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Abstract

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ASTRONOMY

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ON THE MAGNETIC FIELDS OF COLLAPSING MASSES AND THE NATURE OF SUPERSTARS

The discovery of superstars (star-like extragalactic objects 3C48, 3C273-B, and others; see ([1])) and attempts to find a mechanism for the formation of radio galaxies have drawn attention to the problem of the gravitational collapse of large masses of gas ([2], [9]). It remains, however, still completely unclear in what way and under what conditions a cloud of gas or a protostar with a mass reaching $10^8 M_\odot$ can form and collapse as a single whole. Nor has it been shown that, when the nonsphericity of the problem is taken into account, gravitational collapse can in fact lead, at least in some cases, to the appearance of the observed superstars and to the powerful explosions responsible for the formation of radio galaxies. Nevertheless, attempts already now to analyze various possibilities and astrophysical data, proceeding from the assumption of the collapse of large masses (below, for definiteness, we shall call them protostars), seem entirely justified. In ([2]) such an analysis is carried out in two directions. The first of them is connected with going beyond the limits of existing physical ideas (the introduction of a C-field with negative energy density, the assumption of the "creation" of matter). Such attempts seem to us at least premature, and we shall rely on the general theory of relativity without any modifications of it. The second direction, discussed in ([2]), is connected with taking into account the fact that the collapsing protostar possesses a gravitational field (at a distance $r \gg R_g = 2\chi M/c^2$ the gravitational potential in this case, of course, has the Newtonian value $\varphi = -\chi M/r$). Therefore the collapsed protostar contributes to the dynamics of the system—the cluster of galaxies, the individual galaxy, or the binary star, one of whose components is collapsing. In the accompanying reference frame the collapse time τ is of the order of the free-fall time of a particle in a field with potential $\varphi = -\chi M/r$. Both from this and by a more rigorous method ([2], [3]) we obtain the value $\tau \sim (\chi\rho_0)^{-1/2}$, where $\rho_0 = 3M/4\pi R_0^3$ is the initial density of the protostar (initial radius $R_0 \gg R_g$). Since for an "external observer" (in a region with a quasi-Galilean metric) the surface of the collapsing protostar reaches the gravitational radius R_g only after an infinite time, this surface could in principle be observed for quite a long time. However, because of the fall in luminosity caused by the decrease of the surface and the curvature of light rays ([3]), observing the surface of a collapsing star at any sufficiently late stage of collapse is scarcely possible. Detection of such an object through the deflection, by it, of light rays passing near it from other sources likewise requires exceptionally favorable conditions.

In connection with the above, it seems to us that the discussion of the possible role of the magnetic field of a collapsing protostar deserves special attention; this is the purpose of the present note.

For isotropic compression of a sufficiently well-conducting protostar with initial field H_0, this field, owing to conservation of flux $\int H\,dS \sim HR^2$, will increase according to the law

$$H(R) = H_0 \left(\frac{\rho}{\rho_0}\right)^{2/3} = H_0 \left(\frac{R_0}{R}\right)^2. \tag{1}$$

Understanding by $H(R)$ the field at the surface, and assuming that outside the protostar the field is dipolar, one may suppose that the effective magnetic moment of the protostar changes according to the law

$$\mu(R) \sim H(R)R^3 = H_0 R_0^2 R \sim \mu(R_0)\frac{R}{R_0}, \qquad H(r) \sim \frac{H_0 R_0^2 R}{r^3},$$

where $H(r)$ is the field at a distance $r > R$ from the protostar with radius R. Carrying out the calculation nonrelativistically, we cannot consider the region $R \lesssim R_g$. If, however, one puts $R = \xi R_g$, then, in order of magnitude, the estimates are already suitable for $\xi \simeq 2\div3$. This means that for rough estimates one may nevertheless set $R \sim R_g$. We give three rather arbitrary examples (see Table 1).

Table 1

Example No.	$M/M_\odot$	R_0, cm	ρ_0, g/cm^3	$\tau \sim (\chi\rho_0)^{-1/2}$, sec	R_g, cm	H_0, oerst.	$H(R \sim R_g)$
1	10^8	10^{19}	10^{-16}	$3 \cdot 10^{11}$	10^{13}	10^{-3}	10^9
2	10^3	10^{12}	1	$3 \cdot 10^3$	10^8	1	10^8
3	~ 1	10^{11}	1	$3 \cdot 10^3$	10^5	1	10^{12}

Of course, strong fields can be attained only if during the collapse time τ the field does not have time to decay as a result of finite conductivity. Hence follows the condition (see (4), taking $R \sim R_g$):

$$\tau \ll t_0 \sim \frac{4\pi\sigma(R_g)R_g^2}{c^2}. \tag{2}$$

For a star of the solar type $\sigma_0 \sim 10^{16}$, and if the mean temperature did not change during compression, then $\sigma(R_g) \sim \sigma_0$ and $t_0 \sim 10^6$; for examples Nos. 1 and 2, at the mean temperature of the Sun, we obtain $t_0 \sim 10^{22}$ and $t_0 \sim 10^{12}$ sec. In all cases condition (2) is satisfied.*

Thus, for collapsing protostars one may quite well expect preservation of the field, although a final conclusion cannot be drawn before a more consistent estimate of the electrical conductivity of the object at $R \sim R_g$. The magnetic energy of the protostar

$$W_M(R) \sim \frac{H^2}{8\pi}\frac{4\pi}{3}R^3 \sim H_0^2 R_0^3 \frac{R_0}{R} \sim W_M(R_0)\frac{R_0}{R}$$

(see (1)). The energy $W_M(R_0)$ is negligibly small in comparison with the gravitational energy $|\Omega(R_0)| \sim \chi M^2/R_0$, and, obviously, $W_M(R)/|\Omega(R)| \sim W_M(R_0)/|\Omega(R_0)|$. For the examples given, this ratio is of order 10^{-6} (for $M \sim 10^8 M_\odot$) and $\sim 10^{-16}$ (for $M \sim M_\odot$). At the same time, in the first case the absolute value $W_M(R_g) \sim 10^{56}$ erg is very large ($|\Omega(R_g)| \sim Mc^2 \sim 10^{62}$ erg for $M \sim 10^8 M_\odot$).

The most important question, of course, is that of the change of the magnetic field in the relativistic phase of collapse. We shall discuss this question in the following communication [10], but for the present we can make in this connection only a few remarks. In the Schwarzschild metric (see, for example, [5]) the field of a constant magnetic dipole, as can be shown, has the form (the dipole is directed–

* Condition (2) is moreover too stringent, since the time for the change of R (the fall time) from R_0 to $R \sim R_g$ is compared with the decay time in the already compressed state. The fall time along the path $\sim R_g$ is of order $\tau_0 \sim R_g/c$. Therefore the necessary condition for preservation of the field evidently has the form $\tau_0 \ll t_0$, i.e.

$$\sigma(R_g) \gg \frac{c}{4\pi R_g} = \frac{c^3}{8\pi\chi M}.$$

placed along the axis $\theta = 0$):

$$H_r = \frac{2\cos\theta}{r^3} f(r)\,\mu, \qquad H_\theta = \frac{\sin\theta}{r^3}\,\Psi(r)\,\mu,$$

$$f(r) = -\frac{3r^3}{R_g^3}\left\{\ln\left(1-\frac{R_g}{r}\right)+\frac{R_g}{r}+\frac{1}{2}\left(\frac{R_g}{r}\right)^2\right\}, \tag{3}$$

$$\Psi(r) = \frac{3r^2}{R_g^2}\left\{\frac{1}{1-R_g/r}+2\frac{r}{R_g}\ln(1-R_g/r)+1\right\}\sqrt{1-R_g/r}.$$

Of course, $f(r) \to 1$ and $\Psi(r) \to 1$ for $r \gg R_g$. It follows from (3) that the dipole field increases without bound as one approaches the gravitational radius ($f(r) \simeq -3\ln(1-R_g/r)$ and $\Psi(r) \simeq 3(1-R_g/r)^{1/2}$ as $r \to R_g$). In such a field the component of the energy-momentum tensor $T_0^0 = -H^2/8\pi$ increases as $(1-R_g/r)^{-1}$, and the total field energy outside the protostar

$$W_{M,\mathrm{rel}}(R) = -2\pi\int_0^\pi\int_R^\infty T_0^0\left(1-\frac{R_g}{r}\right)^{-1/2} r^2\sin\theta\,d\theta\,dr \to \frac{6\mu^2}{R_g^3}\left(1-\frac{R_g}{R}\right)^{-1/2}$$

for $R = R_g + \varepsilon,\ \varepsilon \ll R_g$, where R is the "radius" of the protostar.

In other words, in comparison with the nonrelativistic value $W_M(R_g) \sim \mu^2/R_g^3 \sim H_0^2R_0^4/R_g$, an additional factor $(1-R_g/R)^{-1/2}$ appears. Therefore, if the magnetic moment μ does not tend to zero as the surface of the collapsing star approaches the singular sphere, the role of the magnetic energy increases and its influence on the collapse itself must be taken into account. In fact, such a situation can hardly occur. First, the mass of the star is

$$M = -\frac{4\pi}{c^2}\int T_0^0 r^2\,dr,$$

and therefore the corresponding contribution of the external magnetic field is characterized rather by the expression

$$\Delta M = \frac{1}{2c^2}\int_0^\pi\int_R^\infty H^2r^2\sin\theta\,d\theta\,dr \simeq \frac{6\mu^2}{R_g^3c^2}\ln\left(\frac{R_g}{R-R_g}\right) \qquad (\text{for } R \to R_g).$$

Second, in the model of a star with a sharp boundary ([3]), as the calculation shows,

$$\mu = \mu(R_0)\,\frac{R_g}{R_0f(R)} \simeq \mu(R_0)\frac{R_g}{3R_0}\ln\left(\frac{R_g}{R-R_g}\right) \qquad (\text{for } R \to R_g).$$

For a star with a diffuse boundary or with a turbulent envelope, the moment μ may not tend to zero, or may tend to zero very slowly ([10]). However, in this case the field H, probably, is everywhere finite, including in the late stages of collapse.

In view of all that has been set forth, the possibility of the existence of a giant magnetosphere around large collapsing protostars appears to merit discussion. The presence of a magnetosphere, of course, radically changes the manifestations of a collapsing protostar from the point of view of an external observer. Thus, for example no. 1, even at a distance $R \sim 10^{15} \sim 10^2 R_g$ the field is $H \sim 10^3$, which leads to a rather large Zeeman splitting of spectral lines. Rotation of the plane of polarization of radio waves will be noticeable at still larger distances.* Such effects appear, however, to be secondary in comparison with the possible role of radiation belts around a collapsing magnetic protostar. The relativistic and nonrelativistic particles forming these belts will

* For example, when the environs of a collapsed magnetic protostar are probed by polarized radio emission from discrete sources (^{6}), a noticeable rotation of the plane of polarization may be observed at distances many orders of magnitude greater than R_g. At the same time the deflection of light rays in the gravitational field of the star is

$$\alpha = \frac{2R_g}{R}$$

(the closest distance of the ray from the protostar is $R \gg R_g$) and can hardly be noticed for $R \gtrsim 10^2 R_g$.

source of electromagnetic waves belonging to the radio, optical, and X-ray ranges. Suffice it to say that the cyclotron frequency of an electron, $\omega_{\mathrm{H}} = eH/mc = 1.76 \cdot 10^7 H$, in example No. 1 ($M \sim 10^8 M_\odot$) reaches the value 10^{16}. In this case, for example, an electron with energy $\sim 10^7$ eV will radiate mainly at the frequency $\omega_m \sim \omega_{\mathrm{H}}(E/mc^2)^2 \sim 10^{19}$ ($\lambda_m \sim 1$ Å). The energy of the particles in the belts may be comparable with the magnetic energy, i.e., for the same example No. 1 may reach 10^{56} erg. Incidentally, we see no reason why this value cannot be increased by several more orders of magnitude (see above). The noteworthy circumstance is that, under the assumption of a magnetic-bremsstrahlung mechanism for the radiation of the super-star 3C273-B, we obtained in (7), for an object of radius $R \sim 10^{16}$ cm, the value $H \simeq 10^2$ and an energy reserve $W \sim 3 \cdot 10^{57}$ erg, necessary to sustain the radiation for 10^3 years. In example No. 1, however, the field is $H \sim 10^2$ at a distance $r \simeq 2 \cdot 10^{15}$ cm. Thus it seems possible to us to advance the hypothesis that "super-stars" are not giant nonequilibrium stars, but radiation belts or magnetoturbulent atmospheres[(10)] around large collapsing magnetic proto-stars. The development of this hypothesis is connected with the need to analyze numerous questions, above all such as the role of magnetic-bremsstrahlung losses and the mechanism of particle acceleration in the belts (the magnetic field of the collapsing proto-star is variable, and therefore in its magnetosphere the action of a vortex electric field must be taken into account). We note that in (2), in order to explain the mechanism of energy injection from a collapsed proto-star into interstellar space, the existence of a C-field is assumed. If the proto-star has a magnetosphere, however, such injection is possible as a result of known mechanisms. From this point of view, in order to explain "energy pumping" in the Crab Nebula (see, for example, (2)), one might suppose that the collapsing supernova of 1054 is surrounded by a sufficiently powerful magnetosphere (even for $M \sim M_{\odot}$, the field energy in the magnetosphere W_M needed to explain the observations may be still considerably less than $Mc^2 \sim 10^{54}$ erg). As has already been pointed out, such a magnetosphere may in principle also be a source of X-ray radiation (this possibility is of interest in connection with the discovery of a discrete source of X-rays[(8)]).

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