Mon. Not. R. astr. Soc. (1975) **173**, 161–165.

SLOWLY ROTATING NEUTRON STARS AND TRANSIENT X-RAY SOURCES

A. C. Fabian

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

(Received 1975 April 10)

SUMMARY

A neutron star in a weak stellar wind from a binary companion will spindown because of pulsar emission and the 'propeller' mechanism of Illarionov & Sunyaev. Large density fluctuation in this wind can then turn the neutron star into a transient X-ray source with a relatively long rotation period. The transient X-ray source, Ariel 1118−61, which has a period of 6·75 min is shown to be in general agreement with the above considerations.

1. INTRODUCTION

Ives, Sanford & Bell-Burnell (1975) have recently discovered a transient X-ray source (Ariel 1118−61) with a period of 6·75 min which Pringle & Webbink (1975) interpret as the orbital period of a very close binary system. We shall here consider an alternative model involving a slowly rotating magnetized neutron star.

The rotation period, P, of a magnetized neutron star is most readily observable in the range $\sim$10 ms to $\sim$10 s. Pulsar emission dominates periods less than a few seconds, and accretion in close binary systems can, under certain conditions, make the neutron star detectable by its X-ray emission if $P\sim$ 1–10 s (e.g. Her X-1, Cen X-3).

A fast rotating neutron star ($P \ll 1$ s) in a close binary system will initially spindown because of pulsar emission, the energy for which is derived from the rotational energy of the neutron star. A stellar wind from the companion will suppress the pulsar mechanism when the pulsar radiation pressure can no longer balance the wind pressure. Further spindown will occur by the 'propeller' mechanism of Illarionov & Sunyaev (1975). Here the asymmetry of the pulsar magnetosphere creates shocks on the leading edges as they spin round in the wind, assuming that the magnetic axis is inclined to the rotation axis. This results in dispersal of the wind material at the expense of rotational energy of the neutron star.

Spindown ceases, or at least diminishes, when matter starts to be accreted by the neutron star. This can only occur when the magnetospheric radius, R_M, is less than the corotation radius, R_Ω, otherwise centrifugal forces would fling the matter off (Pringle & Rees 1972; Davidson & Ostriker 1973). R_M is obtained roughly by balancing the wind pressure, ρV^2 (where ρ is the wind density in the vicinity of the magnetosphere and V its velocity) to the pressure in the magnetic field, $B^2/8\pi$;

$$R_M \simeq 1{\cdot}6\times 10^7\,\rho^{-1/6}\left(\frac{V}{5.10^7\ \mathrm{cm\ s^{-1}}}\right)^{-1/3}\left(\frac{B_*}{10^{12}\ \mathrm{gauss}}\right)^{1/3}\left(\frac{R_*}{10^6\ \mathrm{cm}}\right)\mathrm{cm} \qquad (1)$$

and

$$R_\Omega \simeq 1.5 \times 10^8 \, P^{2/3} \left(\frac{M_*}{M_\odot}\right)^{1/3} \text{ cm}$$

where R_*, M_* and B_* are respectively the radius, mass and surface field of the neutron star. Once accretion starts, further spindown will be counteracted by the accretion of angular momentum from the infalling material. A balance giving steady accretion will occur when $R_M \simeq R_\Omega$, i.e. when $V \sim 5 \times 10^7$ cm s^{-1},

$$P \simeq 3.2 \times 10^{-2} \rho^{-1/4} \text{ s.} \tag{2}$$

The X-ray luminosity, L_X, must exceed $\sim 10^{36}$ erg s^{-1} in order that kilovolt X-rays be produced from the base of the accretion funnel at the neutron star pole. For a neutron star, $\sim$ 10 per cent of the rest mass energy of accreted material is released as luminosity,

$$L_x \simeq 0.1 \, \dot{M}c^2 \text{ erg s}^{-1}$$

where the rate of accretion of material

$$\dot{M} \simeq \pi R_A{}^2 \rho V$$

and R_A is the accretion radius ($\sim GM/V^2$) (Bondi 1952). Thus for $L_X \gtrsim 10^{36}$ erg s^{-1}, we require $\rho \gtrsim 10^{-13}$ g cm^{-3}, and hence from equation (2) we need $P \lesssim 30$ s. (V is now enhanced by the gravitational field of the star.) This represents the maximum period that a steadily accreting neutron star can have once it has achieved equilibrium. We shall estimate the time scale on which this equilibrium is set up in equation (3).

2. SPINDOWN IN A WEAK STELLAR WIND

In a stellar wind where $\rho \ll 10^{-13}$ g cm^{-3}, the equilibrium value of the rotation period $P \gg 30$ s. The neutron star will not now be detectable by kilovolt X-ray emission unless temporary enhancements in the wind density bring $\rho > 10^{-13}$ g cm^{-3}. Stellar winds are known to be unsteady phenomena and in particular some of the low states of Cen X-3 are attributed to temporary increases in the wind density in that system (Giacconi 1974; Jackson 1975). We propose therefore that the transient X-ray source is a neutron star rotating with a period $P = 6.75$ min, with a companion which emits a stellar wind. On average, the wind density $\rho \sim 4 \times 10^{-17}$ g cm^{-3} (equation (2)), but occasionally the density rises to $\rho \gtrsim 10^{-13}$ g cm^{-3} giving rise to temporary accretion of material by the neutron star and thus a transient X-ray source.

Since neutron stars are probably born with short rotation periods, we must also demand that the time taken to slow the rotation period to 6.75 min is less than the main sequence life of the companion. Initially, spindown will occur by the pulsar mechanism until the pressure due to the magnetic dipole radiation can no longer prevent penetration of material within the light cylinder, R_c (Schwartzman 1971). This occurs when

$$\frac{L_D}{4\pi R_c{}^2 c} \simeq \rho V^2$$

where the luminosity of dipole radiation

$$L_D = \frac{2^5 \pi^4}{3} \frac{m^2}{c^3 P^4} \text{ erg s}^{-1}$$

and m is the magnetic moment of the neutron star. The period is then

$$P_1 \simeq 2\left(\frac{\rho}{4.10^{-17}}\right)^{-1/6}\left(\frac{V}{5.10^7}\right)^{-1/3}\left(\frac{B_*}{10^{12}}\right)^{1/3} \text{ s.}$$

The time to spin down to P_1 losing energy at a rate L_D is

$$t_D \simeq 3\times 10^7 \left(\frac{P_1}{2s}\right)^2 \text{ yr.}$$

We assume that during this time the cosmic rays etc. ejected by the pulsar sweep away any material falling within R_A of the neutron star. t_D is dependent upon the pulsar emission mechanism, the simplest having been considered above. The model of Roberts & Sturrock (1972) for example gives $t_D \sim 10^6$ yr. A much more rapid spindown would probably occur if the pulsar itself initiated the supernova explosion (Ostriker & Gunn 1971).

After t_D we assume that the pulsar emission is suppressed and the ' propeller ' mechanism of Illarionov & Sunyaev (1975) causes further spindown. The rotational energy of the star is transmitted through shocks to the wind material falling within R_A. This gas heats up, and will disperse when it has attained the escape velocity, V_{esc} ($\sim (2GM/R_M)^{1/2}$). Radiation losses will be negligible as the free–free cooling time is $\sim 10^4$ times longer than the escape time if $\rho \sim 10^{-16}$ g cm^{-3}. We find $\frac{1}{2}I(\omega_1^2-\omega^2) = \frac{1}{2}\dot{M}V_{esc}^2$ where I is the moment of inertia of the neutron star ($\sim 0{\cdot}4\, M_*R_*^2$). Then the spindown time by this mechanism,

$$t_{sd} \simeq 3{\cdot}5\times 10^8 \left(\frac{1}{P_1^2}-\frac{1}{P^2}\right)\left(\frac{\rho}{4.10^{-17}}\right)^{-7/6}\left(\frac{V}{5.10^7}\right)^{8/3}\left(\frac{B_*}{10^{12}}\right)^{1/3} \text{ yr.} \qquad (3)$$

Taking $P_1 \sim 2$ s and $P \sim 6{\cdot}75$ min gives $t_{sd} \sim 10^8$ yr.

If the magnetic and rotation axes of the neutron star are parallel, an accretion disk is only likely to form if the wind velocity is sufficiently small ($V \ll 5.10^7$ cm). Nevertheless, magnetic torques will act on the magnetosphere (Pringle & Rees 1972; Lynden-Bell & Pringle 1974) to spin the matter up to V_{esc}, and spin the neutron star down in a time similar to t_{sd}. A disk probably forms if matter is transferred from the companion star by Roche lobe overflow. It is unlikely that a sufficiently small trickle could exist for long enough for spindown to result in $P \sim 6{\cdot}75$ min.

Spinup will occur when matter is accreted by the neutron star. The time scale for this, t_{su}, depends upon the orbital velocity of the system. The rate of accretion of angular momentum (Davidson & Ostriker 1973; Illarionov & Sunyaev 1975) is

$$\frac{dJ}{dt} \sim \frac{\dot{M}}{4}\frac{2\pi}{P_{orb}}\frac{G^2M_*^2}{V^4}$$

giving

$$t_{su} \simeq 10^6 \left(\frac{P_{orb}}{10 \text{ day}}\right)\left(\frac{\rho}{10^{-13}}\right)^{-1}\left(\frac{V}{5.10^7}\right)^7\left(\frac{1}{P_2}-\frac{1}{P}\right) \text{ yr.} \qquad (4)$$

We see that the spinup time to $P_2 \sim 1$ min is $t_{su} \sim 10^4$ yr and depends strongly upon V. Since the spindown time for $P_1 \sim 1$ min is $\sim 10^5$ yr, the neutron star cannot spend more than ~ 10 per cent of its later life accreting material of $\rho \sim 10^{-13}$ g cm^{-3} if its period is to be in the range of minutes. If the stellar wind is always weak, spindown may always be dominant if the spinup torque is small enough. Even when accretion of this weak wind is possible, spindown torques will be exerted by viscous flow around the magnetosphere. The wind density criterion (2) may then be relaxed, and t_{sd} reduced.

3. PARAMETERS FOR THE 6·75 MIN SOURCE AND OTHER TRANSIENTS

The spectrum at maximum intensity given by Ives, Sanford & Bell-Burnell (1975) implies an X-ray energy flux $\sim 5.10^{-9}$ erg cm^{-2} s^{-1} over (2–15) keV. This translates to a distance to the source

$$D \lesssim 1 \cdot 3 \left(\frac{L_X}{10^{36}\ \text{erg s}^{-1}}\right)^{1/2} \text{kpc}.$$

Requiring the main sequence lifetime of its companion to be greater than $\sim 10^8$ yr implies its mass $\lesssim 10\ M_\odot$. Again we note that this depends very specifically upon the pulsar spindown rate and P_1, and therefore this mass limit may well be uncertain to a factor ~ 2.

As an example, we apply the above model to a binary system similar to Cen X-3 but with a much wider separation. Davidson & Ostriker (1973) give $\rho \sim 2 \times 10^{-13}$ g cm^{-3} in the usual ' high ' state and so in order to have $\rho \sim 4 \times 10^{-17}$ g cm^{-3}, we require the binary separation to be $\sim 2 \times 10^{13}$ g and thus $P_{orb} \sim 200$ days. This means that an X-ray eclipse is unlikely and since the orbital velocity $\sim 10^7$ cm s^{-1}, the maximum doppler shift < 1 s. A companion star with a smaller mass loss rate would imply a closer binary separation, but it is interesting to note that a reasonable set of conditions for the 6·75-min source may be inferred from the Cen X-3 system.

The 6·75-min source and similar transient X-ray sources should be identified optically with luminous stars (possibly early-type main sequence, or late-type giant*) and having evidence for binary periods up to ~ 200 days. It is interesting to note that the transient X-ray source, 2U 1543 – 47 has been tentatively identified with a late-type giant (Forman & Liller 1973).

The X-ray emission may be characterized by pulsations of period in the range 1–100 min. The depth of modulation may depend on the angle between the rotation and magnetic axes of the neutron star. If $B_* \ll 10^{12}$ gauss, or if the compact object were a black hole, little or no regular short period modulations would be observed. The observation of transient X-ray sources with $P \sim 1$ min would allow a distinction to be made between the 6·75-min binary model of Pringle & Webbink (1975) and the rotation model presented here. It is unlikely that suitable binary periods would exist much below a few minutes. We note in passing that variations in the time range 2–12 min have been poorly explored by X-ray instruments prior to Ariel-5.

4. CONCLUSIONS

We have shown that at least one of the transient X-ray sources may be due to a large enhancement in the stellar wind incident on a rotating magnetized neutron star in a close binary system. In the normally weak stellar wind, spindown occurs in

* Note that if during the pulsar spindown process little or no wind existed, then $P_1 > 2$ s. t_{sd} (equation (3)) only applies to the mass loss stage and if $P_1 > 10$ s, $t_{sd} < 3 \cdot 5 \times 10^6$ yr.

a time t_{sd} (equation (3)) to periods well in excess of a minute. The rotation period may be stabilized at a period P (equation (2)), which in the case of $P = 6.75$ min, implies a 'normal' stellar wind of density $\rho \sim 4 \times 10^{-17}$ g cm^{-3}. Large density fluctuations causing $\rho \gtrsim 10^{-13}$ g cm^{-3} will then give rise to transient X-ray emission, and providing that this does not occur more than ~ 10 per cent of the time, P will always exceed 1 min.

ACKNOWLEDGMENTS

Many helpful discussions with Dr Jim Pringle are gratefully acknowledged. Professors Martin Rees and Gerry Neugebauer and Dr Marcia Neugebauer and Ron Webbink are thanked for useful comments.

REFERENCES

Bondi, H., 1952. *Mon. Not. R. astr. Soc.*, **112**, 195.
Davidson, K. & Ostriker, J. P., 1973. *Astrophys. J.*, **179**, 585.
Forman, W. & Liller, W., 1973. *Astrophys. J.*, **183**, L117.
Giacconi, R., 1974. Text of talk presented at the *Seventh Texas Symposium on Relativistic Astrophysics*.
Illarionov, A. F. & Sunyaev, R. A., 1975. *Astr. Astrophys.*, **39**, 185.
Ives, J. C., Sanford, P. W. & Bell-Burnell, J., 1975. *Nature*, **254**, 576.
Jackson, J., 1975. *Mon. Not. R. astr. Soc.*, **172**, 483.
Lynden-Bell, D. & Pringle, J., 1974. *Mon. Not. R. astr. Soc.*, **168**, 603.
Ostriker, J. P. & Gunn, J. E., 1971. *Astrophys. J.*, **164**, L95.
Pringle, J. E. & Rees, M. J., 1972. *Astr. Astrophys.*, **21**, 1.
Pringle, J. E. & Webbink, R., 1975. *Mon. Not. R. astr. Soc.*, **172**, 493.
Roberts, D. H. & Sturrock, P. A., 1972. *Astrophys. J.*, **173**, L33.
Schwartzman, V. F., 1971. *Sov. Astr. AJ*, **15**, 342.