CLASSIFICATION OF RADIATING COMPACT STARS

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ABSTRACT

A classification of compact stars depending on the electron distribution in velocity space and the density profiles characterizing their magnetospheric plasma is proposed. Fast pulsars, such as NP 0532, X-ray sources such as Sco-X1 and slow pulsars are suggested as possible evolutionary stages of similar objects. The heating mechanism of Sco-X1 is discussed in some detail.

I. Introduction

The radiation emitted by the magnetosphere of a collapsed star depends primarily on the profile of the distribution function $f_e(v_{\parallel})$ of the plasma electrons, where $v_{\parallel}$ is the particle velocity along the magnetic field. We suggest that three main types of distribution function f_e account for different objects which can be associated with compact stars.

One type corresponds to small electric fields $E_{\parallel}$, along the magnetic field, so that the distribution f_e is a low temperature Maxwellian with a small drift velocity $u_{e\parallel}$ (Fig. 1a). This regime is associated with slow pulsars.

Another type corresponds to larger electric fields $E_{\parallel}$ so that the distribution f_e is a broad high temperature Maxwellian (Fig. 1b). This can be considered as a regime of turbulent heating and is associated with sources such as Sco X-1.

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A third type corresponds to values of the particle density, temperature and $E_{\parallel}$ field for which the distribution function acquires a tail of fast superthermal particles (Fig. 1c). We can call this a runaway regime and consider it typical of stars such as NP 0532.

We refer to compact objects, typically neutron stars, whose mass $M \simeq M_{\odot} \simeq 2 \times 10^{33}$ gr., and radius $a \simeq 10^{6}$ cm. The magnetic field is assumed dipolar on the surface, with an intensity $B_o \simeq 10^{12}$ gauss. We assume, for simplicity, that the dipole axis coincides with the axis of rotation and we consider a region defined by closed magnetic field lines which are contained within the speed of light cylinder (of radius $R_{SL} = c/\omega_o$, where ω_o is the star angular velocity). In this region, the magnetic field is dipolar, there are no electric fields and no currents along the magnetic lines, the plasma corotates rigidly with the star, and no emission occurs. In a second region the lines of force are open, an electric field E can be maintained along them and emission processes can be sustained. This region is within the latitude $\theta_c = (a\omega_o/c)^{1/2}$, and we can argue that the width of the active region is of order $\ell_o \sim \theta_c a = (a^3\omega_o/c)^{1/2}$.

The potential difference, seen in an inertial frame between a pole and a point at about the latitude θ_c is (Deutsch 1955; Goldreich and Julian 1969)

$$\Delta\Phi = \frac{1}{4}\frac{\omega_o}{c} a^2 B_o (\cos 2\theta_c - 1)$$

For the parameters considered above

$$\Delta\Phi \sim 1.7 \times 10^{11} \omega_o^{2} \text{ volt}$$

We assume that the magnetic lines of force in the active regions are connected with the external field of the nebula which may surround the considered star, or of the interstellar plasma. Then it is reasonable to expect that the electric field $E_{\parallel}$ along the active magnetic field lines will result from a potential drop of the order of $\Delta\Phi$.

An important limit for the electric field $E_{\parallel}$ is the classical runaway field E_R (Gurevich, 1962) defined as $E_R = \nu_{ei} m_e v_{th}/e$ where ν_{ei} is the electron-ion collision frequency and v_{th} the electron thermal velocity. This gives the threshold above which the plasma, under the electric field influence and in the absence of collective effects, would lose its cohesiveness and the electrons (so called runaway electrons) would tend to undergo almost free acceleration. In reality when $E > E_R$, plasma collective modes are excited and their effects are equivalent to that of a strongly enhanced collision frequency. Thus, the electron distribution function is kept from running away and a strong anomalous resistivity sets in. This involves a considerable ohmic heating of the plasma, which is commonly called turbulent.

In laboratory experiments, a tail of runaway electrons has been observed to appear when the electric field is slightly below the field E_R so that the effects of a strong turbulence which tends to destroy this tail, are not important. It has been conjectured that a turbulent runaway field E_R^T should exist with $E_R^T >> E_R$, so that for $E > E_R^T$ particles are not affected by two body collisions nor by interactions with plasma collective effects and undergo free acceleration. However, there has not been, as yet, a clear experimental observation of such a threshold.

II. Three Types of Collapsed Stars

Slow Pulsars. Slow pulsars (all pulsars but NP 0532) are observed only at radio-wavelengths. The shape of the pulse is not stable and sometimes varies greatly from pulse to pulse. We assume that, for this class of objects, the electron distribution function in velocity space is a narrow Maxwellian slightly displaced by the electric field $E_{\parallel}$. In particular, there are no fast electrons which could emit in the higher frequency bands. The density profile of the magnetosphere corresponds to a shell of plasma surrounding the star with such a volume that the overall thermal optical emission is not appreciable. Assuming for example that the emission spectrum is a black body at temperature $T \sim 10^6$K, we find that an object at a distance of 100 pc, with a magnetosphere extending for 10 stellar radii, $R \sim 10a \sim 10^7$ cm would have a visual magnitude $m_v \sim 27^m$ and thus could not be seen.

Radio emission can be produced by the coupling of self-excited, low frequency plasma modes (micro-instabilities of the inner magnetosphere) with electromagnetic modes. These plasma modes are likely to be of electrostatic type and to propagate, along the open lines of force on which they are excited, from the shell of dense plasma close to the star up to a region where the plasma density is so low that electromagnetic modes are not strongly damped. It is then reasonable to expect that the pulse irregularities observed in the radio band depend on the characteristics of the regions in which propagation and coupling of plasma modes occurs.

The pulsed emission can be associated with a lack of symmetry of the star magnetic configuration about the axis of rotation.

Thermal X-Ray Sources. We consider Sco-X1 as the best known of the collapsed stars which belong to the second class of objects as indicated earlier. In these stars, the main emission is assumed to result from strong turbulent heating of the magnetospheric plasma, which is supposed to occupy a much larger volume than the one of the collapsed star, that is $R \gg a$. In the case of Sco-X1, the spectrum between 1 and 40 KeV corresponds to a bremsstrahlung emission of a plasma with temperature $T = \alpha_1 \times 5 \times 10^7 \,^\circ K$ (Gorenstein et al. 1968, Meekins et al. 1969) where α_1 accounts for an experimental uncertainty. The received intensity is

$$I = \alpha_2 \times 3 \times 10^{-7} \text{ erg/cm}^2\text{sec}$$

The star distance d is still uncertain and we shall consider $d = \alpha_3 \times 6 \times 10^{20}$cm, a value deduced by proper motion observations (Sofia et al. 1969).

The flux F_ν measured at infrared frequencies ($\nu \sim 10^{14}$Hz) was interpreted by Neugebauer et al. (1969) as being due to black body emission of the plasma at the same temperature as deduced from the X-ray spectrum. In particular according to Neugebauer et al. (1969)

$$F_\nu = \alpha_4 \times 10^{-53}\nu^2 \text{ erg/Hzcm}^2\text{sec}$$

By equating this flux to the one emitted by a spherical black body with radius R and at a distance d we obtain

$$R = \left(\frac{F_\nu}{2\pi kT}\right)^{1/2} cd = 2.7 \times 10^8 \left[\frac{\alpha_4^{1/2}\alpha_3}{\alpha_1^{1/2}}\right] \text{ cm} \tag{1}$$

The bremsstrahlung emissivity of a plasma is given by (Ginzburg 1967):

$$\varepsilon = 1.6 \times 10^{-27} n_e^2 T^{1/2} \text{ erg/cm}^3\text{sec}$$

where n_e is the electron density. The observed value of the emissivity can be taken as:

$$\varepsilon = \frac{3Id^2}{R^3}$$

which corresponds to a total power

$$P_{obs} = 1.3 \times 10^{36}\alpha_2\alpha_3^2 \text{ erg/sec}$$

Then we have,

$$n_e = 3.8 \times 10^{16}\left[\frac{\alpha_2\alpha_1}{\alpha_4^{3/2}\alpha_3}\right]^{1/2} \text{cm}^{-3} \tag{2}$$

The thermal power associated with the current flowing along the star magnetic field is

$$P_{tot} = \int_{volume} E_{o\parallel} J_{\parallel} dV \tag{3}$$

We assume that the toroidal field B_T produced by the current is smaller than the star's dipolar magnetic field B_p. We also notice that, given the high values of the magnetic field in the neighborhood of the star and for reasonable assumptions on the values of n_e and T, the transverse component of the current density $J_\perp$ has to be much smaller than $J_\parallel$. This in order not to generate forces $\underline{J} \times \underline{B}$ that would not be compensated by gravity, pressure gradient and centrifugal effects. Indicating by J_P and J_T the poloidal and toroidal components of the current, the previous requirement is expressed by the relation

$$B_p \cdot J_T - B_T \cdot J_p \simeq 0$$

The charge conservation equation $\nabla \cdot \underline{J} = 0$, then implies $\underline{J} = \alpha\underline{B}$ with $\underline{B} \cdot \nabla\alpha = 0$. Then if we assume that $B_T < B_p$ in the vicinity of the star, we have $J_\parallel \propto \frac{1}{r^3}$ since in a dipolar magnetic field, the cross section of a tube of force increases near the poles as r^3. Therefore, neglecting the spatial variation of the resistivity so that $E_\parallel \propto J_\parallel$, we obtain

$$P_{tot} \simeq 2E_{o\parallel} J_o \int \left(\frac{r}{a}\right)^{-6} \frac{\pi \ell_o^2 r^3}{a^3} dr = \pi a \ell_o^2 E_{o\parallel} J_o \tag{4}$$

where $J_o = J_\parallel(r{=}a)$, $\pi\ell_o^2 \frac{r^3}{a^3} dr$ is the volume element calculated supposing that J follows the magnetic lines of force and represents the linear dimension of the active region of the magnetosphere which we assume of the order of 10^5 cm. The toroidal component of the magnetic field at the poles can be obtained from the Ampere theorem

$$B_{oT} \sim \frac{2\pi}{c} J_p \ell_o \qquad (5)$$

so that (4) can be written as

$$P_{tot} \simeq \frac{c}{2} a\ell_o Bo_T E_{\parallel} \quad \text{(in Gaussian units)} \qquad (6)$$

Assuming $B_{oT} \sim 0.3\underline{B}_{o_\parallel} = 3 \times 10^{11}$ gauss from (5), we have

$$J_{\parallel} \simeq 4.8 \times 10^6 \text{ ampere/cm}^2$$

and taking the average density at the poles $n_o \simeq 4 \times 10^{16}$ cm^{-3}, we deduce a mean velocity of the electrons in the direction of the magnetic field $u_{e_\parallel} \simeq 7.5 \times 10^8$ cm/sec. which is a fraction of the electron thermal velocity

$$V_{th} = \left(\frac{2kTe}{m_e}\right)^{1/2} \simeq 4.4 \times 10^9 \text{ cm/sec}$$

In these conditions and for values of the plasma frequency ω_{pe} less than the electron cyclotron frequency Ω_e, the resistivity has been shown to increase proportionally to the electric field and the average electron drift velocity to saturate at a fraction of the electron thermal velocity (Coppi and Mazzucato 1971; Coppi et al. 1970). In addition, electric field ratios E_o/E_R well in excess of 10^3 have been applied on laboratory plasmas with $\omega_{pe} > \Omega_e$ without destroying their cohesiveness that is, create a global runaway process (Hamberger and Friedman 1968, Hamberger and Jancaric 1970).

On this basis, we assume that large amplitude electrostatic oscillations are induced by the applied electric field so that electrons are trapped in the resulting electrostatic wells. If $\tilde{\Phi}$ is the oscillating electrostatic potential, this can be as large as

$$\tilde{\Phi}_{th} \simeq \frac{kTe}{e} \sim 4.3 \text{ KV} \qquad (7)$$

We recall that the Debye length for the conditions mentioned above is about

$\lambda_D \simeq 4.2 \times 10^{-4}$cm. So the uppermost limit for the oscillating electric fields seen by the particles is of the order $\frac{1}{\lambda_D}\tilde{\Phi}_{th} \simeq 10^7$ volt/cm. On the other hand, the electric field which is necessary to emit the radiated power can be obtained from (6), for the assumed plasma and magnetic field parameters and equating P_{tot} to the observed value $P_{obs} \simeq 1.3 \times 10^{-36}$erg/sec so

$$E_{o_\parallel} = \frac{2P_{obs}}{a\ell_o cB_{oT}} = 10^6 \text{ volt/cm} \tag{8}$$

The value of E_o therefore is well below $\tilde{\Phi}_{th}/\lambda_D$ and we can argue that the direct electric field is not sufficient to overcome the particle trapping and to generate a runaway process. We also notice that the corresponding collisional runaway field is $E_R \simeq 40$V/cm and that in our case $E >> E_R$.

The non thermal tail observed for energies above 40 KeV (Agrawal et al. 1971) can be associated with a very small tail of highly energetic electrons ("super-runaway") riding over the strong electric field fluctuation.

The radiation emitting volume, which was assumed to have a radius R, corresponds to that part of the magnetosphere which is heated by the high thermal conductivity along the magnetic field lines, the energy source being localized in the active regions near the poles. Thus even if the magnetic axis is not aligned with the rotation axis and the emitting regions extend to large latitudes, no beaming of radiation will be present and no pulsation is to be expected.

For the sake of finding an order of magnitude of the angular velocity of the star, we can assume that the emitting regions have a radius of the same order of the speed of light radius $R \sim R_{SL}$. We may justify this assumption by arguing that the radial thermal conduction will tend to drop as, on approaching the light speed cylinder, the magnetic field lines acquire an increasingly larger toroidal component. We have then

$$\omega_o \sim \frac{c}{R} \sim 100 \text{ sec}^{-1}$$

and the rotational energy of the star is

$$E_{rot} = \frac{3}{5} M \omega_o^2 a^2 \sim 10^{49} \text{ erg}$$

In the absence of any indication of the variation of ω_o with time, a rough estimate of the life-time of the source is given by :

$$\tau = \frac{E_{tot}}{P_{obs}} \sim 3 \times 10^4 \text{ years},$$

a time long enough to justify the absence of a shell around this source.

The energy output corresponds to a loss of angular momentum $\dot{\Omega}$

$$\dot{\Omega} = \frac{P_{rot}}{2\omega_o} \sim 6 \times 10^{33} \text{ erg}$$

The angular momentum can leave the star in the form of relativistic particles and photons and be communicated to the plasma beyond the light cylinder. Sco-X1 is also known to exhibit bursts of radio, optical and X-ray emission (flares) (see for example Evans et al. 1970). For this we notice that the plasma in the regions close to the light speed cylinder can be subject to instabilities, for instance of the type transforming magnetic energy into kinetic energy. When the associated perturbation extend to modify the plasma density up to the polar regions, the total overall X-ray emission can also be affected. Otherwise the instabilities will mainly induce a change of optical emission as in the case of solar flares. (Coppi and Friedland 1970).

Fast Pulsars We consider NP 0532 (in the Crab Nebula) as the typical representative of this class. Unlike all other known pulsars, this object exhibits emission in the optical, X and γ-ray domains.

So it is proposed that the high frequency part of the spectrum, from the optical up, is associated with the tail of fast electrons characterizing the distribution function when $E_o > E_R^T$. We notice that most of the measured radiation energy is emitted in this part of the spectrum which, in addition, can be described by a power law. Assuming that a synchrotron or inverse Compton scattering radiation process is involved, the spectrum profile reflects a power law of the electron distribution tail. It is possible to argue that the equilibrium distribution results from a balance between the loss of electron energy perpendicular to the magnetic field and gain due to a scattering process of parallel energy into perpendicular energy (Coppi and Ferrari 1970). Referring to the comparison made between the electric field $E_{o\parallel}$ and the fluctuating field $k_\parallel \tilde{\Phi}$ considered for the case of Sco X-1 (here $k_\parallel$ denotes the typical wave number of electrostatic fluctuations along the magnetic field), we notice that in the present case E_o is likely to be larger, while Φ_{th}/λ_D ought to be smaller because of the lower temperature of the Maxwellian body of the distribution. Therefore a runaway process is likely to set in, and electron distribution function is likely to acquire the profile sketched in Fig. 1(c). In fact, we may take the so-called turbulent runaway field E_R^T as of the order of to Φ_{th}/λ_D.

III. Discussion

We have identified three classes of radiating collapsed stars which are distinguished by the regimes characterizing their magnetospheric plasma.

These regimes depend primarily on the magnetic field, on the electric field parallel to it, and on the electron density distribution. Since these three quantities can change during the evolution of the star, it is possible that the same star will evolve through the three mentioned classes.

At the beginning of the evolution, when the angular velocity is highest, the electric field can be large enough for free acceleration of particles to take place. As was mentioned earlier, this can occur when the electric field is larger than E_R^T.

We can think of the lowering of the electric field below E_R^T as being associated with the star slowing down and progressive heating of the Maxwellian body of the distribution. The object in this stage will be similar to Sco X-1 if the radius of the magnetosphere is many times greater than the radius of the star, $R \gtrsim 10^2 a$.

Finally, when the electric field is no longer large enough to produce sufficiently large ohmic heating, and the plasma density distribution around the star is reduced to a relatively cold shell the radius of which is not much larger than the star's radius, $R \sim a$, the star can emit only at low frequencies via plasma collective effects and is observed as a slow pulsar.

We wish to point out that an evolution which takes into account only the frequency of rotation may suggest that PSR 0833 (Vela pulsar), which has a period three times larger than NP 0532, is an object similar to Sco X-1. On the other hand, no optical counterpart of this radio pulsar has been detected. Thus consideration of the rotation frequency alone appears to be insufficient for a classification of the emission characteristics of a given star. As indicated previously, the possibility of different plasma density profiles around the star and of different electron distribution functions, in addition to a variety of magnetic configurations, should be taken into account in assessing its evolutionary stage.

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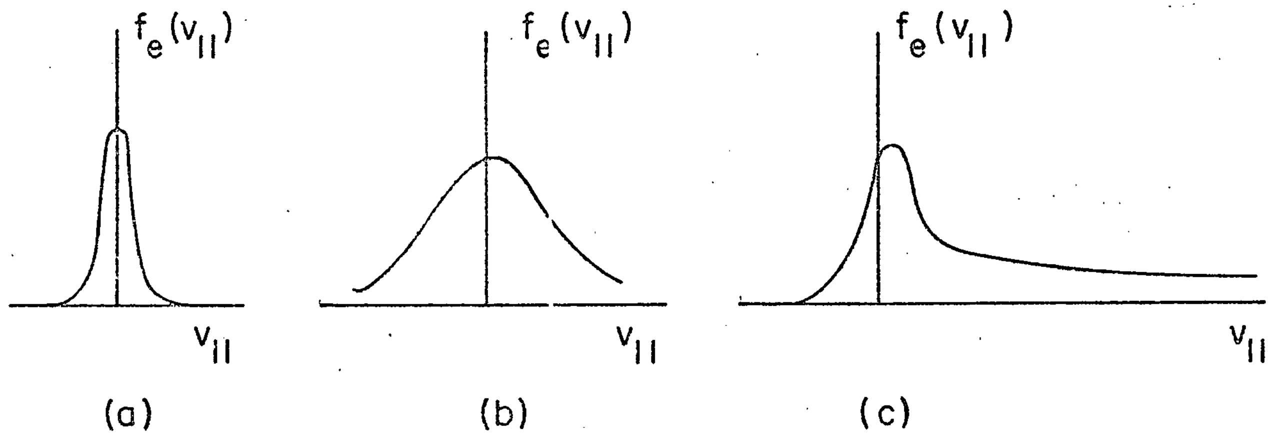
Caption to Figure 1

Typical distribution functions characterizing three types of collapsed stars.



$f_e(v_{||})$
$v_{||}$
(a)
$f_e(v_{||})$
$v_{||}$
(b)
$f_e(v_{||})$
$v_{||}$
(c)