must be 1 mK, the value corresponding to the characteristic energy of the UCNs involved. Candidates for such a moderator are the gels of impurity nanoparticles in superfluid ^{4}He [16–18], which are prepared from inefficient neutron-absorbing materials such as, for example, heavy water or deuterium. Experiments to study the interaction of neutrons with such gels are now underway as a joint effort between our team and the authors of Refs [16–18].

4. Conclusion

In this report we have not attempted to review the subject but limited ourselves instead to presenting the results of our research. The report describes an experiment which has, for the first time, measured the quantum states of a particle in a potential well created by a gravitational field and a horizontal mirror. We also discussed prospects for further developing the experiment. Thus, the narrow resonant transitions between the quantum states of a neutron in the gravitational field of the Earth might be used in precision experiments in fundamental neutron physics — such as the verification of the electrical neutrality of neutrons or measurements of interactions at small distances. Part of the report is devoted to the interaction between neutrons and nanoparticles. In particular, we have discovered and investigated a new loss channel for UCNs in a trap, due to their being weakly heated when interacting with the surface. The heating presumably results from the Doppler shift in UCN energies, caused by their scattering from surface nanoparticles (nanostructures) being in thermal motion. Future research directions in this field include the dynamics of surface nanoparticles, increasing the UCN confinement time in traps, improving the reliability of UCN confinement experiments in fundamental neutron physics, and investigating the possibility of obtaining higher UCN densities by thermalizing neutrons in the gels of ultracold nanoparticles in superfluid ^{4}He.

References

1. Lushchikov V I et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **9** 40 (1969) [*JETP Lett.* **9** 23 (1969)]
2. Nesvizhevsky V V et al. *Nucl. Instrum. Meth. A* **440** 754 (2000)
3. Nesvizhevsky V V et al. *Nature* **415** 297 (2002)
4. Nesvizhevsky V V et al. "Measurement of quantum states of neutrons in the Earth's gravitational field" *Phys. Rev. D* (2003)
5. Strelkov A V, Hetzelt M *Zh. Eksp. Teor. Fiz.* **74** 23 (1978) [*Sov. Phys. JETP* **47** 11 (1978)]
6. Nesvizhevskiĭ V V et al. *Yad. Fiz.* **62** 832 (1999) [*Phys. Atom. Nucl.* **62** 776 (1999)]
7. Strelkov A V et al. *Nucl. Instrum. Meth. A* **440** 695 (2000)
8. Nesvizhevsky V V et al. *Eur. Phys. J.: Appl. Phys.* **6** 151 (1999)
9. Geltenbort P et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **70** 175 (1999) [*JETP Lett.* **70** 170 (1999)]
10. Lychagin E V et al. *Yad. Fiz.* **63** 609 (2000) [*Phys. Atom. Nucl.* **63** 548 (2000)]
11. Lychagin E V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **71** 657 (2000) [*JETP Lett.* **71** 447 (2000)]
12. Nesvizhevsky V V et al. *Phys. Lett. B* **479** 353 (2000)
13. Lychagin E V et al. *Yad. Fiz.* **65** 2052 (2002) [*Phys. Atom. Nucl.* **65** 1995 (2002)]
14. Lychagin E V et al. *Poverkhnost': Rentgenovskie, Sinkhrotronnye Neĭtron. Issled.* (7) 81 (2002)
15. Nesvizhevskiĭ V V *Yad. Fiz.* **65** 426 (2002) [*Phys. Atom. Nucl.* **65** 400 (2002)]
16. Mezhov-Deglin L P, Kokotin A M *Pis'ma Zh. Eksp. Teor. Fiz.* **70** 744 (1999) [*JETP Lett.* **70** 756 (1999)]
17. Kokotin A M, Mezhov-Deglin L P *Fiz. Nizk. Temp.* **28** 235 (2002) [*Low Temp. Phys.* **28** 165 (2002)]
18. Kokotin A M, Mezhov-Deglin L P *Prib. Tekh. Eksp.* **44** (2) 159 (2001) [*Instrum. Exp. Tech.* **44** 279 (2001)]

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On the nature of radio emission from stars of late spectral type

A V Stepanov

1. Introduction

We discuss mechanisms of intense radio emission from stars of late spectral classes: red dwarfs, and close binaries of RS CVn and Algol types. These spectral types (F, G, K, M) are positioned adjacent to the central and bottom parts of the main sequence in the Hertzsprung–Russell diagram, being chosen for following reasons. First, they show strong flaring activity. Second, they are located comparatively close to the Sun (a few units to several tens of parsecs). So the fluxes of their radio emission ($\sim 10^{-3}-1$ Jy) are sufficiently high for detection by modern telescopes. In addition, in order to explain the nature of activity of these stars, the solar–stellar analogies suggested by Gershberg and Pikel'ner [1] more than 30 years ago are largely used.

In contrast to daily observations of the Sun, the radio emission from stars, and especially stellar flares, is a genuine event for astrophysicists. Radio emission from UV Ceti stars was discovered in 1958 by Lowell on the Jodrell Bank telescope (at 204 MHz). Up to the present, radio emission from several hundreds of stars of different spectral types has been registered in the wavelength range from millimeters to decameters. Nevertheless, each observation of radio emission from stars, and especially stellar flares, lends important new information on the processes in stellar atmospheres.

The quiescent radio emission of stars is mainly thermal (bremsstrahlung and synchrotron) but frequently demonstrates a nonthermal character with a brightness temperature $T_b \sim 10^{10}$ K, which is usually related to gyrosynchrotron radiation from fast electrons. Radio emission from stellar flares is characterized by $T_b \sim 10^{10}-10^{16}$ K, a high degree of polarization and clearly has a nonthermal origin.

Table 1 lists energy characteristics of flares from different objects. In spite of radio emission energy from stars being by 4–10 orders of magnitude smaller than, for example, X-ray energy, the radio emission provides extremely rich information about the parameters of stellar atmospheres and processes therein since it is very sensitive to change in the parameters of plasma and high-energy particles. There is a number of excellent reviews [2–7] which describe the results of observations of stellar radio emission and its models. The existing reviews give preference to noncoherent radio emission mechanisms. The present report is dedicated to coherent mechanisms of the flaring radio activity of stars, in particular, to the nonlinear plasma mechanism which is especially effective in stellar coronas.

2. Experimental data

First observations of radio emission from stars were conducted at fixed frequencies. The indubitable progress in the end of the 1980s was due to spectrographic studies of stellar radio emission. Dynamic radio emission spectra of stars (intensity as a function of frequency and time) are similar to solar ones and demonstrate a distinctive fine

Table 1. Forms of flaring energy release (in ergs).

Form of energy release	Sun	Red dwarf	Close binary	
		UV Ceti	RS CVn	Algol
Total energy	$(1-2)\times10^{32}$	$10^{33}-10^{35}$	$\geqslant 10^{38}$	$10^{37}-10^{38}$
UV emission	$(3-5)\times10^{31}$	10^{32}		
Soft X-rays	10^{31}	$10^{30}-10^{33}$	$10^{35}-10^{37}$	$10^{35}-10^{36}$
Optical range	$(1-3)\times10^{30}$	$10^{31}-10^{34}$		
Hard X-rays	$(3-5)\times10^{26}$			
Gamma-rays	$(3-5)\times10^{25}$			
Radio emission	10^{24}	$10^{26}-10^{27}$	$10^{27}-10^{29}$	$10^{27}-10^{28}$
HD motions, shock waves	$(3-10)\times10^{31}$	5×10^{34}	$10^{36}-10^{38}$	$10^{35}-10^{37}$

Table 2. Parameters of coronal flare loops.

Parameter	Sun	Red dwarf	Close binary	
		UV Ceti	RS CVn	Algol
Length l, cm	$(1-10)\times10^{9}$	$2\times10^{9}-3\times10^{11}$	$(5-10)\times10^{10}$	$(2-6)\times10^{11}$
Cross size, cm	$(1-5)\times10^{8}$	$10^{8}-3\times10^{9}$		
Plasma density n, cm^{-3}	$10^{10}-10^{12}$	$10^{10}-10^{12}$	$10^{8}-10^{12}$	$10^{9}-10^{12}$
Plasma temperature T, K	$10^{6}-10^{7}$	$3\times10^{6}-10^{8}$	$(3-9)\times10^{7}$	$(3-7)\times10^{7}$
Magnetic field B, G	$10^{2}-10^{3}$	$3\times10^{2}-10^{3}$	$(0.3-6)\times10^{2}$	$(1-5)\times10^{2}$
Emission measure, cm^{-3}	$10^{47}-10^{50}$	$10^{50}-10^{53}$	$10^{53}-10^{55}$	$10^{52}-10^{54}$

structure, including pulsations, absorption bursts, and spike-bursts [8]. The next important stage in studies of the nature of stellar radio emission, and in particular the structure of stellar coronas and the origin of stellar flares, relates to the very long baseline interferometry (VLBI) providing a high angular resolution of up to fractions of a millisecond of arc. Ultraviolet observations of the Sun by the TRACE spacecraft [9] indicate that active regions represent the system of loops containing dense plasma with a temperature of about $(1-3)\times10^{6}$ K. In the microwave range, such loops are observed at distances below $0.1R_{\odot}$ above the solar photosphere. The solar–stellar analogies suggest that similar loops should be observed on the stars, too. First direct observations of coronal loops were obtained with VLBI for the B component of red dwarf UV Ceti [10]. VLBA/VLA observations at the 3.6-cm wavelength [10, 11] show that loops of dMe stars (UV Ceti, AD Leo, YZ CMi) extend up to distances of 2 to 4 stellar radii, i.e., radio coronas of the stars are much more extended compared to the solar corona. Such emission is usually interpreted as gyrosynchrotron radiation of superthermal electrons in coronal magnetic loops. Although coronal loops of close binary systems of stars have not yet been resolved with the VLBI observations, modern models for radio emission from close binaries also assume the presence of coronal loops with high-energy electrons [12, 13]. X-ray observations by the 'Einstein' and ROSAT spacecrafts [14] show that loops on stars are denser and hotter, up to 10^{8} K. We shall show below that these facts determine to a significant extent the nature of stellar radio flaring.

3. Coherent radio emission mechanisms

3.1 Coronal loop as a magnetic mirror trap

Solar spots occupy less than 0.1% of the disk area. In stellar classes of interest here, the area of stellar spots with a photospheric magnetic field strength of 3–6 kG can be as large as 80% of the stellar disk area. So, the stellar coronas are densely 'packed' with magnetic loops. Parameters of coronal magnetic loops of the Sun and stars are listed in Table 2.

The parameters in Table 2 suggest that the mean free path of particles in the dense thermal plasma is by 3–5 orders of magnitude smaller than the size of the loops. At the same time, the mean free path of electrons with energies $\geqslant 100$ keV exceeds the characteristic size l of coronal loops. The gyroradius r_c of high-energy particles in such magnetic fields is on the order of a few centimeters–meters. Weakly inhomogeneous ($L_B=(\partial B/B\,\partial z)^{-1}\sim l\gg r_c$) magnetic coronal loops with footpoints 'frozen' into the photosphere make up traps with magnetic mirrors for high-energy particles. Therefore, the 'equilibrium plasma + high-energy particles with a loss cone' type distribution forms inside the loops, which is unstable with respect to generation of small-scale waves of different types, such as cyclotron harmonic waves, Langmuir waves, and whistlers.

3.2 Electron cyclotron maser emission

The inverse population due to loss cone leads to the excitation of electromagnetic waves at frequencies multiple to the electron cyclotron frequency ω_c. Here, there is a clear analogy with cyclotron-resonance masers: sources of high-energy particles provide the pumping, collisionless high-energy particles make up the active medium, electromagnetic waves at harmonics of electron cyclotron frequency serve as the working mode, and the dense magnetized plasma and footpoint of the magnetic loop represent the quasi-optical resonator. The intense flaring radio emission from stars, as a rule, is assumed to be the radiation from an electron cyclotron maser (ECM) [4–7]. The ECM emission, which is due to the loss-cone instability, is produced inside a narrow cone across the magnetic field. This is a narrow-band radiation with a dominating extraordinary mode. ECM successfully explains narrow-band ($\Delta\omega/\omega\sim0.01-0.1$) short-term (10–100 ms) solar events — the spike-bursts. However, the realization of ECM in the 'hot' ($10^{7}-10^{8}$ K) stellar coronas meets with the following difficulties:

(1) ECM requires anomalously high values of the coronal Alfven velocity ($>10^{4}$ km s^{-1}), so that the gyrofrequency

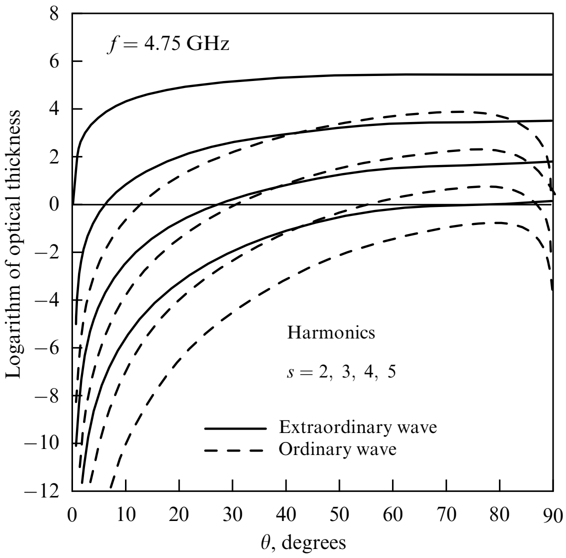

Figure 1. The optical thickness of the gyroabsorption of electromagnetic waves on a frequency of 4.75 GHz as a function of the angle between the magnetic field and the wave vector for $n = 10^{10}$ cm^{-3}, $T = 10^7$ K, and $L_B = 10^9$ cm. The escape 'windows' for the ordinary wave are sufficiently wide ($\sim 10-30°$).

must be higher or on the order of the Langmuir frequency ($\omega_c \geqslant \omega_p$), which is hardly the case in the extended coronal loops.

(2) Another difficulty of ECM relates to the problem of radio radiation escape from the corona [15]. Figure 1 suggests that strong gyroabsorption by thermal plasma in the 'hot' stellar coronas makes extremely narrow 'windows' for escape of the extraordinary wave, several degrees away from the magnetic field direction. For the ECM radiation to escape, an effective mechanism of emission isotropization in the source is required.

(3) The ECM generates narrow-band radiation; thus, it is inappropriate to explain the observed radio emission from stars, which is mainly broad-band ($\Delta\omega \sim \omega$) and is similar to type IV radio bursts from the Sun, on the basis of ECM emission.

(4) ECM gives no explanation for the rich fine structure of the dynamic radio spectra observed.

3.3 Plasma radiation

Observed data, especially dynamic radio spectra of stellar flares [8], evidence a plasma radiation mechanism. Typical features of a plasma mechanism include bursts with rapid frequency drift, sudden reductions of the radio radiation level, pulsations, and polarization of radiation corresponding to an ordinary wave [16, 17]. The plasma mechanism of radio emission, first proposed by Ginzburg and Zheleznyakov [18] to interpret type III solar radio bursts, assumes the generation of plasma (Langmuir) waves with their subsequent conversion into electromagnetic radiation. Nonlinear scattering of plasma waves from the background plasma ions (Rayleigh scattering) leads to radio emission near the Langmuir frequency, and the plasma wave coalescence (Raman scattering) yields radio emission at the second harmonic of the Langmuir frequency.

The plasma waves in stellar coronal loops are excited due to loss-cone instability of the waves of upper hybrid resonance $\omega_{UH} = (\omega_p^2 + \omega_c^2)^{1/2}$ on fast electrons. Electrons can be accelerated up to energies $\geqslant 100$ keV by quasi-stationary electric fields inside magnetic loops driven by convective motions in the photosphere, or by magnetosphere interactions in close binaries. When studying wave instabilities, the 'cold' plasma approximation with zero temperature needs to be recognized as inadequate. The temperature of the plasma background component should be taken into account in dispersion equations. In the 'hot' ($10^7 - 10^8$ K) plasma of stellar coronas, whistlers, which determine, for example, dynamics of high-energy electrons in the solar atmosphere, are suppressed by strong Landau damping. The ECM emission, as was shown above, is absorbed in the corona. In such conditions, the upper hybrid resonance waves, which are generated near the direction perpendicular to the magnetic field, have the largest growth rate. Numerical calculations of instability growth rates of such waves in a 'hot' plasma with moderate magnetic filed ($1 < \omega_p^2/\omega_c^2 < 5$), and with an addition of high-energy electrons with loss cone, demonstrated that the growth rate maximum $\gamma_{max} \approx 10^{-2}(n_1/n)\omega_c$ corresponds to an angle of about 80° between the wave vector and the magnetic field. Here, n_1 and n are the number densities of the high-energy electrons and the background plasma, respectively. The detailed analysis of the loss-cone instability in stellar coronas was performed in Ref. [19].

The solution of the transfer equation for the brightness temperature of the plasma radio emission has the form

$$T_b = \frac{a}{\mu_c + \mu}\left\{1 - \exp\left[-\int_0^L dl\,(\mu_c + \mu)\right]\right\}. \tag{1}$$

The emission and absorption coefficients for radiation of the fundamental tone and the harmonic are

$$a_1 \approx \frac{\pi}{36}\,\frac{\omega_p^3 W_k}{v_g n v_T^2 k}\,, \qquad \mu_1 \approx -\frac{\pi}{108}\,\frac{m_e}{m_i}\,\frac{\omega_p^3}{v_g}\,\frac{1}{nTv_T^2}\,\frac{1}{k}\,\frac{\partial}{\partial k}(kW_k)\,, \tag{2}$$

$$a_2 \approx \frac{(2\pi)^5}{15\sqrt{3}}\,\frac{v_1^5}{\omega_p^2 c^3}\,nTw^2\,, \qquad \mu_2 \approx \frac{(2\pi)^2}{15\sqrt{3}}\,\frac{\omega_p v_1^2}{c^3}\,w\,. \tag{3}$$

In Eqns (1)–(3), $\mu_c = (\omega_p^2/\omega^2)\nu_{ei}$ is the collision absorption coefficient, v_g is the group velocity of the electromagnetic waves, $w = W/nT$, where $W = \int W_k\,dk$ is the plasma wave energy density, v_T is the thermal velocity of electrons, v_1 is the velocity of high-energy particles, and ν_{ei} is the electron–ion collision frequency. The effective length of wave conversion is determined by the characteristic plasma inhomogeneity scale L_n and by the energy ratio of thermal plasma and the accelerated electrons:

$$L \approx 3L_n\left(\frac{T}{E}\right). \tag{4}$$

It should be emphasized that L in the 'hot' coronal loops ($T \sim 1-10$ keV) with electrons of energy $E \sim 30-500$ keV is significantly higher than in the solar corona ($T \sim 100$ eV). This is the answer to the question raised in Ref. [20] of why the efficiency of plasma wave–electromagnetic wave conversion in flares of dMe stars is by several orders of magnitude higher than in solar flares. As seen from Fig. 2, in conditions typical for stellar coronas the harmonic emission dominates over the fundamental tone emission up to a brightness temperature of $T_b \sim 10^{14}$ K. Such a brightness temperature corresponds to the plasma turbulence level $w \sim 10^{-5}$. The exponential increase in the fundamental tone emission (the maser effect)

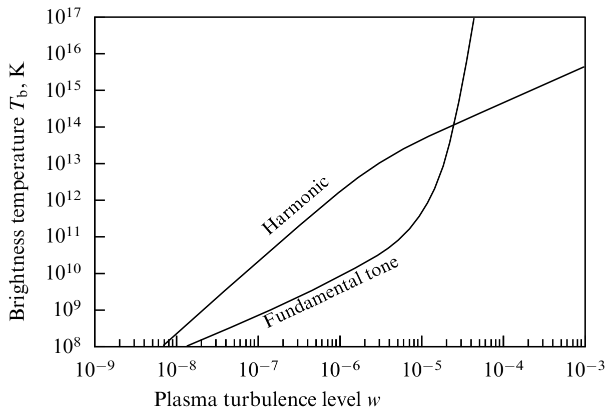

Figure 2. The brightness temperature of the emission of the fundamental tone (1.4 GHz) and the second harmonic as a function of the plasma turbulence level for the typical parameters of AD Leo ($T = 1$ keV, $E = 30$ keV, and $L_n = 3 \times 10^9$ cm).

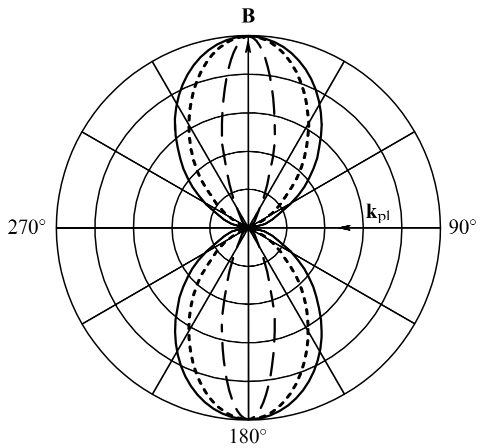

Figure 3. Plot of the angular pattern of the emission at the fundamental tone. The solid line corresponds to the dipole emission $\sim \cos^2\theta$. The maser effect ($\tau = |\mu_1| L \gg 1$) narrows the diagram $\sim \exp(\tau \cos^2\theta)$.

appears for $w > 10^{-5}$. Negative values of the absorption coefficient (2) during Rayleigh scattering, which provides the maser effect, are possible if $\partial(kW_k)/\partial k > 0$ and $|\mu| > \mu_c$, which is realized in stellar coronas.

Relations (2)–(4) correspond to the case of isotropic plasma. The magnetic field changes the spectrum of waves and the radiation pattern. Figure 3 shows normalized radiation patterns for Rayleigh scattering in isotropic plasma (the solid lines) and for $\omega_p^2/\omega_c^2 = 3$ (the dashed lines). The maser effect at a sufficiently high plasma turbulence level leads to further narrowing of the radiation patterns (the long-dashed lines). This effect was first noted by Ginzburg and Zaĭtsev [21] in interpreting the pulsar radio emission by the plasma mechanism. The observed polarization of radiation transferred by the ordinary wave [16, 17] is explained by the source location in the corona below the cut-off level of the extraordinary wave, which naturally holds for the emission at the fundamental frequency. Comparing Figs 1 and 3 we see that the fundamental tone plasma emission easily escapes the source: the ordinary waves escape through the 'transparency windows' without notable absorption. The radiation pattern at twice the plasma frequency (Raman scattering) has a quadrupole character [19], i.e., an additional scattering of waves is required for radio emission to escape the source.

4. Red dwarfs. Fine structure of radio emission

Observations of the active red dwarf AD Leo using large radio telescopes (Aresibo, Jodrell Bank, Effelsberg) operating over the range 1.3–5 GHz revealed the presence of quasi-periodical pulsations against the background of continuum radiation [8, 22, 23]. The period of such high-Q pulsations is of the order of 1–10 s, the modulation depth > 50% and the relative frequency band $\geqslant 10\%$. The pulsations exhibit a frequency drift of 100–400 MHz s^{-1} and a sufficiently large degree of circular polarization (50–100%). Radio bursts with a pulsating structure are characterized by the radiation brightness temperature $10^{10}-10^{13}$ K, which evidences a coherent emission mechanism. Phenomenologically, pulsating radio emission from AD Leo resembles solar type IV pulsating bursts. This led to attempts of explaining the pulsations of AD Leo by MHD oscillations of coronal magnetic loops [8] and pulsating regimes of plasma instabilities [22]. However, the frequency drift of the pulsations suggests rather quasi-periodical injection of fluxes of fast electrons. Consequently, the particle acceleration mechanism in the AD Leo atmosphere provides both the filling of magnetic trap type sources by fast electrons in order to generate the continuum radiation ($\sim 10^{35}$ el. s^{-1}) and the quasi-periodical injection of electron beams into the loops. The electron acceleration in a quasi-steady-state electric field induced by motions of partially ionized plasma in the magnetic loop footpoints can provide such a mechanism [23, 24]. The acceleration mechanism is modulated by proper oscillations of a coronal magnetic arch, which plays the role of the equivalent LRC-circuit. The LRC model [24, 25] allows the estimation of the strength of electric currents in flaring loops ($3 \times 10^{11} - 10^{13}$ A) and the energy stored in them ($10^{34} - 10^{37}$ erg) using the radio emission pulsation period.

Observations of the flare of 31.12.1991 from the red dwarf UV Ceti by the 100-m radio telescope in Effelsberg [26] revealed a series of irregular narrow-band ($\Delta\omega/\omega \sim 1-3\%$) short-term ($\leqslant 0.1$ s) spike-bursts with a brightness temperature of $\sim 10^{12}$ K. On the basis of the coherent plasma mechanism for radio emission it was assumed that the spike-bursts arise due to the upper hybrid frequency wave scattering from the plasma density inhomogeneities which are produced by the plasma turbulence itself. From the frequency, duration, intensity, polarization, and band width of the emission, the plasma number density ($\sim 3 \times 10^{11}$ cm^{-3}), temperature ($\sim 10^7$ K), plasma turbulence level ($w \sim 10^{-6}$), magnetic field (300–800 G), and the characteristic size of the arch inhomogeneity across the field ($\sim 10^9$ cm) were determined.

5. Close binaries

The stronger activity of close binary stellar systems compared to that of single stars is connected with a rapid axial rotation and the binary nature of these systems. Nonetheless, the problem of energy release in close binaries, associated with heating and motion of stellar plasma, shock wave generation, and charged particle acceleration up to high energies, has not yet been solved. The biggest progress in studies of radio emission from such objects has been made in the VLBI observations. The observations at 5 GHz with the angular resolution better than a millisecond of arc [27] revealed the fine spatial structure of flares from UX Ari and Algol. The appropriate radio maps consist of a compact core with a size smaller than that of the active star ($< 0.4 \times 10^{-3}$ second of arc), and a halo that comprises both components of the binary system (3.2×10^{-3} second of arc). In this case, the core coincided with the active component. The flaring emission has fluxes $\sim 10^{-1} - 10$ Jy, i.e., the brightness temperature can be as high as $10^{12} - 10^{16}$ K, which evidences its coherent nature. To interpret this emission, as a rule, ECM or synchrotron radiation of relativistic electrons is usually invoked. These mechanisms, however, fail to explain the salient features of polarization, fine structure, and spectra of radio emission from close binaries. In paper [28], the following arguments were used in favor of the plasma mechanism for radio emission from close binaries. First is the sufficiently high temperature (up to 10^8 K) of the coronas [14] that hampers the ECM emission escaping and, in contrast, increases the plasma mechanism efficiency. Second is the observed polarization of radiation from HR 1099 and UX Ari in the form of the ordinary mode [17]. Third are the rapid variability and the U-like spectral shape of radio emission.

Possibilities of flaring energy release between binary system components are also discussed in the scientific literature. These include interactions between giant magnetic loops belonging to different components and dense current-carrying filaments located between the stars, as well as giant magnetic structures connecting both the components. Paper [29] studies the possibility of a flare in an interstellar current-carrying filament and shows that the dissipation of current with a strength of $10^{12} - 10^{13}$ A in partially ionized matter of the filament can lead to an energy release of order $10^{35} - 10^{37}$ erg, which is sufficient to explain powerful flares in close binaries. Here, the plasma mechanism can play a significant role in radio emission from such flares. In this connection, it seems extremely important to discover intensive radio emission between the binary system components.

6. Conclusions

As noted in the review by Zheleznyakov [2], practically all known radio emission mechanisms in cosmic plasmas have been studied bearing in mind the application to the Sun. However, conditions for realization of such mechanisms on stars, as we have shown, can strongly deviate from those on the Sun. The 'hot' stellar coronal plasma radically changes conditions not only of the wave excitation, but also of their transformation and propagation. In particular, high coronal temperatures reduce the ECM efficiency and favor the plasma mechanism of radio emission. We have considered the nature of radio emission from stars of late spectral classes. Nonetheless, the plasma mechanism can also be important for radio emission from stars of other spectral classes, for example, of chemically peculiar stars.

The VLA observations [30] at frequency 1.4 GHz that concern highly directed, fully polarized coherent radio emission from the magnetic chemically peculiar star CU Virginis were interpreted in Ref. [30] on the basis of the ECM model. However, the ECM model comprehends not only the problem of radiation escape from the source, but also the problem of explaining the spectral width. ECM assumes that a hypothetical accelerator supplies electrons with an energy up to 10 keV. Paper [31] suggests a plasma mechanism for radio emission of CU Vir and gives arguments that help narrow the plasma radio radiation pattern at the fundamental frequency: the magnetic field, nonlinear induced wave scattering process (the maser effect), and regular refraction of radio waves in the stellar corona. These result in a width of angular radiation pattern of about 3°. Therefore, the coherent plasma mechanism explains both the high brightness temperature and the 100% polarization of bursts, as well as the narrow radiation pattern of radio emission from CU Vir.

Further progress in understanding the nature of intense radio emission from stars and, hence, in creating physically justified methods for stellar corona diagnostics and flaring energy release models is related to dedicated observational programs. In this connection, the following observations seem to be in order.

(1) With single-dish radio telescopes, observations of the fine structure of radio emission (the dynamic spectra) in the frequency range from 1 to 43 GHz are important. Here, the study of radio emission pulsations allows us to advance the 'coronal seismology', i.e., to create methods for diagnostics of the plasma parameters and physical processes in stellar coronas, in particular, of the coronal plasma heating. As was shown, the pulsations can be used to estimate the magnitudes of electric currents in the loops and their energy. Observations of the fine structure of radio emission of the 'zebra' type from 'cold' ($\sim 10^6$ K) loops are not excluded. The 'zebra' structure observed in the dynamic radio spectra of the Sun provides the possibility to determine the magnetic field in the corona using frequency intervals between the emission bands ($\Delta\omega \sim \omega_c$). Sudden reductions make it possible to evaluate the parameters of the high-energy electron fluxes injected into the loops.

(2) The VLBI observations provide the possibility to study the form of stellar radio coronas and their structure at different frequencies. In this connection, the VLBI observations of the coronal mass ejection (CME) seem to be actual. The list of applicant objects with possible CME is given in review [32]. The expected mass loss from stars during CME is by 2 – 8 orders of magnitude larger than that from the Sun. Interstellar flares in close binary systems have not yet been studied. The spatial – temporal and polarization characteristics of the interstellar source of radio emission enable us to perform flare diagnostics and to elucidate their nature. The recent communication by J F Lestrade on the discovery of such a source in the VLBI observations is encouraging.

References

1. Gershberg R E, Pikel'ner S B *Comments Astrophys. Space Phys.* **4** 113 (1972)
2. Zheleznyakov V V *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **26** 647 (1983) [*Radiophys. Quantum Electron.* **26** 471 (1983)]
3. Hjellming R M, Gibson D M (Eds) *Radio Stars* (Astrophys. and Space Science Library, Vol. 116) (Dordrecht: D. Reidel Publ. Co., 1985)
4. Dulk G A *Annu. Rev. Astron. Astrophys.* **23** 169 (1985)
5. Kuijpers J *Solar Phys.* **121** 163 (1989)
6. Bastian T S *Solar Phys.* **130** 256 (1990)
7. van den Oord G H J, in *Radio Emission from the Stars and the Sun* (ASP Conf. Ser., Vol. 93, Eds A R Taylor, J M Paredes) (San Francisco, CA: Astron. Soc. of the Pacific, 1996) p. 263
8. Bastian T S et al. *Astrophys. J.* **353** 265 (1990)
9. Schrijver C J et al. *Solar Phys.* **187** 261 (1999)
10. Benz A O, Conway J, Güdel M *Astron. Astrophys.* **331** 596 (1998)
11. Pestalozzi M R et al. *Astron. Astrophys.* **353** 569 (2000)

12. Lestrade J-F et al. *Astrophys. J.* **328** 232 (1988)
13. White S M, in *Cool Stars, Stellar Systems, and the Sun* (ASP Conf. Ser., Vol. 109, Eds R Pallavicini, A K Dupree) (San Francisco, CA: Astron. Soc. of the Pacific, 1996) p. 21
14. Ottmann R, Schmitt J H M M *Astron. Astrophys.* **307** 813 (1996)
15. Melrose D B *Space Sci. Rev.* **68** 159 (1994)
16. Lim J *Astrophys. J.* **405** L33 (1993)
17. White S M, Franciosini E *Astrophys. J.* **444** 342 (1995)
18. Ginzburg V L, Zheleznyakov V V *Astron. Zh.* **35** 694 (1958) [*Sov. Astron.* **2** 653 (1958)]
19. Stepanov A V et al. *Astrophys. J.* **524** 961 (1999)
20. Abada-Simon M et al., in *Cool Stars, Stellar Systems, and the Sun* (ASP Conf. Ser., Vol. 64, Ed. J-P Caillault) (San Francisco, CA: Astron. Soc. of the Pacific, 1994) p. 339
21. Ginzburg V L, Zaitsev V V *Nature* **222** 230 (1969)
22. Güdel M et al. *Astron. Astrophys.* **220** L5 (1989)
23. Stepanov A V et al. *Astron. Astrophys.* **374** 1072 (2001)
24. Zaitsev V V, Urpo S, Stepanov A V *Astron. Astrophys.* **357** 1105 (2000)
25. Zaitsev V V et al. *Astron. Astrophys.* **337** 887 (1998)
26. Stepanov A V et al. *Astron. Astrophys.* **299** 739 (1995)
27. Mutel R L et al. *Astrophys. J.* **289** 262 (1985)
28. Stepanov A V, in *Astrofizika na Rubezhe Vekov. Trudy Vseross. Konf., Pushchino, 17–22 Maya 1999 g.* (Astrophysics at the End of the Century. Proc. All-Russia Conference, Pushchino, May 17–22, 1999) (Eds N S Kardashev, R D Dagkesamanskiĭ, Yu A Kovalev) (Moscow: Yanus-K, 2001) p. 127
29. Ipatov A V, Stepanov A V *Vistas Astron.* **41** 203 (1997)
30. Trigilio C et al. *Astron. Astrophys.* **362** 281 (2000)
31. Kupriyanova E G, Stepanov A V *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **44** 788 (2001) [*Radiophys. Quantum Electron.* **44** 726 (2001)]
32. Houdebine E R, in *Magnetodynamic Phenomena in the Solar Atmosphere — Prototypes of Stellar Magnetic Activity* (Eds Y Uchida, T Kosugi, H S Hudson) (Dordrecht: Kluwer Acad. Publ., 1996) p. 147