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Abstract

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MAGNETOBREMSSTRAHLUNG IN A VARIABLE FIELD AS A MECHANISM OF THE CHANGING LUMINOSITY OF QUASI-STELLAR RADIO SOURCES*

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The purpose of this note is to draw attention to a mechanism for the variable luminosity of quasi-stellar radio sources (quasars) that lies within the framework of the presumed magnetobremsstrahlung nature of their radiation ($^{1—4}$). At present the optical variability of 3C 273-B (^{5,6}) and 3C 48 (^{4,7}) is reliably known; there are grounds (^{7}) for also considering the luminosity of 3C 196 to be variable. In the best-studied source, 3C 273, according to (^{6}), the following are observed: a) systematic oscillations of the brightness with period $P \approx 10$ years; b) phenomena of a "flare" type, with durations from a week to a month and with brightening by up to a factor of two.

The nature of the variable luminosity of quasars is still unknown and constitutes perhaps their most enigmatic feature. A number of hypotheses ($^{7—10}$) have been proposed, in rather general form, to explain short-period fluctuations of luminosity. The only attempt to explain the periodic changes in the brightness of 3C 273 assumes (^{11}) that the radiative equilibrium of the emitting region is subject to periodic perturbations because of interaction with the surrounding medium.

It seems more natural to seek an explanation of the periodic variability primarily in the internal properties of the objects, within the framework of the mechanism of their emission. The optical radiation of 3C 48 has a magnetobremsstrahlung nature (^{4}); with regard to the continuous spectrum of 3C 273, which was formerly considered to be due to $f—f$ transitions (^{12}), serious arguments have also been advanced in favor of a magnetobremsstrahlung nature (^{3}). In this connection it seems reasonable to regard the periodic variations of quasar luminosity as a consequence of oscillations of the principal parameters of the magnetobremsstrahlung mechanism—the magnetic-field strength H and the concentration of relativistic electrons N_e.

The contribution of these fluctuating terms to the observed changes in luminosity may, generally speaking, be different. But in view of the specific condition

$T_o \ll P$ (1), where T_o is the characteristic time of optical losses, it seems natural to associate the long-period changes in brightness primarily with oscillations of the magnetic-field strength, and not with changes in the number of relativistic particles.**

The spectral density of the radiation produced by an ensemble of electrons in a magnetic field is

$$F_\nu \propto K_\nu H^{(\gamma+1)/2} \nu^{-(\gamma-1)/2}, \tag{1}$$

where K_ν is the coefficient in the energy spectrum of relativistic electrons $N_e(E)\,dE = K_\nu E^{-\gamma} dE$, referred to the entire volume of the source. Let, for example, the power of the injectors be constant and independent of the magnetic field, i.e., electrons of unchanging energy and concentration radiate in magnetic field of variable strength (on the realization of this model, see below). Then the relative change in flux is

$$\delta F_\nu / F_\nu = \frac{1}{2}(\gamma+1)\delta H/H = (\alpha+1)\delta H/H, \tag{2a}$$

where $\alpha = (\gamma-1)/2$ is the spectral index. The doubled amplitude of the brightness oscillations of 3C 273 is $\approx 0^m.5$ (5), i.e. $\delta F/F \approx 0.26$. Taking $\alpha = 0.2$ (3), we find $\delta H/H \approx 0.2$. Thus, 20% periodic changes of the magnetic field could produce the observed periodic oscillations of the luminosity.

For the proposed mechanism of variations in the light flux, the light curves at different wavelengths should be in phase, which agrees with observations (7). More important is the circumstance that, because of the non-power-law character of the spectrum in the high-frequency region (4,8,12,14) and the displacement (during oscillations of the magnetic field) of the frequency corresponding to the maximum of the synchrotron-radiation spectrum of an individual electron, some change in the color indices along the light curve should occur. The latter is indeed observed (4,7).

Variations of the magnetic field in quasars may in principle be due to causes of either geometrical or (and) physical character.

I. **Geometrical nature of the variability of the magnetic field.** The simplest geometry that realizes periodic modulations of the field is rotation of

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** Of course, the number of injected particles may depend on the magnetic field. We wish only to emphasize that in this case the cause of changes in the light flux is variations of the magnetic field.

the source, in which the line of sight intersects regions of different strength of a quasiregular inhomogeneous field. In this case the variations in the luminosity of the object are described, for constant injector power and without allowance for the nonsphericity of the nucleus, by formula (2a)*. An a priori basis for the expected rotation is the closeness, noted in (11), of the orbital frequency of a particle moving in the gravitational field $M/\odot = 10^8$ at a distance $R = 2 \cdot 10^{16}$ cm (these values are usually used as the parameters of the nucleus of 3C 273 (6,14,18)) to the frequency of the brightness variations of 3C 273. Obviously, the circular frequency of a test particle can also be regarded as an upper value of the angular velocity of the optical source.

Let us note that rotation of a nucleus emitting a continuous spectrum may not be reflected dynamically in the atmosphere, where the emission lines are formed. On the contrary, the assumption (8) of the presence of rotation of the envelope, together with the spectroscopically observed velocities, leads to a law of rotation of the inner region and the envelope of the form $\omega \propto r^{-1}$, or $v \approx \text{const}$. The latter requires large masses $\sim 10^9 \div 10^{10} M_\odot$ for their small concentration toward the center, which contradicts the comparatively small mass of the atmosphere (14,15). Moreover, the profiles of the emission lines are not purely rotational (3) and indicate the probable presence of nonstationary dynamical motions of the atmosphere.

Although rotation of the nucleus appears quite admissible, in view of the absence of its observational confirmation it is expedient to consider another possibility, one promising more consequences comparable with observations.

II. **Physical nature of the variability of the magnetic field.** The region from which the observed light flux comes (it is already a comparatively thin radiating layer (1)) may be subjected to the action of periodic disturbances propagating from within, which modulate the magnetic field of the source. A possible physical mechanism that ensures the emergence of such disturbances is the pulsation of a massive star (superstar) located inside the quasar nucleus. Let us roughly estimate its parameters.* If the structure of the superstar, in whose quasi-stationary equilibrium radiation plays the decisive role, is approximated by a polytrope of index $n = 3$, then the proper frequency of its adiabatic radial pulsations (16) is

$$\sigma_0 = 2\pi/P = \left[{}^{9}/_{10}\,(\Gamma - {}^{4}/_{3})\,\pi G \rho_c\right]^{1/2} . \tag{3}$$

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* The small magnitude of the polarization of the optical radiation of 3C 273 (13) does not contradict the ordering of the magnetic field, since strong depolarization occurs already in the thin surface layer of the optical source, where the regular field passes into a chaotic inhomogeneous field of the nucleus (maintaining the nucleus in a quasistationary state). If, however, rotation is not the direct cause of the variability, then the mechanism of the latter may be connected with the very character of the confinement of the nucleus by the magnetic field (periodic circulation of the plasma; see Sec. II).

Here

$$\Gamma = \beta + (4 - 3\beta)^2(\gamma - 1)/[\beta + 12(\gamma - 1)(1 - \beta)]$$

is the adiabatic exponent of the mixture of plasma and radiation; $\beta \equiv p_g/(p_g + p_r)$; ρ_c is the unperturbed central density (for $n = 3$, $\rho_c = 54.18\,\bar{\rho}$ (17)). In the case of interest to us, when $\beta \ll 1$ and $\gamma = 5/3$ (ideal plasma), $\Gamma = {}^4/_3 + \beta/6 + \ldots$. If β and the molecular weight μ are constant over the "star," one may use, for the order-of-magnitude estimates we need, the exact result of polytropic theory $\mu\beta = 4.33\,M_\odot^{-1/2}$, where the coefficient corresponds to the polytrope $n = 3$ (see, for example, (19)), so that $\Gamma - {}^4/_3 = 1.44\,M_\odot^{1/2}$. For a superstar mass $M_\odot = 10^5$, the observed value of the luminosity-oscillation period $P \approx 10$ yr corresponds, according to (3), to $\rho_c \approx 5 \cdot 10^{-7}$ g/cm^3; in this case $R \approx 2 \cdot 10^{15}$ cm and $T_c \approx 10^6\,^\circ$K (the relativistic correction to the pulsation frequency is negligibly small here). Under these conditions the nuclear energy output is still insufficient, and the superstar shines only at the expense of the work of contraction, unless it has a concentration of matter toward the center substantially greater than that of a polytrope with $n = 3$ (ordinary variable stars are better described by models with high concentration).

Although the superstar may constitute only a small fraction ($\sim 10^{-3}$) of the dynamical mass of the quasar nucleus, its magnetic field is a substantial part of the field in which the optical electrons radiate. Such a field in the magnetosphere (tens of oersteds at $R \gtrsim 10^{16}$ cm for 3C 273 (1)) gives the dipole component of the relic field $H \approx 10^4$ oersteds, formed during contraction in the course of magnetic collapse (21) of a large mass from a state, for example, with $\rho_0 \approx 10^{-26}$ g/cm^3, $H_0 \approx 10^{-7}$ oersted. The presence of a large field in the superstar strongly counteracts convection, which transports energy. It can be shown that, since the radiative thermal conductivity greatly exceeds the magnetic and radiative viscosities, convection proceeds in the form of an oscillatory instability leading to the propagation of a wave with growing amplitude (22) and promoting the maintenance of the superstar’ s pulsations.

If, under changes in the magnetic-field strength caused by pulsation of the superstar surface, the density of relativistic electrons of a given energy, averaged over the period, remains unchanged, then $K_\nu \propto r^3$, and, taking into account conservation of magnetic flux during pulsations, from (1)

$$\delta F_\nu/F_\nu = {}^1/_2(\gamma - 2)\delta H/H. \tag{2b}$$

In this case, for $\gamma \approx 2$, luminosity oscillations under changes in the field should be absent owing to the compensating change in the number of relativistic particles in the radiating region. If, however, the injection conditions themselves depend on the field and, say, the energy of the incoming particles changes adiabatically with the change in the size of the region, then $K_\nu \propto r^{-(\gamma-1)}$ and

$$\delta F_\nu / F_\nu = \gamma \, \delta H / H. \qquad (2c)$$

In the latter case, obviously intermediate between (2a) and (2b), for the periodic brightness oscillations of 3C 273 one requires $\delta H/H \approx 0.2$, so that the required change in the size of the emitting region is $\delta r/r \approx 0.1$. For comparison, we note that for Cepheid oscillations $\delta r/r \approx 0.05 \div 0.1$.

Apparently, oscillations of the magnetic field occur against a dynamic background, accompanied by secular contraction of both the nucleus (as a result of energy dissipation) and the super-star (if the nuclear output in it is insufficient), and, possibly, by some expansion of the emitting layer as the luminous flux from the nucleus increases. The condition that the magnetic field be frozen into the plasma will lead to a systematic decrease in the field strength and, consequently, to a decrease in luminosity. Already for expansion of the emitting layer in 3C 273 with $v = 10^6$ cm/sec, model (2c), as is easy to show, gives a fall of the luminous flux by $0^{\mathrm{m}}.4$ per century. It is interesting that just such a secular weakening of the brightness is quite confidently noted in observational material covering about 80 years (6,23). If the super-star in a quasi-stellar radio source is still in a state of secular contraction, the period of its pulsations will vary as $\rho_c^{-1/2}$ in accordance with (3).

Field modulations may also be due to circulation motions in the nucleus (24). Because pure periodicity of the latter is impossible, turbulence is inevitable, leading to phenomena of the "flare" type. Along with the magnetic-field fluctuations it causes, sporadic changes in the brightness of a quasi-stellar radio source may also receive a contribution from ejections of relativistic particles. The choice between the various possible combinations of δH and δN_e in this case, as in the case considered above of periodic field oscillations, can be made by analyzing changes in color indices; parallel measurements of the gamma-ray flux from 3C 273 are of great importance, since its variations will differ quantitatively depending on whether or not, along with the density of thermal photons, the concentration of relativistic electrons is changing. It is not excluded that in some quasars observed at the stage of strong concentration of matter toward the center, the radio luminosity will also prove variable.

Summing up what has been said, it seems possible to conclude that luminosity oscillations of quasi-stellar radio sources are an effective indicator of changes in their magnetic field caused by internal processes in the central regions.

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* Similar estimates, based on orienting values for the mass and size of the object, were given earlier in (2), wh

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