GLEAM-X J162759.5−523504.3 as a white dwarf pulsar

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Abstract

The low frequency radio source GLEAM-X J162759.5−523504.3 emits pulsed coherent polarized emission like that of radio pulsars. Yet its period of 18.18 min (1091 s) is hundreds of times longer than those of confirmed radio pulsars, and if it is a neutron star its mean radiated power exceeds the upper limit on its spin-down power by more than an order of magnitude. This may be explained if it is a white dwarf pulsar, with a moment of inertia several orders of magnitude greater than those of neutron stars. The Lorentz factor of the emitting charge bunches may be bounded from below by the widths of the temporal substructure of their radiation. If the emission is curvature radiation, the radius of curvature may be estimated from the Lorentz factor and the frequencies of emission; it is consistent with a white dwarf’s inner magnetosphere but not a neutron star’s.

Keywords Radio continuum: transients · Stars: white dwarfs · Stars: pulsars

1 Introduction

“Pulsar” has had many meanings. Originally it referred to periodic rotation-powered coherent radio emission from magnetic neutron stars (Gold 1968), some of which were soon discovered also to emit periodic but incoherent visible light, X-rays and gamma-rays. It has sometimes been broadened to mean any periodic emission from a rotating object, including incoherent accretion-powered thermal X-rays in “X-Ray Pulsars” and magnetically-powered X-rays in “Anomalous X-Ray Pulsars”.

Here I will consider a pulsar to be an object that emits periodic pulses of rotation-powered coherent radio radiation, whether or not that is accompanied by emission at other frequencies. Coherent emission requires plasma processes to create charge “bunches”. Astronomical objects that emit coherently are naturally grouped together, even if their parameters differ quantitatively.

The original pulsars were rotating neutron stars with no significant source of plasma external to their magnetospheres. Most of them are single; the minority in binary systems are separated from their companions by distances much greater than their radius of light cylinders $R = c/\Omega$, where $\Omega$ is their angular frequency. Such binary pulsars radiate as if they were single, although they may produce winds that interact with their companions, and mass-losing companions may turn the pulsar into an accreting X-ray source that does not emit coherent radio radiation.

2 A white dwarf pulsar

Since the early days of pulsar astronomy there has been speculation that a rotating magnetic white dwarf might show pulsar-like activity, although Zhang and Gil (2005) appears to be the first explicit discussion of processes in the magnetosphere of a white dwarf analogous to those of neutron star pulsars. The words “white dwarf pulsar” appear in over 100 abstracts, most of which discuss incoherent periodic emission, usually of visible light. One binary star, AR Sco, with periodic incoherent radio and visible emission at the beat frequency between a white dwarf’s rotation and the orbital frequency, has been proposed as a white dwarf pulsar (Marsh et al. 2016). However, coherent radio emission has not been reported and its companion is well within the white dwarf’s radius of light cylinder, suggesting that the physical processes involved differ from those of traditional radio pulsars. Models involving interaction between the two stars have been developed (Geng et al. 2016; Katz 2017).
The recently discovered (Hurley-Walker et al. 2022) periodic radio transient GLEAM-X J162759.5−523504.3 is a candidate for the first true white dwarf pulsar. It has a period of 18.18 minutes (1091 s) and its pulses show low frequency (72–215 MHz) emission with a brightness temperature \( \sim 10^{16} \) K implying coherent emission. It has no known binary companion with which to interact. It thus meets the criteria of a classical pulsar, although its period is hundreds of times longer than any of theirs (however, Beniamini et al. (2022) have suggested that ultra-long period magnetic neutron stars may exist).

GLEAM-X J162759.5−523504.3 differs from all known classical pulsars in one important way. The measured upper bound on the rate of change of its period implies, using the usual estimate of a neutron star’s moment of inertia of \( \sim 10^{45} \) g cm\(^2\), an upper bound on its spin-down power of \( 1.2 \times 10^{28} \) erg/s (Hurley-Walker et al. 2022). This is exceeded by its instantaneous pulse luminosity (in the band of observation, surely an underestimate) of up to \( 4 \times 10^{31} \) erg/s. Averaging over the pulse duty factor of about 1% (this is equivalent to assuming the radiation is emitted into a fraction of 4 steradians equal to the measured duty factor) indicates a mean radiated luminosity \( \sim 4 \times 10^{29} \) erg/s. This may be an overestimate because we may be favorably situated near the peak of its beam pattern (observational selection makes that likely), but the mean radiated power still exceeds the spindown power by more than an order of magnitude. This is physically impossible for a rotation-powered object. No classical pulsar emits more than about 1% of its spindown power as coherent radio emission (Szary et al. 2014).

As pointed out by Hurley-Walker et al. (2022), the obvious resolution of these two difficulties—the anomalously long rotation period and the insufficient spin-down power—is that the object is a white dwarf rather than a neutron star. White dwarves have moments of inertia \( \sim 10^{50} \) g cm\(^2\), about five orders of magnitude greater than that of a neutron star, increasing the estimated spin-down power to \( 10^{33} \) erg/s, sufficient to power the radio emission with plausible (\( \ll 1 \)) efficiency.

Because of their large moments of inertia, white dwarves rotate more slowly than neutron stars; GLEAM-X J162759.5−523504.3 would be an unusually fast-rotating white dwarf without accretional spin-up, but not the fastest known. For example, SDSS J125230.93−023417.72 has a period of 317 s (Reeding et al. 2020), WD 1832+089 has a period of 353 s (Pshirkov et al. 2020), RE J0317−853 has a period of 725 s (Barstow et al. 1995; Ferrario et al. 1997) and ZTF J190132+145808.7 has a period of 6.94 minutes (Caiazzo et al. 2021). The photometric variability is likely attributable to strong magnetic fields, nonuniform over the surface. ZTF J190132+145808.7 has magnetic fields in the 600–900 MG range (Caiazzo et al. 2021), while the magnetic field of RE J0317−853 is several hundred MG (Ferrario et al. 1997) and SDSS J125230.93−023417.72 has a starspot with a field of 5 MG (Reeding et al. 2020). No measurement of the magnetic field of GLEAM-X J162759.5−523504.3 exists, but the similarity among these objects hints that it might also be strongly magnetic, which would be consistent with its being a pulsar.

### 3 Lorentz factors

The radiation mechanism of pulsars is not understood, and naïve curvature radiation models have difficulty explaining the formation and maintenance of charge “bunches” (Melrose 1992). Despite this, pulsars do radiate coherently. Here I adopt the frequency scaling of curvature radiation with the Lorentz factor of the radiating charges. The Lorentz factor is estimated by assuming that the observed pulse width, an envelope over any temporal micro-structure, indicates the angular width of their rotating radiation pattern. This scaling is expected to apply to maser curvature emission, in which maser amplification creates the radiating charge “bunches”, as well as to naïve curvature radiation models.

The observed temporal structure of a pulsar pulse is a convolution of comparatively slow variation resulting from its beam sweeping over the observer with the intrinsic time dependence of its radiated power. The radiated power might be steady, might consist of a large number of nanoshots, or might be anything in between. A plausible assumption is that averaging over any rapid fluctuations in radiated power yields the observed pulse envelope, indicating the radiation beam width. This would also apply if the radiated power is steady. The beam width is constrained by the Lorentz factor of the radiating charge bunches, and indicates their Lorentz factor if the charge bunches are more narrowly collimated.

In order for radiation from a rotating emitter with period \( P \) to have temporal structure of full width at half-maximum (FWHM) \( \Delta t \) it must be beamed into an angle

\[
\theta \lesssim \frac{2\pi \Delta t}{P}. \tag{1}
\]

In GLEAM-X J162759.5−523504.3 temporal structure as fine as \( \Delta t \approx 0.5 \) s has been observed (Fig. 3 of Hurley-Walker et al. (2022)), implying \( \theta \lesssim 3 \times 10^{-3} \) radian. If this radiation is produced by accelerated relativistic charges, their Lorentz factor \( \gamma \) must satisfy (Rybicki and Lightman 1979)

\[
\gamma \gtrsim 0.9/\theta \approx 300. \tag{2}
\]

This inequality is an approximate equality for a narrowly collimated particle beam. Charges whose velocity vectors are spread by angles larger than the reciprocal of their...
Lorentz factor produce a radiation pattern set by their angular dispersion rather than by their Lorentz factor, making Eq. (2) an inequality.

Curvature radiation is expected for charges in strong magnetic fields, in which their transverse motion rapidly decays by synchrotron radiation, or is not excited because nonresonant electric fields perpendicular to strong magnetic fields are not effective accelerators. If curvature radiation is the emission process then the radius of curvature $\rho$ may be estimated from the expression for the peak of the spectrum of emission by a relativistic particle (Jackson 1999)

$$\nu_{\text{peak}} \approx 0.3 \gamma^3 \frac{c}{\rho}, \quad (3)$$

or

$$\rho \approx 0.3 \frac{\gamma^3 c}{\nu_{\text{peak}}} \gtrsim 1.5 \times 10^9 \text{ cm}, \quad (4)$$

where Eq. (2) has been used to set a bound on $\gamma$, and $\nu_{\text{peak}} \approx 200 \text{ MHz}$ is the middle of the frequency band of Fig. 3 of Hurley-Walker et al. (2022), from which $\theta$ and $\gamma$ have been bounded. This is consistent with radiation in a white dwarf magnetosphere, but not in a neutron star magnetosphere. It could be reconciled with a neutron star magnetosphere only if radiation extended to frequencies of hundreds of GHz, which would exacerbate the (already forbidding) energetic problems with neutron star models.

4 Discussion

The long period and emitted power of GLEAM-X J162759.5−523504.3 both point to its nature as a white dwarf pulsar, the first such object identified whose physics and radiation mechanism could resemble those of classical radio pulsars. This hypothesis is supported by the Lorentz factor inferred from the temporal substructure of at least one of its pulses, that implies a large radius of curvature of the magnetic field lines if the emission is curvature radiation.

That Lorentz factor also implies an electron energy about four orders of magnitude less than the inferred (Hurley-Walker et al. 2022) brightness temperature (in energy units). This is direct evidence of coherent emission, the defining feature of classic pulsars.

The possible similarity between GLEAM-X J162759.5−523504.3 and strongly magnetic, fast-rotating, white dwarves suggests that the former object, a coherent radio emitter, might be a promising target for optical observations to test the prediction made here that it is a white dwarf, although at its estimated distance of about 1 kpc it might be forbiddingly faint. If it were bright enough, optical observations could also determine its magnetic field, spectroscopically or polarimetrically. The fast-rotating, strongly magnetized, white dwarves would be promising targets for low frequency radio observations to determine if any of them are white dwarf pulsars.

The model discussed here differs from previous models. Loeb and Maoz (2022) predict a hot, luminous subdwarf at the location of GLEAM-X J162759.5−523504.3, while Ekşi and Şasmaz (2022) predict no visible object there, a small $\dot{P}$, a ~0.1 s spin periodicity in addition to the long observed period, and likely a luminous pulsar wind nebula.

Author contributions Author 1 did the research and wrote the paper.

Data Availability This theoretical study did not generate any new data.

Declarations

Competing interests The authors declare no competing interests.

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