THE ASTROPHYSICAL JOURNAL, 365:L9–L12, 1990 December 10


# X-RAY PULSAR 1E 2259+586: A MERGED WHITE DWARF WITH A 7 SECOND ROTATION PERIOD?

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*Received 1990 August 20; accepted 1990 September 26*

## ABSTRACT

The enigmatic X-ray pulsar 1E 2259+586, located at the center of the supernova remnant G109.1−1.0, may be a recent merger of two white dwarfs, with a present rotation period of $P = 6.98$ s. The required mass is higher than 1.32 $M_\odot$, making 1E 2259+586 the most massive white dwarf known. The surface gravity is well over $10^9$ cm s$^{-2}$, allowing the effective temperature to be as high as $2 \times 10^6$ K, and opening up a possibility that the observed soft X-rays come from the white dwarf photosphere. The rate of rotational energy loss implied by the observed period increase is $|\dot{E}_{\rm rot}| \approx 10^{36}$ ergs s$^{-1}$, a factor of a few more than the observed X-ray luminosity. If the interstellar extinction toward 1E 2259+586 is 4 mag, then the optical counterpart should be fainter than 26 mag. Observational and theoretical tests of this scenario are discussed.

*Subject headings:* nebulae: supernova remnants — stars: binaries — stars: neutron — stars: white dwarfs — X-rays: general

## I. INTRODUCTION

The 6.98 s periodicity of the X-ray source 1E 2259+586 was discovered by Fahlman and Gregory (1981, 1983). The source is located close to the center of the supernova remnant G109.1−1.0 (Gregory and Fahlman 1980; Hughes, Harten, and van den Bergh 1981). The distance to the remnant, its age, and the minimum energy in magnetic fields and relativistic particles, are estimated to be 3.6–5.2 kpc, (1.2–1.7) × $10^4$ yr, and $\sim 7 \times 10^{50}$ ergs, respectively. Throughout this *Letter* we adopt a distance to the pulsar of approximately 4 kpc, i.e., the same as that estimated for the supernova remnant.

Among the known X-ray pulsars, 1E 2259+586 stands alone on three accounts: it has an unusually soft spectrum, it has an unusually stable period with a very stable and positive $\dot{P} = 5.9 \times 10^{-13}$ s s$^{-1}$ (Davies, Wood, and Coe 1990 and references therein), and it seems to be a single star (Davies *et al.* 1989). It is not surprising that all attempts to explain it within the standard framework have been unsuccesful so far (cf. Davies, Wood, and Coe 1990, and references therein).

A new type of model is explored in this *Letter:* a rapidly spinning, massive, highly magnetized white dwarf that has been recently formed by a merger of two ordinary white dwarfs. Such a merger scenario was proposed to explain Type Ia supernovae (Iben and Tutukov 1984; Paczyński 1985). However, model calculations have not demonstrated so far that the product of a binary white dwarf merger actually explodes as a Type Ia SN. It seems that a rapidly rotating single object is likely to remain as a stellar remnant of the fusion (Mochkovitch and Livio 1989; Webbink and Iben 1989; Benz *et al.* 1990; Iben 1990).

## II. A MODEL

The classical X-ray pulsars are accreting neutron stars in close binaries, with periods between 0.07 and 800 s (cf. Nagase 1989 and references therein). There are two radio pulsars which are also X-ray pulsars: the Crab and PSR 1509−58, with yet another X-ray pulsar in LMC: PSR 0540−69, which presumably has radio emission too weak to be detectable. Their periods are 33, 150, and 50 ms, respectively, and all these periods are increasing on time scales of about $10^3$ yr (Seward, Harnden, and Helfand 1984).

Some accreting magnetized white dwarfs also show periodic X-ray variability with their rotation periods either synchronized (polars) or nonsynchronized (intermediate polars) with the binary orbit. These are not recognized as X-ray pulsars, even though they exhibit pulsar-like, periodic variations in their X-ray fluxes (e.g., Swank *et al.* 1977; White 1981) with typical periods of a few hours.

All these objects, pulsars and polars alike, have hard X-ray spectra, though polars also have a very strong soft X-ray component. Frequently a strong iron K-shell emission is seen near 7 keV in the accretion-driven sources (Rothschild *et al.* 1981; Nagase 1989; and references therein).

1E 2259+586 cannot be explained in terms of classical X-ray pulsars. With very few exceptions, the rotational periods of accreting pulsars are decreasing, with a lot of noise readily detectable in the period derivative, $\dot{P}$. Some recurrent transients, like A0535+26, have their rotational periods increased during the OFF state, when the "propeller" mechanism makes the accretion impossible and transfers angular momentum out of the neutron star (Li *et al.* 1979; Ziółkowski 1980). The stability of the period, the positive and stable $\dot{P}$, the absence of any evidence of binary nature of 1E 2259+586, and the unusually soft X-ray spectrum make it incompatible with this scenario.

All three X-ray/radio pulsars have very short and stable periods, with $\dot{P} > 0$. The rate of change of their rotational energy and surface magnetic fields can be estimated following Ostriker and Gunn (1969)

$$\dot{E}_{\rm rot} = I\Omega\dot{\Omega} = -4\pi^2 I\dot{P}P^{-3} , \quad (1)$$

$$B \approx \left(\frac{3c^3}{8\pi^2} IR^{-6}\dot{P}P\right)^{1/2} , \quad (2)$$

where $M$, $R$, $I$ are the stellar mass, radius, and moment of inertia. These formulae may be applied to 1E 2259+586, assuming it is a "standard" neutron star with $M \approx 1.4$ $M_\odot$ and $R \approx 10$ km, to obtain

$$\dot{E}_{\rm rot,NS} \approx -4 \times 10^{32} \text{ ergs s}^{-1} , \quad B_{\rm NS} \approx 10^{14} \text{ G} , \quad (3)$$

while the soft X-ray luminosity is somewhat in excess of $10^{35}$ ergs $s^{-1}$ (Gregory and Fahlman 1980; Hughes *et al.* 1981, 1984). In this scenario, the energy source for the X-ray emission is a mystery, and the magnetic field required for the slow-down of rotation is anomalously strong. Therefore, a magnetized, spinning-down neutron star is not a reasonable model for 1E 2259+586.

The periods of all known polars are much longer than 7 s, their spectra are much harder than that of 1E 2259+586, and all polars are accreting members of close binaries, so they cannot be relevant to our problem.

Other, more elaborate models were proposed to explain the unique nature of 1E 2259+586, so far without much success (cf. Davies, Wood, and Coe 1990, and references therein). Therefore, a rather different scenario is proposed here.

Let us suppose that 1E 2259+586 is a single, magnetized, spinning white dwarf. Let us adopt $M_{WD} \approx 1\ M_\odot$, $R_{WD} \approx 0.01\ R_\odot$. The rotational energy can be easily estimated. The rate of rotational energy loss due to magnetic dipole radiation, and the corresponding surface magnetic field can be calculated with equations (1) and (2). We have

$$E_{rot,WD} \approx 10^{50}\ \text{ergs}\ , \quad \dot{E}_{rot,WD} \approx -10^{37}\ \text{ergs s}^{-1}\ ,$$
$$B_{WD} \approx 10^{8}\ \text{G}\ . \qquad (4)$$

The rate at which rotational energy is lost is comfortably higher than the X-ray luminosity, while the strength of the required magnetic field is in the range found among the magnetic white dwarfs.

Let us consider now a possible evolutionary scenario, a relation to the supernova remnant, and the nature of the X-ray emission, all within the framework of a spinning white dwarf.

The first issue which comes up is the compatibility of a strong magnetic field and a rapid rotation. About 2%–3% of all white dwarfs are known to have magnetic fields in the range of $2 \times 10^6$ to $5 \times 10^8$ G, with a broad peak between $10^7$ and $10^8$ G, but all these objects are very slow rotators (Schmidt 1989; Wickramasinghe 1989). A possible scenario for the formation of a rapidly spinning white dwarf is through a merger of two components of a short period binary made of two ordinary white dwarfs. The rate of such events was estimated by Iben and Tutukov (1984) to be about one per century in our Galaxy, and the events were supposed to account for Type Ia supernovae. The rates were estimated on the basis of reasonably well understood evolution of close binaries, and should be good to within a factor of a few. However, it is not clear that such mergers lead to explosions (Iben 1990, and references therein). It seems that the formation of a single, rapidly rotating object is at least as likely. Perhaps a mixed scenario is possible: some matter is ejected, while some is left as a rapidly spinning stellar remnant of a merger.

The average mass of a field white dwarf is about 0.55 $M_\odot$, with $\frac{2}{3}$ of all objects falling within 0.12 $M_\odot$ of this value, and with extended tails toward high and small masses (cf. McMahan 1989, and references therein). A slightly larger average mass of 0.60 $M_\odot$ is found for nuclei of planetary nebulae (Weidemann 1989, and references therein). Therefore, a typical product of a nondestructive merger may have a mass in the range (1.1–1.2) $M_\odot$ with some products being substantially more or less massive. Such an object is likely to spin close to the "breakup" velocity when it is formed.

The pulsar 1E 2259+586 cannot be much older than $P/\dot{P} \approx 3 \times 10^5$ yr, but it may be as young as $\sim 1.5 \times 10^4$ yr, if it is related to the supernova remnant. In either case it is very young by any white dwarf standards. Yet, during its lifetime as many as $10^2$, or even $10^3$ white dwarfs have merged within our galaxy, i.e., the formation of rapidly spinning massive white dwarfs is a relatively common phenomenon, provided the products of mergers are not completely disintegrated in supernova explosions.

The next issue is the energy source for the observed X-ray emission. As it is only a fraction of the rotational energy losses, it may be somehow powered by rotation, as it is the case with the X-ray/radio pulsars. However, an interesting clue may be provided by the X-ray variability. Koyama *et al.* (1989) found that "the ratios of the pulsed flux to the average flux are ~3%, ~25%, and ~35%, respectively, at 1.5 keV, 3 keV, and 6 keV." The rapid increase of the pulsed fraction with energy may suggest that X-ray emission is a high-energy tail of the thermal emission from a hot white dwarf atmoshere. In this case, a very small difference in the effective temperature between the magnetic pole and the magnetic equator could produce a very large difference in the flux emerging at high energies. An alternative possibility is that the large variations of the pulsed fraction with energy are caused by contamination from the supernova remnant. X-ray observations with a better angular resolution could resolve this ambiguity.

The most obvious problem with the thermal origin of the soft X-rays is that for any reasonable white dwarf temperature we have $h\nu \gg kT$. A white dwarf of ~1 $M_\odot$ with a hydrogen-deficient atmosphere has an Eddington luminosity of $\sim 2.5 \times 10^{38}$ ergs $s^{-1}$. This corresponds to the effective temperature of the white dwarf of $kT_{eff} \approx 0.1$ keV, and the Planck curve peaks near 0.3 keV. The X-ray emission observed in 1E 2259+586 is in the range 1–10 keV, with a peak near 3 keV, i.e., about 10 times above the Planck peak. Is it possible for a white dwarf photosphere to radiate $\sim 10^{35}$ ergs $s^{-1}$ in 1–10 keV X-rays? There are no such models, but a useful comparison can be made with Sirius B.

Sirius B is a white dwarf with $T_{eff} \approx 30{,}000$ K, $kT_{eff} = 0.0026$ keV, $L_{tot} \approx 2 \times 10^{30}$ ergs $s^{-1}$, and $L_X \approx 10^{28}$ ergs $s^{-1}$ at about 0.26 keV (Shipman 1976; Martin *et al.* 1982). The soft X-ray emission is well understood in terms of thermal emisson from the photosphere: the strong X-ray flux is made possible by a relatively small opacity at 0.26 keV. It is interesting that as much as 0.5% of the total photospheric luminosity is radiated with photons that have energy about 30 times higher than the peak of Planck curve.

The proposed scenario makes 1E 2259+586 the first object of the kind, so we cannot use analogies with other objects. The estimates presented so far have not encountered any serious problems with energetics, and did not require any special circumstances. Unfortunately, there are no quantitative models for the process of merging, the subsequent nuclear burning and cooling, and no models for a ~3 keV X-ray flux from a very hot white dwarf atmosphere. Therefore, a truly quantitative analysis cannot be done at this time. Yet, some estimates can be made.

Models of seven white dwarfs rotating uniformly with critical angular velocities were selected from Tables 10 and 11 of Geroyannis and Hadjopoulos (1989). These are models a1–a7 in Table 1, and the following parameters are given: mass $M$, central density $\rho_c$, the minimum rotation period $P_{rot}$, the maximum rotational energy $E_{rot}$, the maximum effective temperature $T_{max}$ compatible with the surface gravity $g$, and the apparent visual magnitude $m_{v,0}$ corresponding to the

TABLE 1

PARAMETERS FOR RAPIDLY ROTATING, HOT WHITE DWARFS

| Model | $M$ ($M_\odot$) | $\log \rho_c$ (g cm$^{-3}$) | $P_{rot}$ (s) | $\log E_{rot}$ (ergs) | $\log \dot{E}_{rot}$ (ergs s$^{-1}$) | $\log B$ (G) | $kT_{max}$ (keV) | $\log g$ (cm s$^{-2}$) | $m_{v,0}$ (mag) |
|---|---|---|---|---|---|---|---|---|---|
| a1......... | 1.516 | 10.79 | 0.45 | 50.28 | ... | ... | 0.274 | 10.55 | 23.6 |
| a2......... | 1.509 | 9.29 | 2.00 | 49.99 | ... | ... | 0.167 | 9.69 | 22.0 |
| a3......... | 1.482 | 8.83 | 3.04 | 49.91 | ... | ... | 0.146 | 9.46 | 21.6 |
| a4......... | 1.468 | 8.68 | 3.48 | 49.88 | ... | ... | 0.140 | 9.39 | 21.5 |
| a5......... | 1.399 | 8.21 | 5.27 | 49.79 | ... | ... | 0.122 | 9.15 | 21.1 |
| a6......... | 1.277 | 7.72 | 8.09 | 49.65 | ... | ... | 0.105 | 8.89 | 20.7 |
| a7......... | 1.077 | 7.20 | 13.02 | 40.44 | ... | ... | 0.089 | 8.60 | 20.3 |
| b1......... | 1.407 | 9.90 | 6.98 | 48.36 | 35.59 | 9.25 | 0.197 | 9.98 | 22.6 |
| b2......... | 1.394 | 9.60 | 6.98 | 48.55 | 35.78 | 9.09 | 0.178 | 9.81 | 22.3 |
| b3......... | 1.374 | 9.30 | 6.98 | 48.73 | 35.96 | 8.94 | 0.162 | 9.64 | 22.0 |
| b4......... | 1.346 | 9.00 | 6.98 | 48.90 | 36.13 | 8.79 | 0.147 | 9.47 | 21.7 |
| b5......... | 1.307 | 8.70 | 6.98 | 49.07 | 36.30 | 8.64 | 0.134 | 9.31 | 21.5 |

maximum effective temperature $T_{max}$ and no interstellar extinction. 1E 2259+586 has to be fainter than $m_{v,0}$ if its effective temperature is lower than $T_{max}$, and/or if it suffers any interstellar extinction. All models have $\mu_e = 2$, i.e., they are made of helium, carbon, or oxygen. The numbers for ion would be somewhat different, as $\mu_{e,\mathrm{Fe}} = 2.15$.

The maximum temperature was calculated with the Eddington condition

$$F_{max} = \frac{cg}{\kappa}, \quad \sigma T_{max}^4 = \frac{cGM\mu_e}{0.4R_p^2}, \tag{6}$$

where $R_p$ is the polar radius of the model, and $\kappa = 0.4/\mu_e$ is the electron scattering opacity. The absolute bolometric magnitude of a star with Eddington luminosity is given as

$$M_{bol} = -7.2 - 2.5 \log (M/M_\odot) . \tag{7}$$

The bolometric correction for very hot stars may be calculated as

$$\mathrm{BC}_{[mag]} \equiv M_{bol} - M_v \approx 30.5 - 7.5 \log T_{[K]} = -22.5 - 7.5 \log kT_{[keV]} , \tag{8}$$

where $T_{[K]}$ and $kT_{[keV]}$ is the effective temperature of the star expressed in kelvins and keV, respectively. Equation (8) gives bolometric corrections to better than 0.1 mag for $T > 28{,}000$ K. In the absence of interstellar extinction, the apparent visual magnitude of 1E 2259+586 may be calculated as

$$m_{v,0} = M_{bol} - \mathrm{BC} + (m - M) = 28.3 - 2.5 \log (M/M_\odot) + 7.5 \log kT_{[keV]} , \tag{9}$$

where $(m - M) = 13.0$ is the adopted distance modulus.

The models a1–a7 in Table 1 can be used to estimate the minimum mass of a white dwarf that can rotate with the period of 6.98 s. The interpolation between models a5 and a6 gives $M_{min} \approx 1.32\ M_\odot$. It is apparent that the critical period is a rapidly decreasing function of the white dwarf mass. For a mass somewhat above $M_{min}$ the structure of a white dwarf rotating with the period of 6.98 s can be reasonably approximated with a spherical model. Five such models, b1–b5, are presented in Table 1. Their rotational energy was calculated as $E_{rot} = I\Omega^2/2$, $\Omega = 2\pi/P = 0.900\ \mathrm{s}^{-1}$, with the moment of inertia $I$ being that of a spherical model. The rate of rotational energy loss, $\dot{E}_{rot}$, and the surface magnetic field $B$ were calculated with equatons (1) and (2), assuming that moment of inertia does not depend on $\Omega$, and that the observed increase of the pulsar period, $\dot{P} = 5.9 \times 10^{-13}$ s s$^{-1}$, is caused by the magnetic dipole radiation.

The observed period of 1E 2259+586 requires the white dwarf to have a mass in excess of 1.32 $M_\odot$. Therefore, the average mass of the two progenitors had to be above 0.66 $M_\odot$, a perfectly reasonable value. With the mass in the range 1.32–1.41 $M_\odot$, the rate of rotational energy losses of 1E 2259+586 is in the range (0.4–2) $\times 10^{36}$ ergs s$^{-1}$, somewhat more than the observed X-ray luminosity. The surface magnetic field is between $0.4 \times 10^9$ and $2 \times 10^9$ G, and the maximum possible effective temperature $kT$ is between 0.13 and 0.20 keV, or so. Finally, the optical counterpart of 1E 2259+586 will be fainter than the apparent visual magnitude 21.5–22.5, even if there is no interstellar extinction. If the pulsar is at a distance of 4 kpc, then extinction of about 4 mag is very likely, and it will make the detection of the optical thermal radiation impossible. If the white dwarf luminosity is below the Eddington limit, as seems very likely, then the apparent visual flux will be reduced still more.

## III. DISCUSSION

The model outlined in this *Letter* is speculative at this time. It will take a lot of theoretical and observational work to check whether it is correct. However, it does not require anything special. It is true, that 1E 2259+586 would be the first product of a white dwarf merger to be identified, but such processes were considered by theoreticians for many years, and the rate of white dwarf mergers in our galaxy was estimated to be $10^{-2}$ yr$^{-1}$ (Iben and Tutukov 1984). It is not known at this time how the merger would proceed: would it trigger a Type Ia supernova with a total disintegration of the merging white dwarfs; will a single, rapidly rotating object be left with no significant mass loss; or will there be some mass loss, possibly with a significant release of energy? These are very difficult processes to model (Iben 1990, and references therein), and the progress is likely to be semiempirical. Therefore, detailed studies of 1E 2259+586 are very important because no other object has previously been studied as a possible remnant of white dwarf merger.

If the pulsar is associated with the supernova remnant, then the question arises: Can a white dwarf merger release the required energy, estimated at $\sim 7 \times 10^{50}$ ergs (Hughes, Harten, and van den Bergh 1981)? The total amount of nuclear energy available in two white dwarfs with a total mass $\sim 1.4\ M_\odot$ is $\sim 3 \times 10^{51}$ ergs. Such a white dwarf may store up to $5 \times 10^{50}$ ergs in differential rotation (Geroyannis and Hadjopoulos

1989, and references therein). The energy of the SNR is of the same order of magnitude, but it is not known if it can actually be released during the merger. At this time the merger scenario can neither predict a formation of SNR like G109.1 − 1.0, nor can the merger be ruled out by the probable association between the SNR and the pulsar.

More realistic models of the merger process are very desirable, but they are also very difficult to calculate. If one takes the merged, axially symmetric, differentially rotating and hot white dwarf as the starting point, then viscous evolution and thermal cooling of the model is much easier to calculate. It is important to know how hot the white dwarf may be $10^4$ or $10^5$ yr after the merger.

The most direct confirmation of the proposed model may come from model atmospheres of very hot white dwarfs. It seems that an extension of the work by Barstow (1990) to log $g = (9.3–10.0)$, and $T = (0.5–2) \times 10^6$ K and a variety of chemical compositions could answer the question: can the observed soft X-ray flux be explained in terms of thermal emission from a hot white dwarf? In particular, can the absorption line observed at 6.5 keV be explained in terms of iron absorption? A positive result would be a strong evidence that 1E 2259 + 586 is a white dwarf. A negative result would require a nonthermal explanation of X-rays. This is energetically possible as $|\dot{E}_{rot}| > L_X$ but would make a theoretical computation of the spectrum very difficult and unreliable.

Observations of 21 cm absorption toward G109.1 − 1.0 would allow a reasonable distance estimate, as the object is in the direction where the galactic rotation curve should produce unambiguous results. A better distance estimate would lead to a better age and energy etimate for G109.1 − 1.0.

Better X-ray timing data would be very useful. In particular, if properly spaced observations could determine the period and the period derivative with high enough precision, then pulse counting would become possible, and this in turn would allow a much more precise determination of the pulse ephemeris. In this way $\ddot{P}$ could be measured with a 10–20 yr time baseline, assuming that the pulse timing can be done to better than 0.1 s, and that $|\ddot{P}| \approx \dot{P}^2 P^{-1} = 5 \times 10^{-26}\ \mathrm{s}^{-1}$. If these precise timing data demonstrate that the pulse period and its derivatives are very stable, then the case for rotation as the underlying clock will be strengthened.

So far no variation in the pulse-averaged X-ray flux has been observed. The lower the limit to the variability, the stronger the case for nonaccretion origin of the energy responsible for X-ray emission, because all known accretion-driven X-ray sources are strongly variable. And, since rotation of a neutron star cannot possibly power the observed emission (cf. eq. [3]), the more stable the observed emission, the stronger the case that 1E 2259 + 586 is a white dwarf.

I would like to acknowledge many useful comments and suggestions by W. H. G. Lewin. This project was supported in part by the NSF grant AST-8718432.

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