GLITCHES IN THE X-RAY PULSAR 1E 2259+586

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ABSTRACT

Starquakes are considered for fast-rotating magnetic white dwarfs. The X-ray pulsar 1E 2259 + 586 may be such a white dwarf. It is shown that in this case starquakes may be responsible for the decrease of the mean spin-down rate which was observed for 1E 2259 + 586 between 1987 and 1990. The required mass of the white dwarf which is identified with 1E 2259 + 586 is \( \sim 1.4 - 1.5 M_\odot \), making this X-ray pulsar the most massive white dwarf known.

1. INTRODUCTION

The X-ray pulsar 1E 2259+586 is located close to the center of the young supernova remnant G109.1 – 1.0 whose age is estimated to be \((1.2 - 1.7) \times 10^4\) yr (Gregory and Fahlman 1980; Hughes, Harten and van den Bergh 1981). The period of the pulsar, \( P = 6.98\) s, is suitable for an ordinary binary X-ray pulsar. But, 1E 2259 + 586 exhibits several peculiarities: (1) the period shows an unusually stable spin-down trend with a small rate of \( 5.9 \times 10^{-13} \text{ s s}^{-1} \) (Davies, Wood and Coe 1990); (2) no orbital Doppler modulation of the pulsar period has been discovered (Koyama et al. 1989); (3) there is no firm evidence for an optical counterpart (Davies and Coe 1991), and (4) it has an unusually soft X-ray spectrum. Therefore, Davies et al. (1989) have suggested that 1E 2259 + 586 is a single star. However, this X-ray pulsar cannot be a single neutron star in which, like a radio pulsar, spin-down power is a source of the radiation. The point is that for a neutron star with the observed spin period and the spin-down rate, the spin-down power cannot be larger than \( 10^{33} \text{ ergs s}^{-1} \), while the soft X-ray luminosity of 1E 2259 + 586 is \( \sim 10^{35} \text{ ergs s}^{-1} \) (Fahlman and Gregory 1981; Davies, Wood and Coe 1990).

It was suggested by Paczyński (1990) that the enigmatic X-ray pulsar 1E 2259 + 586 is a single fast-rotating white dwarf with a strong magnetic field, \( B_s \sim 10^9 \) Gauss, at its surface. The required mass of the white dwarf is higher than \( 1.32 M_\odot \). This lower limit is because of a centrifugal instability for the white dwarf if its mass is smaller than \( 1.32 M_\odot \). Such a massive white dwarf may be the product of a white dwarf merger. Since the moment of inertia for a massive white dwarf is more than \( \sim 10^4 \) times larger than for a neutron star, the spin-down power of the white dwarf may be as high as \( \sim 10^3 \times 10^{36} \text{ ergs s}^{-1} \), which is more than enough to explain the X-ray luminosity of 1E 2259 + 586. The soft X-ray emission of 1E 2259 + 586 can be explained by the radiation of the hot gas in the polar caps (Usov 1993). This gas is heated by the flux of positrons which are created in the magnetosphere of the white dwarf.

It was shown recently (Iwasawa, Koyama and Halpern 1992) that the spin-down rate, which was consistent with a constant value for the first 10 years of observations, from 1978 to 1987, has decreased by a factor of 2 between 1987 and 1990. Using this, Iwasawa, Koyama and Halpern (1992) have concluded that the single white dwarf model of Paczyński (1990), which required a stable \( \dot{P} \), is ruled out for 1E 2259 + 586. In this paper I have argued that this conclusion
is premature. The point is that if an essential part of the white dwarf is solid, starquakes have to have happened occasionally in the process of deceleration of the white dwarf rotation. In turn, these starquakes may result in sudden changes of $P$, which are similar to the pulsar glitches. One of these changes of $P$ may be responsible for the decrease of the mean spin-down rate which was observed between 1987 and 1990.

2. STARQUAKES AND THE PULSE PERIOD EVOLUTION

Let us consider a fast-rotating magnetic white dwarf with a solid core. As the rotation of the white dwarf slows down because of the electromagnetic torque, centrifugal forces on the core decrease, and gravity pulls it toward a less oblate shape, thereby stressing it. When stresses in the core reach a critical value, the core cracks, some stress is relieved, and the excess oblateness, due to the core rigidity, is reduced. The moment of inertia of the white dwarf is suddenly decreased, and by conservation of angular momentum the angular velocity of the white dwarf rotation, $\Omega = 2\pi/P$, is suddenly increased. This is similar to the starquakes which were considered for neutron stars to explain the pulsar glitches (Ruderman 1969; Baym and Pines 1971; Pines, Shaham and Ruderman 1972).

The oblateness of a rotating white dwarf may be characterized by the following dimensionless parameter:

\[ \varepsilon = \frac{I - I_o}{I_o}, \tag{1} \]

where $I$ is the moment of inertia of the white dwarf, and $I_o$ is its moment of inertia in the case that the white dwarf does not rotate.

Since the angular momentum of the white dwarf is conserved in the quake, the sudden change in the oblateness is

\[ \Delta \varepsilon = \frac{\Delta I}{I} = \frac{\Delta P}{P}, \tag{2} \]

where $\Delta I$ is the change of $I$, and $\Delta P$ is the jump of $P$.

The characteristic time between quakes is (Baym and Pines 1971)

\[ t_q \simeq \tau_s \frac{\omega_q^2}{\Omega^2} | \Delta \varepsilon |, \tag{3} \]

where $\tau_s = P/\dot{P}$ is the time that characterized the rate at which the white dwarf slows down due to loss of rotational energy [$\tau_s \approx 3 \times 10^5$ yr for 1E 2259 + 586],

\[ \omega_q^2 = \frac{2D^2}{BI_o}, \quad D = \frac{3}{25} \frac{GM_c^2}{R_c}, \tag{4} \]

\[ B = 0.42 \left( \frac{4\pi}{3} R_c^3 \right) \frac{Z^2 c^2 n_A}{a^2}, \quad a = \left( \frac{2}{n_A} \right)^{1/3}, \tag{5} \]

$n_A = \rho_c/A m_p$ is the ion density, $\rho_c$ is the density of matter in the white dwarf core, $A$ is the atomic weight of ion, $Z$ is its electric charge, $m_p$ is the mass of
The more reasonable value of $\Gamma$ is 150.

The more reasonable parameters of the white dwarf which is identified with 1E 2259 + 586 are the mass of the white dwarf $M \simeq 1.45 M_\odot$ (see below), the stellar radius $R \simeq 3 \times 10^8$ cm, $M_e \simeq 1 M_\odot$, $R_e \simeq 2 \times 10^8$ cm, $\bar{\rho}_e = M_e / (4\pi / 3) R_e^3 \simeq 6 \times 10^7$ g cm$^{-3}$, and $I_o \simeq 10^{50}$ g cm$^2$. Substituting these parameters into equations (2) - (5), for the white dwarf which consists of iron, $Z = 26$ and $A = 56$, we obtain $D \simeq 10^{50}$ ergs, $n_\Lambda \simeq 7 \times 10^{29}$ cm$^{-3}$, $a \simeq 1.4 \times 10^{-10}$ cm, $B \simeq 10^{49}$ ergs, $\omega_q^2 \simeq 20$ s$^{-2}$, $t_q \simeq 7 \times 10^6 / \Delta \varepsilon$ yr. Taking into account equation (2), we have the following relation between $t_q$ and $|\Delta P| / P$ for 1E 2259 + 586:

$$t_q \simeq 7 \times 10^6 \frac{|\Delta P|}{P} \text{ yr} \quad (6)$$

The available observational data on the changes of the pulse period of 1E 2259 + 586 from 1978 to 1990 are given in Figure 1. This data may be in agreement with the single white dwarf model of 1E 2259 + 586 if we assume the existence of glitches with $\Delta P = -(1-2) \times 10^{-5}$ s and $t_q \simeq 3 - 10$ yr or more (see Fig. 1). For this value of $\Delta P$ equation (6) yields $t_q \simeq 10 - 20$ yr, which might be uncertain within a factor of 2-3. This value of $t_q$ is consistent with the data on the evolution of the pulse period of 1E 2259 + 586.

One of the main assumptions which we have used in this paper is the existence of massive solid core inside the white dwarf which is identified with 1E 2259 + 586. The cooling of white dwarfs and their crystallization were considered mainly for white dwarfs with mass $M \sim 0.6 M_\odot$, the ”typical” mass remnant of single-star evolution (for a review, see D’Antona and Mazzitelli 1990). For such a white dwarf the time, $\tau_{cr}$, from its formation to the stage of crystallization is $\sim 10^8 - 10^9$ yr. This is much more than the age of the X-ray pulsar 1E 2259 + 586 in the model of Paczyński (1990) in which the pulsar cannot be much older than $\tau_s = P / P \simeq 3 \times 10^5$ yr, but it may be as young as $\sim 1.5 \times 10^4$ yr, if it is related to the supernova remnant G109.1 - 1.0. The value of $\tau_{cr}$ drops with increasing $M$, and it may be as small as $\sim 10^5$ yr for the white dwarf with the mass $M \sim 1.4 - 1.5 M_\odot$ which relates to 1E 2259 + 586. Indeed, for a plasma containing only one species of ion, the temperature of crystallization is (see, for example, Van Horn 1971; D’Antona and Mazzitelli 1990)

$$T_{cr} = 2.28 \times 10^7 \Gamma^{-1} \frac{Z^2}{A^{1/3}} \left( \frac{\rho}{10^6 \text{ g cm}^{-3}} \right)^{1/3} \text{ K}, \quad (7)$$

where $\Gamma$ is the dimensionless parameter which is somewhere between 64 and 210. The more reasonable value of $\Gamma$ is 150.

Substituting $\Gamma = 150, Z = 26$ and $A = 56$ into equation (7) we have

$$T_{cr} \simeq 2.7 \times 10^7 \left( \frac{\rho}{10^6 \text{ g cm}^{-3}} \right)^{1/3} \text{ K}. \quad (8)$$
The temperature inside a massive white dwarf with the age $\sim 10^5$ yr is not higher than $\sim 10^8$ K (Vila 1966; Savedoff, Van Horn and Vila 1969). A pure iron matter with this temperature has to crystallize if its density is equal or more than $\sim 5 \times 10^7$ g cm$^{-3}$ (see equation (8)). Both the mean density and the density at the center of a white dwarf increase very sharply when the white dwarf mass goes to the edge of stability (Geroyannis and Hadjopoulos 1989 and references therein). Using the paper of Geroyannis and Hadjopoulos (1989), we can see that the main part of the white dwarf mass is inside of the surface at which the density is equal to $5 \times 10^7$ g cm$^{-3}$ only if the mass of the white dwarf is $\sim 1.4 - 1.5 M_\odot$. Therefore, if the white dwarf, which is identified with 1E 2259 + 586, consists of iron and its mass is near the edge of stability, $M \simeq 1.4 - 1.5 M_\odot$, the assumption that the main part of the white dwarf mass is solid is reasonable.

3. DISCUSSION

In this paper I have suggested the existence of glitches with the amplitude $\Delta P \simeq - (1 - 2) \times 10^{-5}$ s and the characteristic time between glitches $t_q \simeq$ a few $\times (1 - 10)$ yr for the enigmatic X-ray pulsar 1E 2259 + 586. This is in agreement with the single white dwarf model of Paczyński (1990) for 1E 2259 + 586. The observation of glitches would be a confirmation of this model.

The other way to verify the single white dwarf model is the observation of $\gamma$-rays from 1E 2259 + 586. The point is that fast-rotating white dwarfs, $P \simeq$ a few s, with strong magnetic field, $B_\delta \sim 10^8 - 10^9$ Gauss, are similar to the radio pulsars, and both the particle acceleration to ultrarelativistic energies and generation of $\gamma$-rays have to be in their magnetospheres (Usov 1988, 1993). If 1E 2259 + 586 is such a white dwarf, the expected flux of $\gamma$-rays with energies $\sim 10^2 - 10^3$ MeV may be high enough to be detected by EGRET (Usov 1993).

FIGURE CAPTION

Figure 1. Pulse period history of 1E 2259 + 586 from 1978 to 1990. The solid line is the best fit to the points before 1989 without glitches. The dashed lines show the fit to the points with glitches. The amplitude of the glitches is somewhere between $10^{-5}$ s and $2 \times 10^{-5}$ s. The characteristic time between glitches may be as small as a few years (see Fig. 1b). In this case the spin-down rate between glitches is essentially more than the mean spin-down rate for the first 10 years of observations.

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