomalously high values for pulsed gamma-ray flares[5];

the low correlation between the number N_{tp} of energetic protons, estimated from gamma-ray line emission, and the number $N_{esc,p}$ of protons escaping into interplanetary space[30,31];

the variations of the e/p ratio that exceed by a factor of 30 or more the variations of the ratio of fluences of the nuclear (4-8 MeV) and continuum ($E_\gamma > 30$ keV) gamma-ray emissions of flares[15];

the range in which the rati of the SCR electron flux to the fluence of continuum gamma-ray emission varies is ~100 times smaller than the range of variation of the ratio of the SCR proton flux to the fluence of nuclear gamma-ray emission.

[1] D. C. Ellison and R. Ramaty, Astrophys. J. 298, 400 (1985).
[2] G. E. Kocharov, Itogi Nauki Tekh., Astron. 32, 43 (1987).
[3] R. P. Lin, Space Sci. Rev. 16, 189 (1974).
[4] V. G. Kurt, Yu. I. Logachev, V. G. Stolpovskii, et al., Space Res. 19, 407 (1979).
[5] P. Evenson, S. Yanagita, and D. J. Forrest, Astrophys. J. 283, 439 (1984).

[6] G. E. Kocharov, G. A. Koval'tsov, and L. G. Kocharov, in: Proceedings of the 18th International Cosmic Ray Conference, Vol. 4, Tata Inst. for Fundamental Research, Bombay, India (1983), p. 105.
[7] H. V. Cane, R. E. McGuire, and T. T. von Rosenvinge, Astrophys. J. 301, 448 (1986).
[8] E. I. Daibog, V. G. Kurt, Yu. I. Logachev, et al., in: Proceedings of the 20th International Cosmic Ray Conference, Vol. 3, Nauka, Moscow (1987), p. 47.
[9] V. G. Kurt, Yu. I. Logachev, V. G. Stolpovskii, and E. I. Daibog, in: Proceedings of the 17th International Cosmic Ray Conference, Vol. 3, CEN Saclay, Gif-sur-Yvette, France (1981), p. 63.
[10] V. F. Mel'nikov, T. S. Podstrigach, V. G. Kurt, and V. G. Stolpovskii, Kosm. Issled. 24, 610 (1986).
[11] Yu. I. Logachev, Z. A. Mel'nikov, V. F. Mel'nikov, et al., Catalog of Solar Cosmic Ray Events and Radio Emission of Solar Flares at the Time of Venera 13 and Venera 14 Observations [in Russian], Nauchno-Issled. Radiofiz. Inst., Gor'kii (1987).
[12] E. I. Daibog, V. G. Kurt, Yu. I. Logachev, et al., Izv. Akad. Nauk SSSR, Ser. Fiz. 51, 1825 (1987).
[13] T. Bai, Astrophys. J. 308, 312 (1986).
[14] E. I. Daibog, V. G. Kurt, Yu. I. Logachev, et al., Izv. Akad. Nauk SSSR, Ser. Fiz. 52, 2403 (1988).
[15] E. L. Chupp, D. J. Forrest, J. M. Ryan, et al., Astrophys. J. 263, 195 (1982).
[16] X. N. Hue and R. E. Lingenfelter, Sol. Phys. 107, 350 (1987).
[17] E. I. Daibog, V. G. Kurt, Yu. I. Logachev, and V. G. Stolpovskii, Kosm. Issled. 27, 113 (1989).
[18] H. Nakajima, T. Kosugi, K. Kai, and S. Enome, Nature (London) 305, 292 (1983).
[19] S. F. Kennel and H. E. Petschek, J. Geophys. Res. 71, 1 (1966).
[20] D. G. Wentzel, Astrophys. J. 208, 595 (1976).
[21] B. M. Schulze, A. K. Richter, and G. Wibberentz, Sol. Phys. 54, 207 (1977).
[22] V. L. Ginzburg and S. I. Syrovatskii, The Origin of Cosmic Rays [in Russian], Izd. Akad. Nauk SSSR, Moscow (1963) [translated by H. S. H. Massey, Pergamon Press, New York (1964)].
[23] D. V. Melrose and J. V. Brown, Mon. Not. R. Astron. Soc. 176, 15 (1976).
[24] M. R. Kundu and L. Vlahos, Space Sci. Rev. 32, 405 (1982).
[25] B. V. Somov, Itogi Nauki, Tekh., Ser. Astron. 34, 79 (1987).
[26] V. A. Mazur and A. V. Stepanov, Astron. Astrophys. 139, 467 (1984).
[27] V. V. Zaitsev and A. V. Stepanov, Sol. Phys. 99, 313 (1985).
[28] P. A. Bespalov and V. A. Trakhtengerts, Alfvén Masers [in Russian], Inst. Prikl. Fiz. Akad. Nauk SSSR, Gor'kii (1986).
[29] P. A. Bespalov and V. V. Zaitsev, in: Solar Maximum Analysis. Proceedings of an International Workshop, Irkutsk, USSR, V. E. Stepanov and V. N. Obridko (eds.), VNU Science Press, Utrecht (1987), p. 247.
[30] M. E. Pesses, B. Klecker, G. Gloeckler, and D. Hovestadt, in: Proceedings of the 17th International Cosmic Ray Conference, Vol. 3, CEN Saclay, Gif-sur-Yvette, France (1981), p. 36.
[31] E. W. Cliver, H. V. Cane, D. J. Forrest, et al., in: Proceedings of the 20th International Cosmic Ray Conference, Vol. 3, Nauka, Moscow (1987), p. 61.
[32] G. M. Simnett, Space Sci. Rev. 16, 189 (1974).

Translated by Edward U. Oldham

Multifrequency observations of pulsars

R. N. Manchester, M. V. Popov, and V. A. Soglasnov

Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted April 11, 1989)
Pis'ma Astron. Zh. 15, 1001–1007 (November 1989)

The results of research on the pulses of five pulsars, observed synchronously at 410 MHz (on the Parkes 64-m radio telescope in Australia) and at 928 and 5860 MHz (on the 70-m radio telescope at Ussuriisk) are presented. Correlation between intensity fluctuations over the entire frequency range is observed in the emission of the pulsars PSR 1133 + 16 and PSR 1929 + 10. The relative time shift between the mean profiles of PSR 1749—28 at 410 and 928 MHz is probably related to an inaccurate dispersion measure. It is proposed that the observed phenomenon may be governed by the dynamics of electron–positron plasma production at the jump in electric potential above the surface of the neutron star.

INTRODUCTION

Many characteristics of pulsar radio emission have a definite frequency dependence. The mean pulse profile varies with frequency, both in shape and in the relative intensities of individual components and in the longitude differences among them. The total radio flux density, as well as the mean characteristics of the subpulses and micropulses, also vary with frequency. The frequency dependence of these characteristics of pulsar radio emission can be studied by comparing observtions performed at different times and even on different instruments.[1,2] Observtions of individual pulses carried out synchronously at several frequencies are considerably more enlightening. Comparing the shapes and intensities of individual pulses at different frequencies makes it possible to ascertain how broad-banded pulsar radio emission mechanism is and what the nature of the spectral peculiarities of this emission mechanism might be. Because of the logistical and technical difficulties of carrying out simultaneous

TABLE I

PSR	DM	Δt, msec	DM'
1133+16	4.8413	−0.1	4.84
1642−03	35.665	+2.2	35.78
1749−28	50.88	−7.5	50.50
1822−09	19.33	−2.3	19.21
1929+10	3.176	+1.6	3.25

0360-0327/89/06 0436-04 $02.00