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THE ELECTRIC CHARGE OF STARS

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Stars carry electrical charges, the sign and magnitude of which are determined by exchange processes between the star and the surrounding medium. The corresponding potential differences in the case of dense objects (neutron stars, and also bodies existing near their own gravitational radius) may reach tens of billions of volts, and are able to accelerate positrons, which should be produced near dense objects, up to similar energies.

THE goal of the present communication is to show that processes involving the exchange of matter between stars and the surrounding medium should lead to the existence of an appreciable electric charge on stars.

Of course, certain stars possess a regular magnetic field and they are also able to induce certain emf's due to their rotation. However, the magnitude of these emf's sharply depends on the specific conditions near the object, and the corresponding charges are neutralized quite near to the star. According to what is stated below, astronomical bodies are electrostatic generators even in the complete absence of any magnetic fields associated with them.

If stars existed in vacuum, then they might carry arbitrary charges on them. In actual fact, however, there is a continuous exchange of matter: matter either falls in on the object (accretion) or else it is ejected from it (ejection), or else both processes go on simultaneously. Exchange strictly fixes the charges on stars.

Let us go on to the calculations. From the conditions for a steady state, it follows that in the course of the exchange the ion currents and the electron currents are always identical: $n_i v_i = n_e v_e$. Let us show that the concentrations in the currents are also identical with a large degree of accuracy: $n_i = n_e$. In fact, the gravitational attraction of a star necessarily exceeds the electrostatic interaction of the surplus of charges which exist inside a sphere of radius r:

$$GMm_p > e^2 \delta n r^3 \equiv e^2 \delta n (\Delta M / m_p n); \qquad (1a)$$

here M denotes the mass of the star, m_p and e are the mass and charge of a proton, $\delta n \equiv |n_i - n_e|$, and r is the distance of interest to us from the star. From (1a) it follows that

$$\delta n / n < (Gm_p^2 / e^2)(M / \Delta M). \qquad (1b)$$

As is shown in the Appendix, for each star of mass M there exists a minimum intensity $[dM/dt]_{min}$ of the exchange processes. The mass of matter which is moving near the object always exceeds the value

$$\Delta M_{min} = [dM / dt]_{min} R / v \geqslant 100\ \text{g}; \qquad (1c)$$

here R denotes the radius of the star, v denotes the velocity of the matter for $r \sim R$; $R/v = \min \simeq 10^{-4}$ sec is reached for neutron stars and for collapsing stars. Thus, according to (1b) one always has $\delta n/n < 10^{-4}$. In typical situations the "margin" is impressive: for the sun $\delta n/n < 10^{-18}$ and for pulsars in the Crab nebula $\delta n/n < 10^{-15}$. Thus, the equality $n_e = n_i$ and consequently also $v_e = v_i$ are satisfied with a high degree of accuracy.

Since the boundary conditions for particles of both types are the same, then the equality of the velocities stipulates the equality of the accelerations:

$$\begin{gathered} w_i = w_{gr} - ZF_{el} / m_i - \nabla p_i / nm_i - F_{r(i)} / m_i, \\ w_e = w_{gr} + F_{el} / m_e - \nabla p_e / nm_e - F_{r(e)} / m_e, \\ w_i = w_e. \end{gathered} \qquad (2)$$

Solving this system of equations, we find

$$F_{el} = \frac{m_i}{m_i + Zm_e}\left[F_{r(e)} + \frac{\nabla p_e}{n} - \frac{m_e}{m_i}\left(\frac{\nabla p_i}{n} + F_{r(i)}\right)\right]. \qquad (3)$$

Here F_{el} and F_r denote the electrostatic and radiative forces, Z denotes the charge on an ion, ∇p_i (∇p_e) denotes the gradient of the sum of the ionic (electronic) pressure and the pressure on the particles due to magnetic fields which are frozen in the plasma; the velocity of motion of the plasma is assumed to be nonrelativistic.

If the absorption of the radiation in lines is large, so that $F_{r(i)} > (m_i/m_e) F_{r(e)}$, then the star may turn out to be negatively charged. Below we shall investigate the opposite case in detail; from a practical point of view it is of more interest; it occurs when the ionization of the gas is appreciable and $F_{r(i)} \ll (m_i/m_e) F_{r(e)}$. In this connection the star carries a positive electric charge. The corresponding potential is given by

$$\varphi_{el} \approx \frac{m_i c^2}{e} \frac{\varphi_{grav}}{c^2} \frac{F_{r(e)} + \nabla p_e/n}{F_{grav(i)}} = 9.4 \cdot 10^8 \frac{m_i}{m_p} \frac{\varphi_{grav}}{c^2} \left(\frac{L}{ZL_0} + \alpha \right) \text{ [V]}, \quad (4)$$

where e denotes the electron charge, φ_{grav} is the gravitational potential on the surface of the star, L is the luminosity of the star, L_0 denotes the luminosity at which the radiative repulsion of the gas would be comparable with the gravitational attraction of the star (see[1]). The quantity α is determined by the exchange processes. In connection with the accretion which accompanies the transition through the velocity of sound, $\alpha \ll 1$; for subsonic accretion (precipitation) $\alpha \lesssim 1/2$; for emission $\alpha \gtrsim 1/2$. In the interior of the star $\alpha = 1/2$ and $\varphi_{el} \approx m_i \varphi_{grav}/2e$—this is the well-known "thermodynamic" electro-potential.[2]

If one talks about electrons, then the electrostatic force which attracts them to the star is essentially cancelled by the radiative force and by the pressure gradient. However, positrons must also exist near dense objects.[1)] For positrons all three forces are directed away from the star, which will lead to their acceleration.

The effective gravitational potential of dense objects may reach 0.5 c^2. In a number of cases their luminosity is extremely large. Many of them definitely pass into the ejection stage. Finally, from the surface of neutron stars and in supernova explosions we can imagine the ejection of not only protons, but also the ejection of much heavier nuclei with masses up to 200 to 300 m_p. Therefore, near dense objects positrons can be accelerated up to hundreds of millions of volts (and in the case $m_i \gg m_p$—even up to tens of billions of volts). The acceleration mechanism is purely electrostatic, the radiation pressure (see[6]) for a gas of ultrarelativistic particles moving away from the star is small due to the Doppler effect.

If the density of the fundamental plasma, realizing the exchange, is appreciable, then the radiation pressure on these particles is generally directed to the side of the star and consequently it will decelerate them.[2)] Actually, in this connection the isotropic (scattered) component of the radiation is large and the velocity of the positron turns out to be larger than the "group" velocity of light, v = u/ϵ (u denotes the energy flux and ϵ is its density). A steady-state regime is established in which the radiation damping of the positron is equal to the electrostatic force acting on it. For powerful spherically-symmetric accretion on a neutron star, the energy of the positrons "at infinity" turns out to be of the order of 5 to 15 MeV due to this cause.[4] However, the radiation damping effects should be unimportant for accretion in binary systems, when the incoming gas is concentrated in a thin disk, and also for sufficiently weak ejection; we recall that the electrical potential (4) does not depend on the ejection power. Coulomb losses and positron annihilation are always negligible.

We note that an additional difference of the potentials appears in connection with accretion in the atmosphere of the star: the mean free path of the incident electrons in the atmosphere is incomparably smaller than the mean free path of the ions; therefore the electrons diffuse in the atmosphere in the wake of the ion beam, that is, an electrical current flows through the atmosphere. The corresponding Joule losses determine the difference of the potentials; for example, when the ejection power on a neutron star is close to its maximum value, then $\Phi \sim 10^6$ V.

Positrons which are injected by dense objects can then be accelerated by the magnetic fields in interstellar space and enter into the composition of cosmic rays. We note that in order to support the observed density of the positron component in the volume of the Galactic halo, the simultaneous operation of one to ten sources having a power $L_{e^+} = 10^{35}$ erg/sec (for $E^{inj}_{e^+} = 10$ MeV) is necessary.

APPENDIX

Let us consider the intensity of the exchange processes. Powerful ejection prevents accretion. For an isolated object the corresponding critical value[7] is given by

$$Q_{ej}^{min} = 10^{27} \left(\frac{M}{M_\odot} \right)^2 \left(\frac{v_{ej}}{c} \right) \left(\frac{10^4 [°\text{K}]}{T_c} \right)^2 \left(\frac{n_c k T_c + H_c^2/8\pi}{10^{-12} [\text{dyne/cm}^2]} \right) \left[\frac{\text{erg}}{\text{sec}} \right]. \quad (5)$$

Here M denotes the mass of the star, v_{ej} denotes the velocity of the departing particles, T_c denotes the temperature of the interstellar plasma, and n_c is the number of atoms in one cubic centimeter. The values of all quantities are taken near the radius $r_c = GMm_p/kT$. After this, as Q drops below Q^{min} the emission changes to accretion.[7] For accretion, the mass flux into the star is given by[1]

$$\left[\frac{dM}{dt} \right]_{accr} = \delta(\gamma) \frac{4G^2M^2}{c^3} \rho_c \left(\frac{kT_c}{mc^2} \right)^{-3/2} \approx 10^{11} \left(\frac{M}{M_\odot} \right)^2 \left(\frac{T_c}{10^{4}°\text{K}} \right)^{-3/2} n_c \left[\frac{\text{g}}{\text{sec}} \right]. \quad (6)$$

From (5) and (6) it is clear that the minimum intensity of the exchange processes is realized when the star ejects relativistic particles in the critical regime (5).

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1) In connection with accretion on a collapsing body, positrons must exist because of the high temperatures in the incoming gas, [3] for accretion on neutron stars—because of direct nuclear collisions, [4] and in connection with ejection from neutron stars—because of the heating of the plasma by coherent radiation. [5]

2) This comment is due to Ya. B. Zel'dovich.

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[5] E. V. Levich and R. A. Syunyaev, Izv. vuzov. Radiofizika 13, 12 (1970).

[6] L. É. Gurevich and A. A. Rumyantsev, Zh. Eksp. Teor. Fiz. 47, 1829 (1964) [Sov. Phys.-JETP 20, 1233 (1965)].

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