Mon. Not. R. astr. Soc. (1980) **192**, *Short Communication*, 11P–14P

SS 433: A freely precessing neutron star?

A. C. Fabian *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

Received 1980 April 1

Summary. Jets emerging from diametrically opposite points fixed on the surface of a freely precessing neutron star can explain naturally the motion of the spectral features of SS 433. If the rotation axis of the neutron star is close to the line-of-sight, the equations describing the velocity shifts reduce to a similar form to the equations that are applied to the precessing jet model. The hydrogen and helium observed in emission may originate from the surface of a companion star, about which the neutron star is in orbit. This companion induces the ~ 13-day radial velocity and photometric variations and may be responsible for the elongated shape of W 50.

Studies of SS 433, and perhaps of Her X-1, may provide valuable insight into the interior structure of neutron stars.

The remarkable motion of the emission features in SS 433 (Margon *et al.* 1979; Liebert *et al.* 1979) appears to be due to Doppler shifts in two oppositely moving regions of gas (Fabian & Rees 1979). Observations over the past year or so have shown that the motion recurs with a period of ~ 164 day and may be explained by opposing steady jets with velocities ~ $c/4$ which precess about a common axis (Milgrom 1979; Martin, Murdin & Clark 1979; Abell & Margon 1979; Margon, Grandi & Downes 1980; Murdin, Clark & Martin 1980). The mechanism responsible for the precession is uncertain: Martin & Rees (1979) and Begelman *et al.* (1980) have suggested general relativistic effects in a very close binary system (of period ~ 4 min); van den Heuvel, Ostriker & Petterson (1980) invoke a precessing accretion disc in a binary system of dimensions similar to those of the massive X-ray binaries. In this paper I propose that SS 433 is a rapidly rotating neutron star undergoing *free* precession. The emission, averaged over a rotation period, then originates in two opposing cones, the opening angle of which varies with the free-precession period of 164 day. The instantaneous emission may indeed originate in opposing jets aligned along the magnetic axis of the neutron star.

Free precession of a neutron star has been earlier invoked to explain discrepancies in pulsar timing (Ruderman 1970) and the 35-day cycle of Her X-1 (Brecher 1972; Lamb *et al.* 1975; Shaham 1977). Following Lamb *et al.* (1975), I shall consider the simplest case, in which the rotational behaviour of the neutron star is described by two moments of inertia; the axial component $I_{\parallel}$ and the equatorial component $I_{\perp}$. The precession frequency Ω_p is then given by

$$\Omega_p = \frac{I_\parallel - I_\perp}{I_\perp} \Omega_r \cos\alpha, \tag{1}$$

where α is the angle between the rotation axis $\mathbf{\Omega_r}$ and the figure axis. I assume that jets emerge radially along the magnetic dipole axis, $\boldsymbol{\mu}$, which is inclined at an angle χ to the figure axis. The free precession of this system means that the magnetic poles occur at co-latitudes θ (where $\mathbf{\Omega_r}$ lies along $\theta = 0$), which vary as

$$\cos\theta = \cos\alpha \cos\chi + \sin\alpha \sin\chi \cos\Omega_p t. \tag{2}$$

Ruderman (1970) gives a figure illustrating this motion (note that χ here is equivalent to his β). The jets then describe two opposing cones over the rotation period $P_r = (2\pi/\Omega_r)$, the opening angles of which vary as equation (2) over the precession period $P_p = (2\pi/\Omega_p)$. The width of the emission lines depends on the angle, i, between the line-of-sight and the rotation axis, $\mathbf{\Omega_r}$, and the intrinsic width θ_w of the instantaneous jets. Assuming that the latter is negligible, the apparent relative velocity spread of the lines is $\cos(\theta + i)$ to $\cos(\theta - i)$. Since this velocity spread is observed to be $\lesssim 0.1$, i must be $\lesssim 5°$ (depending on θ). This does imply that the orientation required in order to observe such narrow lines is relatively unlikely, with a probability of ~ 0.5 per cent. However, it must be noted that only values of $i \sim 0$ give rise to intense narrow lines. The general apparent velocity profile is

$$\frac{dF}{du} = \left[2\pi v \sin i \sin\theta \left\{ 1 - \left(\frac{u/v - \cos i \cos\theta}{\sin i \sin\theta} \right)^2 \right\}^{1/2} \right]^{-1}, \tag{3}$$

where F is the apparent intensity of emission (assumed to originate uniformly over the cone), u is the apparent velocity and v is the jet velocity. This profile is generally asymmetric and terminates in a cusp at either end. A value of $i = 0$, for which the observer is looking straight down the rotation axis, gives a line redshift, z, of

$$(1 + z) = \gamma\,(1 + v/c \cos\alpha \cos\chi + v/c \sin\alpha \sin\chi \cos\Omega_p t), \tag{4}$$

where γ is the Lorentz factor for the jet velocity, v. This is of identical form to the relevant equation for the 'standard' model in which the jet precesses with a 164-day period (Abell & Margon 1979). The observational fit provided to this last model by Margon *et al.* (1980) then shows that α and χ are 20.°4 and 79.°7, or vice versa. A more detailed fit of the free precession model may define i and could allow for three principal moment of of inertia components.

So far I have shown that a kinematic model based on free precession can explain the motion of the emission lines in a natural manner. It is not obvious what mechanism accelerates matter in the instantaneous jets, although some processes are discussed by Milgrom (1979), Begelman *et al.* (1980) and by Davidson & McCray (1980). The ~ 13-day period observed in the optical and infrared (Crampton, Cowley & Hutchings 1980; Giles *et al.* 1980; Margon *et al.* 1980), together with the obvious necessity to accelerate hydrogen and helium, suggests that the freely precessing neutron star may be in a ~ 13-day orbit about a companion 'normal' star. Coning pencil beams of fast particles or photons emitted by the neutron star may accelerate and excite the outer envelope and wind of such a star, which is probably of early type. I note that the velocity of ~ 80 000 km s^{-1} inferred for the steady jet is comparable to the escape velocity of a neutron star. The expanding supernova remnant W 50, that was generated at the formation of the neutron star, may have been distorted by the binary companion to give its present elonged shape (Geldzahler, Pauls & Salter 1979). The binary system may also be responsible for the linear structure observed through *VLB* radio observations (Spencer 1979). Note that $\mathbf{\Omega}_r$ need not necessarily be aligned with the axis of orbital motion.

The 164-day period may have been shorter in the past. Gottlieb & Liller (1979) found a period of ~ 162 day from the Harvard plate collection. This is compatible (through equation 1) with P_r increasing with time as the neutron star spins down, provided that α and the ratio of $I_\parallel$ to $I_\perp$ do not change. If the jets are the sole source of energy loss, then the pulsar period must be less than

$$P_r = 3.6 \times 10^{-3} I_{45}^{1/2} L_{40}^{-1/2} t_4^{-1/2} \text{ s}, \tag{5}$$

where the (average) moment of inertia is $10^{45} I_{45}$ g cm^2, the power in the jets is $10^{40} L_{40}$ erg s^{-1} and the spin-down time-scale $(P/\dot{P})$ is $10^4 t_4$ yr. The value of 2×10^{-10} for $(I_\parallel - I_\perp)/I_\perp \cos\alpha$ thus derived from equation (1) is not unreasonable for a neutron star (Pines & Shaham 1974). Energy loss through dipole (pulsar) radiation constrains the period to exceed

$$P_r = 7.9 \times 10^{-3} m_{30}^{1/2} L_{40}^{-1/4} \text{ s}, \tag{6}$$

where the magnetic moment is $10^{30} m_{30}$ G cm^3. A surface magnetic field B of $\lesssim 5 \times 10^{10}$ G on a neutron star of radius 10 km brings equations (5) and (6) into agreement. (I note that the neutron star could be powered by accretion from a disc if $i \sim 0$, since the disc need not then obscure our line-of-sight. Significant effects would, of course, occur when $\theta = 90°$.)

Since the emission emerges from the surface of a cone, the brightnesss temperature restrictions (see Fabian & Rees 1979; Margon *et al.* 1979) are relaxed somewhat, as compared with a 'standard' jet model. The emission may originate from within a radius of $\sim 2 \times 10^{12}$ cm. The power L in the jets may also be less than that in the 'standard' jets by a factor $\sim (\theta_j R_j/\theta_f R_f)^{1/2}$, where θ_f, θ_j and R_f, R_j are the instantaneous jet opening angles and characteristic emission-lengths in the free precession and 'standard' jet models respectively. L may be much less than 10^{40} erg s^{-1} if $\theta_w \lesssim 1°$ and/or the filling factor for emission-line material is small.

The free-precession model outlined above may be observationally investigated further by seeking special relativistic effects (aberration etc.) and refining the jet velocity curve. The short rotation period of the neutron star may not be easily detectable. The gas inferred to surround the object may interfere with radio emission and might anyway lead to acute dispersion problems. P_r is probably smeared out in the optical lines since the emission region is much larger than cP_r. The X-ray emission of SS 433 may, in part, be due to the jets shocking the surrounding gas and need not reflect P_r unless the cooling times are very short. Starquakes and other motions associated with the spin-down of a rapidly rotating neutron star may cause simultaneous variations in the approaching and receding cones. Time delays between the two cones may be $\lesssim 5$ min. It is unlikely that the nearer approaching cone significantly obscures the receding cone, especially if the filling factor is small. Other systems similar to SS 433 may be difficult to identify unless the inclination of the rotation axis is small. I assume that the assymmetry necessary for free precession was injected during the supernova explosion. It is possible that most pulsars pass through such a phase, the duration of which depends upon L and B, but the jets are only optically observed if there is a companion star to provide the necessary gas. SS 433 may spin down to form a more conventional X-ray binary in a few million years.

Finally, free precession may be the 'clock' for the 35-day cycle of Her X-1 (Brecher 1972; Lamb *et al.* 1975). Recent *Ariel V* observations presented by Parmar, Sanford &

Fabian (1980) indicate that a precessing outer disc may not explain the nature of the X-ray obscuration associated with that cycle (Katz 1973; Petterson 1979). It appears that the quasi-periodic obscuration arises deep within the smallest disc compatible with the Her X-1/HZ Her system. Steady X-ray emission from magnetic poles oscillating between colatitudes of $\sim 70^\circ$ to $\sim 100^\circ$ may generate both primary and secondary states of the X-ray source, and yet not conflict with changes in pulse shape, determined during the primary on-state (Joss *et al.* 1978). Free precession of SS 433 and perhaps of Her X-1 may be important tools in developing our understanding of the structure of neutron stars.

Acknowledgments

I thank Bruce Margon and Martin Rees for helpful discussions. I am grateful to the Radcliffe Trust for financial support.

References

Abell, G. O. & Margon, B., 1979. *Nature,* **279,** 701.
Begelman, M. C., Sarazin, C. L., Hatchett, S. P., McKee, C. F. & Arons, J., 1980. *Astrophys. J.,* in press.
Brecher, K., 1972. *Nature,* **239,** 325.
Crampton, D., Cowley, A. P. & Hutchings, J. B., 1980. *Astrophys. J. Lett.,* in press.
Davidson, K. & McCray, R., 1980. Preprint.
Fabian, A. C. & Rees, M. J., 1979. *Mon. Not. R. astr. Soc.,* **187,** 13P.
Geldzahler, B. J., Pauls, T. & Salter, C. J., 1979. *Astr. Astrophys.,* in press.
Giles, A. B., King, A. R., Jameson, R. F., Sherrington, M. R., Hough, J. H., Bailey, J. E., Cunningham, E. A., Glass, I. S., Carter, B. S., Catchpole, R. M., Roberts, G., Axon, D. J. & Allen, D. A., 1980. Preprint.
Gottlieb, E. W. & Liller, W., 1979. *IAU Circ. 3354.*
Joss, P. C., Fechner, W. B., Forman, W. & Jones, C., 1978. *Astrophys. J.,* **225,** 994.
Katz, J. I., 1973. *Nature,* **246,** 87.
Lamb, D. Q., Lamb, F. K., Pines, D. & Shaham, J., 1975. *Astrophys. J.,* **198,** L21.
Liebert, J., Angel, J. R. P., Hege, E. K., Martin, P. G. & Blair, W. P. 1979. *Nature,* **279,** 384.
Margon, B., Ford, H. C., Katz, J. I., Kwitter, K. B., Ulrich, R. K., Stone, R. P. S. & Klemola, A., 1979. *Astrophys. J.,* **230,** L41.
Margon, B., Grandi, S. A. & Downes, R. A., 1980. *UCLA Preprint No. 85.*
Martin, P. G., Murdin, P. G. & Clark, D. H., 1979. *IAU Circ. 3358.*
Martin, P. G. & Rees, M. J., 1979. *Mon. Not. R. astr. Soc.,* **189,** 19P.
Milgrom, M., 1979. *Astr. Astrophys.,* **76,** L3.
Murdin, P., Clark, D. H. & Martin, P. G., 1980. Preprint.
Parmar, A. N., Sanford, P. W. & Fabian, A. C., 1980. *Mon. Not. R. astr. Soc.,* **192,** 311.
Petterson, J. A., 1975. *Astrophys. J.,* **201,** L61.
Pines, D. & Shaham, J., 1974. *Comm. Astrophys. Space Sci.,* **6,** 37.
Ruderman, M., 1970. *Nature,* **225,** 838.
Shaham, J., 1977. *Astrophys. J.,* **214,** 251.
Spencer, R., 1979. *Nature,* **282,** 483.
van den Heuvel, E. P. J., Ostriker, J. P. & Petterson, J. A., 1980. *Astr. Astrophys.,* **81,** L7.

Note added in proof

A similar model for SS 433 is discussed by J. Shaham in a paper (*Astrophys. Lett.,* **20,** 115) which appeared while this paper was in press.