A COCOON MODEL FOR THERMAL X-RAY SOURCES AND 'OSCILLARS'

KRISHNA M. V. APPARAO
Tata Institute of Fundamental Research, Bombay, India

(Received 19 June, 1972)

Abstract. A gas cocoon surrounding a neutron star can be heated to a high temperature by the low frequency radiation emitted by the neutron star whose rotation axis is inclined to its magnetic axis. This heated gas can emit X-rays and may be identified with thermal X-ray sources. If the neutron star emission shows periodicities larger than the cooling time of the gas, these will be reflected in the emission of X-ray; the recently observed X-ray sources which show oscillations and quasi-periodicities ('Oscillars') may be such sources.

Recently a class of models have been proposed (Coppi and Treves, 1971; Davidson et al., 1971; Apparao, 1971a) where a compact rotating object enveloped by a gas cocoon has been suggested as possible explanations of thermal X-ray sources. In these models the energy for heating the gas is derived from the rotational energy of the compact object. In the model of Coppi and Treves (1971) the central object is a neutron star and the heating is due to Joule heating by the rotating fields within the light cylinder. Davidson et al. (1971) also use a fast rotating neutron star as the supplier of energy and the heating of gas far away from the light cylinder is achieved by ionization loss of energetic particles produced by the neutron star. Apparao (1971a) considers a rotating magnetic white dwarf star as the central object which is assumed to be an oblique rotator; the heating of the gas is achieved by the absorption of the low frequency radiation emitted by the oblique rotator.* In this paper, the central object is assumed to be a rotating neutron star (oblique rotator), and the heating of the cocoon is achieved by absorption of the low frequency radiation emitted by the neutron star as in the white dwarf case. The present model requires a neutron star of comparatively larger period of rotation (and therefore more stable) as compared to the other models, in which the period of rotation of the compact body is close to that corresponding to the centrifugal break-up. The gas cocoon in the present model is closer to the compact body than in the models of Davidson et al. (1971) and Apparao (1971a) and consequently the hot gas can be bound. In addition, it provides a qualitative explanation of periodic and sporadic oscillations recently discovered in some X-ray sources.

To fix some parameters of the model we use the observational data of Sco X-1. The energy emitted as X-rays by Sco X-1 is about \(10^{37}\) ergs\(^{-1}\) with an uncertainty of a factor of ten which is due to the uncertainty in the estimation of the distance of the gas cocoon.

* Heating of the gas by the low frequency radiation by induced compton process has been considered by Levich and Syunyaev (1971). The application of the theory in the present context is being investigated.
the object. The X-ray emission is due to free-free emission by hot gas with an electron density, \( n_e \), ranging between \( 10^{14} \text{ to } 4 \times 10^{16} \text{ cm}^{-3} \) and the radius of the volume occupied by the gas ranging between \( 3.5 \times 10^8 \text{ to } 10^{10} \text{ cm} \); the smaller radius is associated with the higher density.

If we require that the oblique rotator (neutron star) give out energy as low frequency radiation at the rate of \( 10^{37} \text{ erg s}^{-1} \), then using the expression (Goldreich, 1969) \( \frac{dE}{dt} \approx 10^{-28} B^2 R^2 / \rho^4 \text{ erg s}^{-1} \), where \( B \) is the neutron star surface magnetic field (\( \sim 10^{12} \text{ G} \)), \( R \) is its radius (\( 2 \times 10^6 \text{ cm} \)), we calculate the period of rotation \( P \) of the oblique rotator to be about 100 ms \(^{-1} \). The low frequency radiation is emitted beyond the light cylinder whose radius in the present case is about \( 5 \times 10^8 \text{ cm} \).

The low frequency radiation is absorbed by the plasma if \( \gamma \Omega \omega_0 < \omega_p^2 \) (Gunn and Ostriker, 1971) or can accelerate high energy particles if \( \gamma \Omega \omega_0 > \omega_p^2 \) here \( \Omega \) is the angular velocity of the star = \( 2\pi / P \); \( \omega_0 \) is the gyrofrequency which is \( 1.8 \times 10^7 B_r \), where \( B_r \) is the magnetic field near the light cylinder; \( \omega_p \) is the plasma frequency = \( 6 \times 10^4 n_e^{1/2} \); \( \gamma \) is the Lorentz factor for particles at injection. The magnetic field \( B_r \) is about \( 6 \times 10^4 \text{ G} \) using a dipole field for the neutron star giving \( \omega_0 \approx 10^{12} \). Using the models of free-free emission of X-rays, the value \( n_e \), corresponding to the radius of \( 5 \times 10^8 \text{ cm} \) is about \( 3 \times 10^{16} \); this gives \( \omega_p \approx 10^{13} \). In the present model \( P = 10^{-1} \text{ s} \) giving \( \Omega \approx 10 \).

Using \( \gamma \approx 1 \), the value \( \gamma \Omega \omega_0 \approx 10^{13} \) which is much less than \( \omega_p^2 \). Thus the presence of the high density plasma does not allow acceleration of particles near the light cylinder as in the case of pulsars (Gunn and Ostriker, 1971), and the low frequency radiation is absorbed by the gas to heat the gas. A similar conclusion can be arrived at using the condition given by Rees (1971).

The binding of the gas cocoon near the light circle can be shown qualitatively. The rms speed of particles due to kinetic motion at temperatures in the region \( 10^7 \text{ to } 10^8 \text{ K} \) (which is the temperature needed for X-ray emission) is about 100 times smaller than the escape velocity of the particles at the light circle. In addition the strong magnetic field in this region (\( \sim 10^5 \text{ G} \)) should also help in binding the gas; the magnetic field density is about \( 10^9 \text{ erg cm}^{-3} \), while the kinetic energy density of the particles is about \( 10^8 \text{ erg cm}^{-3} \). Thus it seems the hot gas can be bound near the light circle; the stability of the system is however difficult to discuss because of lack of knowledge of the configuration of the magnetic field in this region.

The rate of cooling of the gas with a temperature of about \( 5 \times 10^7 \text{ K} \) is approximately given by \( 2 \times 10^{-23} n_e^2 \text{ erg cm}^{-3} \text{ s}^{-1} \) (Cox and Tucker, 1969) using \( n_e \approx 3 \times 10^{16} \) in the present case the rate of cooling is about \( 2 \times 10^{10} \text{ erg cm}^{-3} \text{ s}^{-1} \). The energy content of the gas is about \( 3 \times 10^8 \text{ erg cm}^{-3} \), yielding a cooling time of the order of about \( 10^{-2} \text{ s} \). This is lower than the basic periodicity of the neutron star calculated above. The low frequency electromagnetic radiation beam (Apparao, 1971b) heats some region of the cocoon all the time so that the X-ray emission seems continuous. However in the case of pulsars, whose central objects are thought to be neutron stars (see ter Haar, 1972), intensity fluctuations and strong periodic components in the radio emission have been observed (Taylor et al., 1969; Lang, 1970). These periodicities are of the order of several seconds and greater. If these are ascribed to the rotating