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A precessing neutron star model for E 2259+586

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Summary. We consider the possibility that the pulsating X-ray source E2259+586 is a neutron star of mass $M \simeq 0.3 M_\odot$, spin period $P_s \simeq 4$ ms, and magnetic moment $\mu_{\rm magn} \simeq 10^{28}$ ergG^{-1}. The observed period $P = 6.98$ s is interpreted as due to free precession of the solid neutron star whose oblateness is $\varepsilon_0 \sim 7\ 10^{-2}$. Ways of discriminating from accretion models are discussed.

Key words: X-ray sources – precession – neutron stars

1. Observations of E2259+586

E2259+586 is a pulsating X-ray source with period $P = 6.98$ s and $\dot{P} = 7.1\ 10^{-13}$ discovered by Fahlam and Gregory (1980) with the EINSTEIN observatory in December 1979. Further observations were made with the EINSTEIN observatory (1980 July, see Fahlam and Gregory, 1981, and 1981 January, see Fahlam and Gregory, 1983b) and with EXOSAT (1984 December, see Morini et al., 1988; Hanson et al., 1988).

The pulsating source is nearly at the centre of a semi-spherical X-ray shell (CTB109+1.0) extending on its eastern side and a jet-like feature seems to connect E2259+586 with this envelope. The shell structure is observed also in the radio and optical maps (see Gregory et al., 1983; Hughes et al., 1983, 1984; Fahlam et al., 1982; Middleditch et al., 1983). The observation of a rather high [S II]/Hα ratio suggests the shell is the remnant of a supernova explosion.

Using the surface brightness-diameter relation of Caswell and Lerche (1979), one can estimate a distance for the remnant $D \simeq 5$ kpc, a linear diameter $\phi \simeq 24$ pc and an approximate age, as from the Sedov model, $\tau \simeq 10^4$ yr.

Radio studies of the region (Hughes et al., 1983, 1984) did not reveal the presence of a pulsating radio signal and of a compact radio source in the neighbouring of E2259+586.

Observations at optical and infrared wavelengths (Fahlam et al., 1982; Middleditch et al., 1983) posed a severe limit on a possible visible counterpart for E2259+586. Middleditch et al. (1983) estimate a magnitude $m_B \simeq 23.5$ mag for a candidate 9" south-east from the EINSTEIN HRI position (the extinction is $A_B \simeq 5.0$ mag). A possible infrared pulsation downshifted of 1 mHz with respect to the X-ray one was reported in one occasion (Middleditch et al., 1983), but not subsequently confirmed.

An orbital modulation at $P_{\rm orb} = 2300$ s with a projected semiaxis 0.16 ltsec $< \alpha_x$ seni $<$ 0.21 ltsec was reported by Fahlam and Gregory (1983b) using the EINSTEIN data (search between 1000 s and 10000 s). However, this orbital period was not confirmed, on the basis of the same EXOSAT data, both by Morini et al. (1988) (search between 750 s and 80000 s) and by Hanson et al. (1988) (search between 500 s and 43200 s). No periods were found in these ranges with statistical significance.

The spectral analysis of EXOSAT data by Morini et al. (1988) gives a soft pulsed spectrum with luminosity $L_p = 9.1\ 10^{34}$ erg s^{-1} (bremsstrahlung) or $L_p = 2.8\ 10^{34}$ erg s^{-1} (blackbody) and a diffuse luminosity of $L_d = 1.3\ 10^{36}$ erg s^{-1} in the range (0.1 – 10) keV. This is close to the results of Hanson et al. (1988) which give a total luminosity $L_d = 10^{36}$ erg s^{-1} and a pulsed one $L_p = 10^{35}$ erg s^{-1} in the range (0.5–4.0) keV ($D = 3.6$ kpc). In a simple thermal model, both groups report a typical temperature $kT_{\rm pulsed} \simeq$ keV for a density column $N_{\rm H} \simeq$ (0.4 – 0.8) 10^{22} cm^{-2}.

2. Proposed models of the source

Various suggestions have been made to account for the characteristics of E2259+586, even if no model has been worked out in detail.

Fahlam and Gregory (1983b) and Hanson et al. (1988) indicate as the most plausible model that of accretion from a disc formed through Roche lobe overflow in a close binary system consisting of a central magnetized neutron star and a non degenerate companion of low mass. The observed low luminosity corresponds to $\dot{M} \sim 10^{15}$ g s^{-1} and the unusual spin down could be due to torques from a retrograd rotation of the disc itself. This would be the only case of steady spin down of a X-ray pulsator (see, on this regard, the recent observations of TENMA and GINGA reported by Kojama et al., 1987).

Another possibility suggested by Hanson et al. (1988), which doesn't require a retrograde motion, is the binary disc accretion model proposed by Ghosh and Lamb (1979, and references therein). In this picture a central magnetized neutron star slows down because of a braking coupling between the inflowing material and the magnetosphere in the outer edge of a rapidly rotating disc. The companion is thought to be a non degenerate helium star of $M = 0.37\ M_\odot$ in a very close orbit.

The main uncertainties of the accretion models are, however, the absence of any clear identification of an orbital (and possibly short) period and the lack of a convincing visible counterpart. Moreover, the jet-like feature produced by the accretion disc remains unexplained, since in the frame of accretion models one expects that jets are related to luminosities close to the Eddington limit ($L_{\rm Edd} \sim 10^{38}$ erg s^{-1}). As noted by Morini et al. (1988), uncommon too are the absence of a substantial luminosity

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variability and the unusually soft X-ray spectrum, contrary to what is typically observed in many other pulsating X-ray binaries.

An interesting possibility suggested by Morini et al. (1988), is that the source is a highly magnetized, rapidly rotating white dwarf slowing down by the emission of dipole radiation. However, the spin period would be alarmingly close to the stability limit for a white dwarf, and the required surface magnetic field ($B > 10^9$ G) would be among the highest ever observed in white dwarfs (see, e.g. Schmidt et al., 1986). Moreover, the association with the shell would be coincidental.

Because of the mentioned difficulties, we investigate the possibility that the object is a rapidly rotating neutron star and that the observed period is due to free precession. This possibility has been already mentioned by Hanson et al. (1988). We note that we consider the accretion picture as viable, and it will be compared with the precession one in the discussion section.

3. A free precession model

Free precession in neutron stars was examined in the context of theories for explaining the rapid post-glitch behaviour of the Crab and the Vela pulsars, in a starquake or creep scenario (see, e.g., Ruderman, 1970; Pines and Shaham, 1974; Baym et al., 1976; Alpar and Ogelman, 1987 and references therein). The theory involves the study of elastic strains and stresses of bodies subject to gravitational and rotational deformation (see, e.g., Love, 1920; Pines and Shaham, 1972a). The main results we use here derive from the latter paper. We also refer to neutron star parameters as calculated for different types of equation of state by Baym and Pines (1971, BPS eq. of state), Pines and Shaham (1972b, BBP eq. of state) and Pandharipande, et al. (1976, TI, TI1, TI2 eq. of state).

From the Euler equations for a nearly spherical, incompressible, rotating, axially symmetric and not necessarily completely solid star, one finds (Pines and Shaham, 1972a) that the precession frequency Ω_p is related to the spin frequency Ω_s by:

$$\Omega_p = \frac{3}{2}\frac{B}{A+B}\varepsilon_0 \Omega_s. \tag{1}$$

A and B represent quantities related to the gravitational and elastic energy stored in the star, and ε_0 is the initial reference oblateness for a strain free star. An estimate for A (exact for an incompressible and homogeneous star, accurate to within a factor of two for a star with a thick crust) is given by (Love, 1920)

$$A = -\frac{1}{5} E_{\mathrm{grav}}, \tag{2}$$

where E_{grav} is the gravitational binding energy of the star.

For a self-gravitating sphere B is given by (Love, 1920):

$$B = \frac{57}{50}\left(\frac{4}{3}\pi R^3\right) C_{44}, \tag{3}$$

where

$$C_{44} = 0.3711 Z^2 e^2 n_N^{4/3} \cdot 2^{-1/3}. \tag{4}$$

(C_{44} is the shear modulus of a bcc lattice of nuclei of density n_N, interacting via an unscreened Coulomb interaction, e is the electron charge, Z is the atomic number). The actual values of A

Table 1. Precession analysis. The first four columns give the mass of the model neutron star, the total radius R_5, the inner radius of the crust $R_{\mathrm{cr},5}$ and the solid core radius $R_{\mathrm{co},5}$ in units of 10^5 cm. $I_{0,44}$ is the moment of inertia (in units of 10^{44} g cm^2), A_{52} and B_{48} are the energy parameters (see text) (in units of 10^{52} erg and 10^{48} erg respectively) as calculated by Baym and Pines (1971), Pines and Shaham (1972b) and Pandharipande et al. (1976). P_s is the spin period (in ms), $\dot{P}_s$ its derivative, $L_{\mathrm{tot},36}$ is the total luminosity (in 10^{36} erg s^{-1}) and ε_0 the star oblateness. The last column gives the adopted equation of state: BPS (see Baym and Pines, 1971), BBP (see Pines and Shaham, 1972b) and TI (see Pandharipande et al., 1976)

$M/M_\odot$	R_5	$R_{\mathrm{cr},5}$	$R_{\mathrm{co},5}$	$I_{0,44}$	A_{52}	B_{48}	P_s	$\dot{P}_s$	$L_{\mathrm{tot},36}$	ε_0	Eq. of state
0.09	248	0	0	2.72	0.015	6.1	19.4	$2.0\ 10^{-15}$	2.9	$4.8\ 10^{-2}$	BPS
0.10	59.3	0.5	0	0.56	0.016	5.1	10.4	$1.1\ 10^{-15}$	2.1	$3.2\ 10^{-2}$	BPS
0.15	17.3	4.8	0	0.62	0.072	3.8	3.6	$3.7\ 10^{-16}$	19	$6.6\ 10^{-2}$	BPS
0.41	10.8	7.4	0	2.00	0.56	2.0	1.1	$1.1\ 10^{-16}$	$6.7\ 10^{2}$	$2.9\ 10^{-1}$	BPS
0.10	53	0	0	0.61	0.04	19.1	9.0	$9.1\ 10^{-16}$	3.1	$1.9\ 10^{-2}$	BBP
0.15	17	4.3	0	0.60	0.11	23.1	4.9	$5.0\ 10^{-16}$	10	$2.2\ 10^{-2}$	BBP
0.20	12.9	5.3	0	0.70	0.19	16.4	3.2	$3.2\ 10^{-16}$	28	$3.6\ 10^{-2}$	BBP
0.25	11	5.8	0	0.84	0.32	10.1	2.0	$2.1\ 10^{-16}$	81	$6.5\ 10^{-2}$	BBP
0.30	10.1	6.1	0	1.1	0.45	7.9	1.6	$1.7\ 10^{-16}$	$1.6\ 10^{2}$	$9.4\ 10^{-2}$	BBP
0.10	306	0	0	5.3	0.03	6.3	15.5	$1.6\ 10^{-15}$	8.8	$7.3\ 10^{-2}$	TI
0.29	19.7	0	0	3.0	0.25	14.3	4.1	$4.2\ 10^{-16}$	71	$7.0\ 10^{-2}$	TI
0.73	16.8	7.1	0	10.1	1.5	27.2	2.3	$2.4\ 10^{-16}$	$7.5\ 10^{2}$	$1.3\ 10^{-1}$	TI
1.08	16.3	10.1	0	16.3	3.3	19.1	1.4	$1.5\ 10^{-16}$	$3.2\ 10^{3}$	$2.5\ 10^{-1}$	TI
1.93	12.7	11.1	7.0	21.9	17.8	$14.4\ 10^{4}$	8.3	$8.4\ 10^{-16}$	$1.3\ 10^{2}$	$1.8\ 10^{-3}$	TI
1.90	14.9	12.4	5.3	29.5	12.6	$6.2\ 10^{4}$	9.3	$9.4\ 10^{-16}$	$1.4\ 10^{2}$	$2.7\ 10^{-3}$	TI1
1.97	14.2	12.1	6.8	28.0	15.0	$13.2\ 10^{4}$	9.7	$9.8\ 10^{-16}$	$1.2\ 10^{2}$	$2.0\ 10^{-3}$	TI1
1.90	13.9	11.9	5.2	25.8	14.3	$6.0\ 10^{4}$	8.2	$8.3\ 10^{-16}$	$1.5\ 10^{2}$	$2.6\ 10^{-3}$	TI2
1.92	12.9	11.0	6.7	21.2	18.2	$12.6\ 10^{4}$	7.9	$8.0\ 10^{-16}$	$1.4\ 10^{2}$	$1.8\ 10^{-3}$	TI2

and B depend on the chosen equation of state and mass for the neutron star. This is illustrated in Table 1.

In the quadrupolar approximation for the deformations one has for the oblateness (Baym and Pines, 1971):

$$\varepsilon_0 = \frac{I_0 \Omega_0^2}{4A}, \tag{5}$$

where Ω_0 is the spin of the neutron star at the time the crust solidified and I_0 is the moment of inertia. In the following we make the approximation that the present angular velocity is close to the initial one, whose validity can be checked a posteriori. Therefore, one has:

$$\Omega_s \sim \Omega_0 \tag{6}$$

From Eqs. (1), (5) and (6), one obtains for the spin period P_s and the precession period P_p:

$$P_s = \left(\frac{3}{2}\frac{\pi^2 I_0 B}{(A+B)A}\right)^{\frac{1}{3}} P_p^{1/3}, \tag{7}$$

$$\dot{P}_s \simeq \frac{P_s}{P_p}\dot{P}_p. \tag{8}$$

The total luminosity due to radiation damping is obviously:

$$L_{tot} = I_0 \Omega_s \dot{\Omega}_s \tag{9}$$

which, in terms of p_p and $\dot{P}_p$, becomes:

$$L_{tot} = I_0 \left(\frac{3 I_0 B}{16\pi(A+B)A}\right)^{-\frac{2}{3}} P_p^{-5/3} \dot{P}_p \tag{10}$$

The total luminosity L_{tot} must be equal or larger than the observed one, the inequality applying, for instance, to the case of significant gravitational wave energy losses. Therefore, one has:

$$L_{tot} \geq L_{obs} \sim 10^{36}\,\mathrm{erg\,s^{-1}}. \tag{11}$$

For each neutron star model, from the observed values of P_p and $\dot{P}_p$ and Eqs. (7), (8), (10) one can obtain P_s, $\dot{P}_s$ and L_{tot}. This is done in Table 1.

We consider as viable configurations for the precession picture those which satisfy Eq. (11) and yield a rotational period P_s not conflicting with the stability of the neutron star. This latter condition is taken in the form:

$$P_s > 1\ \mathrm{ms}. \tag{12}$$

Various configurations satisfying these criteria can be found in the range of low masses ($(0.09-0.41) M_\odot$ for BPS stars, $(0.10-0.30) M_\odot$ for BBP stars, $(0.10-1.08) M_\odot$ for TI ones) and in the range of much higher masses ($(1.90-1.97) M_\odot$ for TI stars). However, the low mass cases ($\sim 0.1\ M_\odot$) may be out of the region of stability of neutron stars and, therefore, they will not be discussed any further. The higher mass neutron stars exhibit a different type of problem. In fact, they are only partly solid, so one should take into account the internal frictional dissipation between the superfluid core and the crust and the subsequent precessional damping. According to the most recent model of Alpar and Ogelman (1987) on the precession of superfluid cores through vertex creep, one can infer an upper limit for the damping on timescales $\tau_d \leq 1$ yr, which leads us to exclude this possibility.

Therefore, the most interesting configuration appears a star in the intermediate range of masses, with a solid structure, described, for instance, by the TI equation of state. As shown in the table, the typical parameters of such a star are $M \simeq 0.3\ M_\odot$, $R \simeq 2.10^6$ cm, $I_0 = 3.0\ 10^{44}\ \mathrm{g\,cm^2}$, $A = 2.5\ 10^{51}$ erg, $B = 1.4\ 10^{49}$ erg and the corresponding calculated parameters $P_s \simeq 4$ ms, $\dot{P}_s = 4.2\ 10^{-16}$, $L_{tot} \simeq 7.1\ 10^{37}\ \mathrm{erg\,s^{-1}}$, $\varepsilon_0 \simeq 7.0\ 10^{-2}$.

Since the deceleration timescale is $\tau \simeq P_s/\dot{P}_s \simeq 3\ 10^5$ yr, if the age of the system is $\sim 10^4$ yr, it is reasonable to assume that the present neutron star configuration is close to that at its formation.

We note that in this case, on account of an estimated mean density $\rho \simeq 10^{13}\ \mathrm{g\,cm^{-3}}$, a fraction of the neutrons should form a superfluid in the crustal material and cause a damping of the wobble amplitude through pinning torques (see, e.g., Alpar and Ogelman, 1987). However, the problem of damping could turn out not to be critical, if we choose an appropriate value for the pinning parameter, i.e. $E_p \simeq 0.15$ MeV, and for the internal temperature of the star, i.e. $kT \simeq 5$ keV, since in this case the wobble damping timescale becomes similar or larger than the assumed age of the SNR. With these values, also the frictional energy dissipation should result much less than $10^{36}\ \mathrm{erg\,s^{-1}}$.

Another important aspect of the precession scenario is related to the emission of gravitational radiation by the star, since it could overwhelm the limit given by L_{tot}. The formula for the gravitational power is given by (see, e.g., Alpar and Pines, 1985, and references therein):

$$L_{grav} \simeq \frac{32 G I_0^2 \Omega_s^6 \varepsilon_{eff}^2}{5c^5} \tag{13}$$

ε_{eff} is the so called effective triaxiality of the neutron star, for which an estimate is given by Alpar and Pines (1985):

$$\varepsilon_{eff} \simeq \frac{3}{16}\frac{B}{16A+B}\varepsilon_0 \sin 2\theta_0, \tag{14}$$

where θ_0 is the wobble amplitude.

From the condition $L_{grav} \leq L_{tot}$, we find that a viable configuration should correspond to a wobble amplitude $\theta_0 \simeq 1^0$. Such a small angle, less than the limit for crust cracking, seems to be consistent with the wobble phase amplitude given in the paper by Ruderman (1970), however it clearly represents a critical constraint to the model.

4. Discussion

We assume that the electromagnetic energy loss is roughly described by the Deutsch formula (1955) for dipole radiation. Therefore (in the CGS system)

$$L_{obs} \leq \frac{2}{3}\frac{\sin^2\chi \mu^2 \Omega_s^4}{c^3} \leq L_{tot}, \tag{15}$$

where μ is the magnetic moment and χ its inclination. This yields

$(2.7\ 10^{27} \leq \mu \sin\chi \leq 2.3\ 10^{28})\ \mathrm{erg\,G^{-1}}$.

Note that, unless χ is very small, the magnetic moment is about a factor 10^2-10^3 below that of the Crab nebula pulsar.

Our main requirement for the electrodynamics of this low field pulsar is that $\sim 10^{35}\ \mathrm{erg\,s^{-1}}$ are released in the X-ray band and $\sim 10^{36}\ \mathrm{erg\,s^{-1}}$ go into the heating of the nebula. This is consistent with the suggestion by Fahlam and Gregory (1983a) that the jet-like feature connecting the central source with the shell is due to the precession of two oppositely directed X-ray beams emitted by a central pulsar, and that the observed radio structure is due to synchrotron radiation by accelerated electrons interacting with the walls of the SNR.

Since we suppose that the source is a rapidly rotating neutron star, one can expect it is a source of high energy radiation too. The maximum available potential drop in the homopolar generator model of Goldreich and Julian (1969) is a fraction of that of the Crab Nebula pulsar (NP0531+21). As a rough approximation for giving an upper limit to the γ-ray flux from E2259+586 one could either scale that of NP0531+21 to the distance of the source, or assume that the overall spectral shape are similar and scale on the observed X-ray fluxes. In the two cases one finds, at 100 MeV, $I_\gamma \leq 10^{-6}$ phcm^{-2} s^{-1} and $I_\gamma \leq 10^{-8}$ phcm^{-2} s^{-1}. This is consistent with the absence of a prominent COSB source, but makes the system an interesting candidate for more sensitive instruments.

A system which may have some affinity with E2259+586 is the X-ray source E0630+178, the possible counterpart of the strong γ-ray source 2GC195+04 (Geminga) (Bignami et al., 1983). Also in this case the optical to X-ray ratio is small, $L_{\rm opt}/L_x = 5.6\ 10^{-4}$. Assuming a distance 0.7 kpc, consistent with the discussion of Halpern and Tytler (1988), the X-ray luminosity turns out to be $L_x \sim 10^{32}$ erg s^{-1}. The scaling of the γ-ray flux with distances is again consistent with the absence of a COSB source at the position of E2259+586. The analogy between E2259+586 and Geminga could be even stronger if the 60 s period claimed by some authors and disputed by others (see, for an enlightening discussion, Halpern and Tytler, 1988) were real. In fact, after the first report of this period from the SASII group (Thomson et al., 1977), a precession picture for Geminga, close to the present one, was proposed by Maraschi and Treves (1977).

As we have mentioned in the introduction, an alternative viable model to the precessing neutron star are the accretion models. There are several ways for discriminating between the two pictures. Should a binary period be discovered, the accretion model would be highly favoured. On the other hand, if a rapid periodicity will be evidentiated, the precession picture would become highly attractive. On this regard we note that a direct detection of the rapid periodicity in X-rays could be easier than for low mass X-ray binaries, since in the present case one does not expect a thick plasma cloud to surround the neutron star and dilute the pulsation. Of course, also the radio band should be further explored for rapid periodicities, but in that case a negative result could be attributed to a beaming out of the line of sight, or to confusion introduced by the nebula.

The main uncertainties and difficulties for the precession scenario depend, however, as we noted in Sect. 3, on the assumptions for the pinning parameters and internal temperature of the neutron star and a possible overwhelming gravitational radiation. Obviously, if the precession hypothesis proved correct, the central source in CTB109 would appear of the outmost interest to explore and test equations of state of neutron stars.

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