ELECTRIC FIELD NEAR A ROTATING NEUTRON STAR

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An electric field near a rotating magnetized conducting sphere is found in the cases when the sphere (a) rotates in vacuum and (b) is surrounded by a magnetosphere. The accretion of the interstellar neutral hydrogen onto the cold neutron star is discussed.

1. ELECTRIC FIELD IN VACUUM NEAR A ROTATING MAGNETIZED STAR

We consider a conducting sphere of radius a rotating with the angular velocity $\bar{\Omega}$ and possessing the dipole magnetic moment $\bar{m}$. An electric potential Φ in the frame of reference rotating rigidly with the sphere is given by (Fawley et al., 1977)

$$\Delta\Phi + 2\bar{\Omega}\bar{B}/c = 0 , \quad \bar{E} = -\operatorname{grad}\Phi . \tag{1}$$

The solution of the equation for Φ with the boundary conditions $\Phi|_{r=a} = \Phi_o$, $\Phi|_{r\to\infty} = 0$ is given by (Tsygan, 1980)

$$\Phi = \Phi_o \frac{a}{r} + \frac{3(\bar{\Omega}\bar{n})(\bar{m}\bar{n}) - \bar{\Omega}\bar{m}}{3ca}\left(\frac{a}{r} - \frac{a^3}{r^3}\right); \quad \bar{n} = \frac{\bar{r}}{r} . \tag{2}$$

For the uncharged sphere $\Phi_o = -2\bar{\Omega}\bar{m}/3ca$. The electric field $\bar{\varepsilon}$ in the nonrotating (laboratory) frame of reference is

$$\bar{\varepsilon} = \bar{E} + [\bar{B}[\bar{\Omega}\bar{r}]]/c , \tag{3}$$

in agreement with the results obtained by Deutsch (1955).

2. ELECTRIC FIELD IN THE PRESENCE OF A MAGNETOSPHERE

Now we consider the case when the neutron star possesses a magnetosphere rotating rigidly with the star (Goldreich and Julian, 1969). We shall calculate the electric field in cone-like regions where the magnetic lines are open, assuming that these regions are not filled with a

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plasma. At $(r-a) \gg R$ ($R = a\theta_o$ is the radius of the polar cap) the solution of the equation for Φ with the boundary conditions $\Phi|_s = \Phi_1 = \text{const}$ may be expressed as

$$\Phi(\eta,\xi,\phi) = \Phi_1 + F(\eta,\xi) + \psi(\eta,\xi)\cos\phi \; ; \quad (4)$$

$$F(\eta,\xi) = \Omega m \cdot \cos\alpha \cdot \theta_o^2 (1-\xi^2)/ca \; ;$$

$$\psi(\eta,\xi) = 3\Omega m \cdot \sin\alpha \cdot \theta_o^3 \sqrt{\eta}\, \xi (1-\xi^2)/4ca \; ;$$

where $\eta = r/a$, $\xi = \theta/\theta_o \sqrt{\eta}$, $\theta_o = \sqrt{\Omega a/c} \ll 1$, and α is the angle between the vectors $\bar{\Omega}$ and $\bar{m}$. The solution near the polar caps ($r-a \sim R$) is given by (Tsygan, 1980)

$$F(\eta,\xi) = \frac{4\Omega m \cdot \cos\alpha}{ca} \theta_o^2 \sum_{i=1}^{\infty} \frac{2 J_0(k_i\xi)}{J_1(k_i) k_i^3} \left\{ 1 - \exp\left[\frac{k_i(1-\eta)}{\theta_o} \right] \right\}$$

$$\psi(\eta,\xi) = \frac{6\Omega m \cdot \sin\alpha}{ca} \theta_o^3 \sum_{j=1}^{\infty} \frac{2 J_1(x_j\xi)}{J_2(x_j) x_j^3} \left\{ 1 - \exp\left[\frac{x_j(1-\eta)}{\theta_o} \right] \right\} \quad (5)$$

k_i and x_j being the roots of the equations $J_0(k_i) = 0$ and $J_1(x_j) = 0$ respectively; $J_\nu(z)$ is the Bessel function. At the surface of the star the electric field is of the order of $(\Omega a/c)^{3/2} B_o \cos\alpha$. However, across the cone the sign of the field component described by the term $\partial F/\partial\eta$ remains unchanged. Hence, we do not obtain the result which is usually assumed in models of radio pulsars, namely that the field across the cone changes its sign. The second term $-(\cos\phi \cdot \partial\psi/\partial\eta)/a \sim (\Omega a/c)^2 B_o \sin\alpha \cos\phi$ changes its sign but this term is much smaller than the first one (for $|\pi/2 - \alpha| \gg \theta_o$).

3. ACCRETION OF NEUTRAL HYDROGEN ONTO THE COLD NEUTRON STAR

At a surface temperature $T \lesssim 2 \times 10^4$ K the photons emitted from the surface of the neutron star cannot ionize atomic hydrogen (helium). The hydrogen atoms fall freely towards the star and are ionized at the distance from the star $r_{ion} \sim 60\, a\, (B/10^{12})^{2/7}$ by the electric field which exists in the frame of reference co-moving with an atom (Tsygan, 1977). The number of neutral atoms which enter the ionization region per second is given by $dN/dt = n V \pi r_{ion} \cdot 2GM/V^2\ s^{-1}$ (n is the number density of interstellar gas, M is the mass of the star, and V its velocity). The relative number of particles which enter the cones with open magnetic lines is of the order of $r_{ion}\, \theta_o^2/4a \sim 4.5 \cdot 10^{-3}$ with their intensity being about ($\bar{\Omega} \perp \bar{m}$) (Tsygan, 1980) $L \sim 4 \cdot 10^{24}\, (n/1)(3 \cdot 10^7/V)(\Omega/10)^{7/2}\, (B_o/10^{12})^{11/7}$ erg/s. Some part of this intensity may be emitted in the radio spectral band. Electrons and protons striking against the surface of the neutron star will cause 1) heating of the polar caps and 2) knocking secondary particles and γ-quanta out of the surface of the star. Pulling out secondary particles can lead to an increase of the radio luminosity.

REFERENCES

Deutsch, A.: 1955, Ann. Astrophys. 18, p. 1.
Fawley, W.M., Arons, J., and Scharlemann, E.T.: 1977, Astrophys. J. 217, p. 227.
Goldreich, P. and Julian, W.H.: 1969, Astrophys. J. 157, p. 869.
Tsygan, A.I.: 1977, Sov. Astrophys. J. Letters 3, p. 531.
Tsygan, A.I.: 1980, Sov. Astrophys. J. 57, p. 73.

DISCUSSION

WRIGHT: The accretion of neutral hydrogen onto pulsars is an attractive way of explaining long-term variations of the radio emission.

KAHN: Do you really think that the density of the neutral interstellar medium can vary rapidly enough to produce changes in a pulsar on any reasonable timescale?

F.G. SMITH: Only the radio emission varies, so that the variations may be magnified through coherence effects.

VENTURA: Can one rely on idealized Deutsch solutions for induced electric fields in the case of an accreting neutron star? Would the heating of the stellar surface not turn it from a good conductor to a bad conductor?

TSYGAN: The solution presented here is valid when there is no plasma in the cone, or there is very little of it (this happens when neutral hydrogen is accreted).

ARONS: Did you include any plasma of any kind within the cone, or are your solutions for a conducting cone containing a vacuum?

TSYGAN: The appearence of a "hot spot" on a neutron star during accretion of neutral hydrogen can lead to plasma ejection. In Tsygan (1980) I present a solution which includes plasma ejection for the case of an orthogonal rotator.