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GCRT J1745−3009 AS A TRANSIENT WHITE DWARF PULSAR

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ABSTRACT

A transient radio source in the direction of the Galactic center, GCRT J1745−3009, exhibited five peculiar consecutive outbursts at 0.33 GHz with a period of 77.13 minutes and a duration of ∼10 minutes for each outburst. It has been claimed to be the prototype of a hitherto unknown class of transient radio sources. We interpret it as a transient white dwarf pulsar with a period of 77.13 minutes. The ∼10 minute flaring duration corresponds to the epoch in which the radio beam sweeps our line of sight. The bursting epoch corresponds to the episodes in which stronger sunspot-like magnetic fields emerge into the white dwarf polar cap region during which the pair-production condition is satisfied and the white dwarf behaves like a radio pulsar. It switches off as the pair-production condition breaks down.

Subject headings: pulsars: general — radiation mechanisms: nonthermal — stars: magnetic fields — white dwarfs

1. INTRODUCTION

An enigmatic radio bursting source, GCRT J1745−3009, was discovered recently in the direction of the Galactic center (Hyman et al. 2005). This source exhibited five peculiar consecutive outbursts at 0.33 GHz with a period of 77.13 minutes and a duration of ∼10 minutes for each outburst. The radiation is very likely coherent as long as the distance is larger than 70 pc. Although many efforts have been made to interpret it (Hyman et al. 2005; Kulkarni & Phinney 2005; Zhu & Xu 2005; Turolla et al. 2005), this behavior is hard to understand in a straightforward way within the framework of known astrophysical objects. This source has been claimed to be the prototype of a hitherto unknown class of transient radio sources (Hyman et al. 2005). Here we show that the phenomenon is naturally understood if GCRT J1745−3009 is a strongly magnetized white dwarf, whose dipolar magnetic field defines a "lighthouse" beam from the polar cap region, just like what happens in a radio pulsar. The 77.13 minute cycle is the rotation period of the white dwarf, and the ∼10 minute flaring duration corresponds to the epoch in which the radio beam sweeps our line of sight. The bursting epoch corresponds to the episodes in which the pair-production condition is satisfied, so that the white dwarf can behave like a radio pulsar. When the pair production is turned off, the flare ceases, and the white dwarf enters its dormant state.

2. WHITE DWARF PULSARS

White dwarfs are intermediate compact objects that bridge normal main-sequence stars and more compact neutron stars. When our Sun collapses into a white dwarf, its radius will shrink by a factor ∼100. Conserving angular momentum gives a white dwarf period of a few minutes. In reality, the observed white dwarf rotation period is longer, typically hours to days (Kawaler 2004; Wickramasinghe & Ferrario 2000). Our suggested period of ∼77 minutes falls into the lower end of the distribution, which is consistent with the fact that this is the first one that was detected, since it takes a longer time to identify the periodicity of white dwarfs with longer periods and since a shorter period favors pair production, which is the condition for coherent radio emission. Conserving magnetic flux in the Sun during the collapse gives a dipolar magnetic field of only $\sim 10^4$ G at the white dwarf surface. However, in reality, there is a group of magnetized white dwarfs that have a surface magnetic field in the range of 10^6–10^9 G (Wickramasinghe & Ferrario 2000). Some of them spin rapidly with periods around an hour, which could be explained in terms of binary evolution (Ferrario et al. 1997). These fast-rotating magnetized white dwarfs are the objects that we propose here to interpret the pulsating behavior of GCRT J1745−3009.

Magnetic white dwarfs can mimic pulsars in various ways. In particular, it is well known that for a rotating, strongly magnetized object, the electromagnetic force dominates gravity and thermal forces, and the natural outcome is a corotating charge-separated magnetosphere (Goldreich & Julian 1969). Because of the unipolar effect, a large potential drop develops across the polar cap region defined by the last open field lines (Ruderman & Sutherland 1975). The magnetized white dwarf idea has been adopted to interpret the anomalous X-ray pulsars (Paczyński 1990; Usov 1993; cf. Hulleman et al. 2000). Below we show that the magnetized white dwarf model gives a straightforward interpretation of the observational data of GCRT J1745−3009.

A period of $P \sim 77$ minutes defines a light cylinder radius $R_{\rm lc} = cP/2\pi = 2.2 \times 10^{13}$ cm (P/77 minutes). Given a typical white dwarf radius $R_{\rm WD} = 5 \times 10^8$ cm, the polar cap radius is

$$R_{\rm pc} = R_{\rm WD}\left(\frac{R_{\rm WD}}{R_{\rm lc}}\right)^{1/2} = 2.4 \times 10^6 \text{ cm} \times R_{\rm WD,\,8.7}^{3/2}\left(\frac{P}{77 \text{ minutes}}\right)^{-1/2}. \quad (1)$$

Hereafter the convention $Q_x = (Q/10^x)$ is adopted in cgs units. Lacking a measurement of the period derivative $\dot{P}$, one cannot reliably estimate the spin-down rate and the dipolar surface magnetic field at the magnetic pole, B_p. In the following we

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assume $B_p = 10^9$ G. The maximum available unipolar potential drop across the polar cap reads

$$\Phi_{\rm max} = \frac{2\pi^2 B_p R_{\rm WD}^3}{c^2 P^2} = 3.9 \times 10^{10}\ {\rm V} \times B_{p,9} R_{\rm WD,8.7}^3 \left(\frac{P}{77\ {\rm minutes}}\right)^{-2}. \quad (2)$$

The maximum energy of the electrons accelerated in this potential drop is $\gamma_{e,M} = e\Phi_{\rm max}/mc^2 = 7.6 \times 10^4 B_{p,9} R_{\rm WD,8.7}^3 \times (P/77\ {\rm minutes})^{-2}$. The potential drop is about 2 orders of magnitude smaller than that in radio pulsars.

The surface layer of a white dwarf is composed of a nondegenerate electron gas and possibly an ionic lattice (Shapiro & Teukolsky 1983). The lattice melting temperature is $T_m \sim 8.8 \times 10^5$ K $(\rho/10^2\ {\rm ergs\ cm^{-3}})^{1/3}(Z/12)^{5/3}$, where ρ is the density in the surface layer and Z is the atomic number (Mestel & Ruderman 1967). Given a typical surface temperature $T_s \sim 3 \times 10^4$ K, we can see that generally the surface is in the ionic lattice state. For an antiparallel rotator, i.e., $\mathbf{\Omega}\cdot\mathbf{B} < 0$, where $\mathbf{\Omega}$ and $\boldsymbol{B}$ are the vectors for the rotational and magnetic axes, respectively, the polar cap region is populated with positively charged particles. In a corotating magnetic white dwarf magnetosphere, whether or not the surface can provide a free ionic flow into the polar cap region depends on two factors, i.e., whether thermionic emission could overcome the atomic cohesive energy in the surface layer and whether the free atoms are adequately ionized. In strong magnetic fields, the ion cohesive energy is enhanced and depends on the strength of the field, i.e., proportional to $B^{0.7}$ and is about several hundred eV for $B = 10^{12}$ G for iron (Jones 1986; Usov & Melrose 1996). However, when B is lower than $\sim 10^9$ G, which is the general case of the white dwarf pulsar discussed here, the atoms are essentially not influenced by the magnetic field (Lai 2001), so that the atom cohesive energies are similar to the $B = 0$ case. For carbon, which is the likely composition of the white dwarf surface layer, the cohesive energy is $\Delta\epsilon_c \sim 8$ eV per atom, and the first-ionization energy of carbon is $\Delta\epsilon_i \sim 11.3$ eV. The Goldreich & Julian (1969) charge number density at the magnetic pole is $n_{\rm GJ} = (B_p/Pce) = 1.5 \times 10^4\ {\rm cm^{-3}}\ B_{p,9}(P/77\ {\rm minutes})^{-1}$ for GCRT J1745−3009, which is much lower than the number density of carbon atoms in the surface layer, i.e., $n_{\rm atom} \sim \rho/Am_p = 5.0 \times 10^{24}\ {\rm cm^{-3}}\ \rho_2$. For photoionization and thermionic ejection of the ions, even if the ionization/ejection rate decreases exponentially with temperature, the critical temperatures should still be several tens smaller than the temperature defined by the cohesive/ionization energy. Similar to the treatment for the neutron star surface (Ruderman & Sutherland 1975; Usov & Melrose 1996), for the parameters of GCRT J1745−3009, this reduction factor is $\sim \log [Ze\rho(kT)^{1/2}(Am_p)^{-3/2}P/B] = \log [3.8 \times 10^{16}(kT/2.6\ {\rm eV})^{1/2}(P/77\ {\rm minutes})B_{p,9}^{-1}\rho_2(Z/6)(A/12)^{-3/2}] \sim 38$. As a result, the critical temperatures for ionization of the carbon atom and for thermionic ejection of the carbon atoms are $\sim 3.2 \times 10^3$ K and $\sim 2.3 \times 10^3$ K, respectively; both are $\ll T_s \sim 3 \times 10^4$ K, the typical temperature of the white dwarf surface. The temperature at the magnetic pole could be cooler (similar to sunspots), but as long as the temperature is higher than $\sim 3 \times 10^3$ K, the white dwarf surface is able to provide copious ions to supply a Goldreich-Julian space charge–limited flow from the polar cap region (Arons & Scharlemann 1979; Harding & Muslimov 1998). A similar conclusion applies for other surface compositions as well as for the case of a parallel rotator ($\mathbf{\Omega}\cdot\boldsymbol{B} > 0$), in which case an electron-free flow is supplied.

In a space charge–limited flow, a charge-depleted region is developed in the polar cap region due to the general relativistic frame-dragging effect (Muslimov & Tsygan 1992) and the curvature effect of the magnetic field lines (Arons & Scharlemann 1979). The ratio between the potential drops developed for these two components is roughly (Harding & Muslimov 1998) $\sim(\kappa/\theta_{\rm pc})\tan^{-1}\chi$, where χ is the inclination angle between the magnetic and rotational axes, $\theta_{\rm pc}$ is the opening angle of the polar cap region, $\kappa \sim (R_{\rm S}/R_*)$, $R_{\rm S}$ is the Schwarzschild radius, and R_* is the radius of the star (neutron star or white dwarf). For neutron star pulsars, the frame-dragging term dominates unless the inclination is near 90° (Harding & Muslimov 1998). For the white dwarf pulsars, with the parameters of GCRT J1745−3009, we find that $\kappa \sim \theta_{\rm pc} \sim 10^{-3}$, which means that both contributions are comparable. The potential drop develops with height h in the form of (Harding & Muslimov 1998) $\Phi(h) \sim (2\pi B_p/Pc)R_{\rm pc}^2(h/R_{\rm WD})^2$, which achieves the maximum potential $\Phi_{\rm max}$ essentially at $R \sim R_{\rm WD}$. Without pair production, electrons in the acceleration region could gain an energy close to $\gamma_{e,M}$. Below we take a typical electron Lorentz factor $\gamma_e = 5 \times 10^4$.

3. PAIR-PRODUCTION CONDITION

Can the electron-positron plasma needed by pulsar activity be generated in such white dwarfs? This would require generation of seed gamma photons with energies well exceeding the electron rest energy. The dipolar field curvature radius in the white dwarf magnetosphere is very large, i.e., $\rho_d = (4/3)(RR_{\rm lc})^{1/2} = 1.4 \times 10^{11}\ {\rm cm}\ (R/R_{\rm WD})^{1/2}(P/77\ {\rm minutes})^{1/2}$. Near the surface, nondipolar magnetic fields could develop, as is the case of the Sun (sunspots) and presumably also the case of neutron stars (Ruderman & Sutherland 1975; Arons & Scharlemann 1979; Gil & Mitra 2001). However, even if we choose a much smaller curvature radius, e.g., $\rho \sim 10^9$ cm, the typical curvature radiation energy is still too small, i.e., $\epsilon_{\rm CR} = (3/2)(\hbar c/\rho)\gamma_e^3 = 3.7\ {\rm eV}\ \gamma_{e,4.7}^3\rho_9^{-1}$, well below the pair-production threshold.

The typical thermal photon energy is $\epsilon_{\rm th} \sim 2.8kT = 7.3T_{4.5}$ eV for $T_s \sim 3 \times 10^4$ K. Given the typical electron energy and the strength of the local magnetic field, the resonant inverse Compton (IC) scattering is unimportant. The typical resonant IC photon energy (Zhang et al. 1997) is $\epsilon_{\rm IC}^R \sim \gamma_e\epsilon_{\rm B} = 580\gamma_{e,4.7}B_{p,9}$ keV, which is slightly larger than the electron rest energy $mc^2 = 511$ keV but does not meet the pair-production threshold.

The most efficient gamma-ray production mechanism in a white dwarf magnetosphere is nonresonant IC scattering (Zhang et al. 1997). The typical gamma-ray photon energy reads

$$\epsilon_\gamma = \epsilon_{\rm IC}^{\rm NR} = \min(\gamma_e^2 2.8kT, \gamma_e mc^2) = \min(18\ {\rm GeV}\gamma_{e,4.7}^2 T_{4.5}, 26\ {\rm GeV}\ \gamma_{e,4.7}). \quad (3)$$

The second term takes into account the Klein-Nishina limit. The mean free path for an electron to produce one IC gamma-ray photon can be estimated as

$$l_e = (\sigma_{\rm IC}n_{\rm ph})^{-1} = 2.8 \times 10^9\ {\rm cm}\ T_{4.5}^{-3}\left(\frac{\sigma_{\rm IC}}{\sigma_{\rm T}}\right)^{-1}, \quad (4)$$

where $\sigma_{\rm IC}$ and $\sigma_{\rm T}$ are the inverse Compton cross section and Thompson cross section, respectively. When a gamma-ray photon with a typical energy (eq. [3]) is emitted along the magnetic field line, it interacts with the local magnetic fields to produce pairs (Sturrock 1971). The mean free path for the photon to attenuate is (Ruderman & Sutherland 1975)

$$l_{\rm ph} = \chi\rho\left(\frac{B_q}{B_p}\right)\left(\frac{2mc^2}{\epsilon_\gamma}\right) \simeq \max\,(1.7\times 10^8\ {\rm cm}\ \rho_9 B_{p,9}^{-1}\gamma_{e,4.7}^{-2}T_{4.5}^{-1},\ 1.2\times 10^8\ {\rm cm}\ \rho_9 B_{p,9}^{-1}\gamma_{e,4.7}^{-1}), \quad (5)$$

where $\chi \sim 1/15$ has been used, $B_q = m_e^2c^3/e\hbar = 4.4\times 10^{13}$ G is the critical magnetic field, and m_e, e, c, and $\hbar$ are fundamental constants with their conventional meanings. Equation (5) applies when $l_{\rm ph} \ll R_{\rm WD}$ is satisfied, so that the local magnetic field does not decrease too much with respect to B_p. With the typical parameters given above, l_e is larger than $R_{\rm WD}$, and $l_{\rm ph}$ is comparable to $R_{\rm WD}$. This means that the condition for copious pair production is not satisfied [which is defined by the condition $(l_e + l_{\rm ph}) < R_{\rm WD}$] and that the white dwarf is below the so-called pair death line in the P-B_p plane analogous to radio pulsars (Ruderman & Sutherland 1975; Zhang et al. 2000; Hibschman & Arons 2001; Harding & Muslimov 2002; Harding et al. 2002). This explains why GCRT J1745−3009 is dormant under normal conditions, i.e., before and after the observed five bursting cycles.

A crucial point is that GCRT J1745−3009 does not lie deep below the death line and can probably emerge out of the "graveyard" under some circumstances. From equations (4) and (5), we can see that l_e sensitively depends on T and that $l_{\rm ph}$ depends on both ρ and B_p. Since we have witnessed regularly enhanced sunspot activity during the solar cycle, it would be natural to imagine that more tangled magnetic structures would sometimes arise near the white dwarf polar cap region. In fact, the starspots that are analogous to sunspots have most probably been observed in magnetized white dwarfs (Maxted et al. 2000; Brinkworth et al. 2005). During such magnetically active epochs, magnetic reconnection would heat up the local magnetosphere (corona) to higher temperatures. Imagine during one of these magnetic activities that the temperature is raised by at least a factor of 3; l_e (eq. [4]) would be greatly reduced to (much) shorter than $R_{\rm WD}$. Plenty of gamma rays (with typical energy 26 GeV) are generated. In the meantime, stronger (say, $B_p \sim$ several $\times\ 10^9$ G), more curved (say, $\rho \sim 10^8$ cm) magnetic field structures emerge, so that $l_{\rm ph}$ also becomes much smaller than $R_{\rm WD}$. The IC γ-rays that are produced by the primary electrons interact with local strong magnetic fields, leading to copious production of electron-positron pairs. The white dwarf pulsar is then "turned on."

According to the dipolar geometry, the emission altitude could be estimated from the observed 10 minute pulse duration, i.e.,

$$\frac{R_e}{R_{\rm WD}} = \left(\frac{10}{77}\frac{2\pi\sin\alpha}{3}\right)^2\frac{R_{\rm lc}}{R_{\rm WD}} \simeq 3300\left(\frac{P}{77\ {\rm minutes}}\right)R_{\rm WD,8.7}^{-1}(\sin\alpha)^2, \quad (6)$$

where α is the inclination angle between the rotational axis and the magnetic axis. Surprisingly, this "relative" emission height falls nicely on the height-period correlation discovered in radio pulsars (Fig. 2 of Kijak & Gil 2003), suggesting some possible similar underlying physics.

After some time (five periods for GCRT J1745−3009), the "corona" cools down, and the strong magnetic fields disappear. Pair production is turned off. The white dwarf returns back to its dormant phase. By simple analogy, this timescale is different from the solar case. This may be due to the fact that the complex magnetic fields in white dwarfs have a different origin than the magnetic field in the Sun. These magnetic fields may arise from a convective surface layer of the white dwarf (Steffen et al. 1995) or may be due to the Hall effect (Muslimov et al. 1995). If the white dwarf accretes from a companion, one would also expect large-scale effects on magnetic fields.

4. ENERGETICS AND DETECTABILITY

The spin-down energy loss rate of GCRT J1745−3009 could be estimated as

$$\dot{E} = \frac{(2\pi)^4B_p^2R_{\rm WD}^6}{6c^3P^4} = 3.3\times 10^{26}\ {\rm ergs\ s^{-1}}\ B_{p,9}^2R_{\rm WD,8.7}^6\left(\frac{P}{77\ {\rm minutes}}\right)^{-4}. \quad (7)$$

This is not a particularly energetic engine compared with normal pulsars. The 0.33 GHz radio flux at the flare is ∼1.67 Jy. The condition that the radio luminosity not exceed the spin-down luminosity can be derived as

$$d < 0.8\ {\rm kpc}\ (\Delta\Omega_{-2})^{-1/2}B_{p,9}R_{\rm WD,8.7}^3, \quad (8)$$

where $\Delta\Omega$ is the unknown solid angle of the radio emission, which for a slow rotator like GCRT J1745−3009, is conceivably as small as 0.01. Given the uncertainties of $\Delta\Omega$, B_p, and $R_{\rm WD}$, the Galactic center distance (∼8.5 kpc) is not ruled out, although the source could be much closer.

The maximum gamma-ray/X-ray flux would be

$$F_{\rm max}^{\gamma,X} = \frac{\dot{E}}{\Delta\Omega D^2} = 4.8\times 10^{-17}\ {\rm ergs\ s^{-1}\ cm^{-2}} \times (\Delta\Omega)_{-2}B_{p,9}^2R_{\rm WD,8.7}^6\left(\frac{P}{77\ {\rm minutes}}\right)^{-4}\left(\frac{D}{8.5\ {\rm kpc}}\right)^{-2}. \quad (9)$$

This makes its gamma-ray/X-ray emission undetectable. The predicted maximum X-ray flux is very consistent with the X-ray flux upper limit of $\sim 5\times 10^{-10}$ ergs s^{-1} cm^{-2} (Hyman et al. 2005).

If $B_p = 10^9$ G, the expected spin-down rate is

$$\dot{P} = \frac{\dot{E}P^3}{4\pi^2I_{\rm WD}} = 8.2\times 10^{-15}B_{p,9}^2R_{\rm WD,8.7}^6 \times I_{\rm WD,50}^{-1}\left(\frac{P}{77\ {\rm minutes}}\right)^{-1}, \quad (10)$$

where $I_{\rm WD} \sim 10^{50}$ g cm^2 is the moment of inertia of the white dwarf. Even with long-term monitoring, such a small spin-down rate is difficult to measure.

The apparent optical/IR magnitude of a white dwarf at a distance of 8.5 kpc is ∼27–30. Extinction would further suppress the optical flux. Deep IR exposures with large telescopes may lead to the discovery of the counterpart of GCRT J1745−3009, especially if the source is at a closer distance than that of the Galactic center. Line features, if detected, would give a direct measurement of the magnetic field strength through Zeeman spectroscopy to test the hypothesis (Wickramasinghe & Ferrario 2000).

5. DISCUSSION

We have shown that the enigmatic transient radio source GCRT J1745−3009 could be understood within the hypothesis that it is a white dwarf pulsar. If this hypothesis is correct, the detection of this powerful bursting radio source suggests the discovery of a new type of pulsating, occasionally radio-loud, strongly magnetized white dwarfs. The study of this object and future objects (if discovered) would also shed light on the poorly understood coherent radio emission mechanism (see, e.g., Melrose 2004 for a review) of their brethren, neutron star pulsars.

Detecting such a transient white dwarf pulsar also suggests that some "dead" neutron star pulsars, not deep below the death line, may occasionally become active again if strong sunspot-like magnetic fields emerge into their polar cap regions. These transient radio pulsars are waiting to be discovered.

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