GCRT J1745-3009 AS A TRANSIENT WHITE DWARF PULSAR

BING ZHANG$^1$ AND JANUSZ GIL$^{2,1}$

$^1$ Department of Physics, University of Nevada, Las Vegas, NV 89154
$^2$ Institute of Astronomy, Zielona Góra University, Lubuska 2, 65-265 Zielona Góra, Poland

Submitted to The Astrophysical Journal Letters

ABSTRACT

A transient radio source in the direction of the Galactic Center, GCRT J1745-3009, exhibited 5 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 when the radio beam sweeps our line of sight. The bursting epoch corresponds to the episodes when 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: stars: pulsars - stars: white dwarf - radiation mechanism: coherent - radio

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 5 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; Kulka-rni & 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 magnetized white dwarf model 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 ~10^6 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 10^9 – 10^10 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 we propose here to interpret the pulsating behavior of GCRT J1745-3009.

Magnetic white dwarfs can mimic pulsars in various aspects. 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 (Paczynski 1990; Usov 1993, cf. Hulleman et al. 2000). Below we show that the magnetized white dwarf model gives a straightforward interpretation to the observational data of GCRT J1745-3009.

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

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

Hereafter the convention $Q_x = (Q/10^x)$ is adopted in cgs units. Lacking a measurement of the period derivative $\dot{P}$, one can not reliably estimate the spin down rate and the dipolar surface magnetic field at the magnetic pole, $B_p$. In the following we assume $B_p = 10^9$ G. The maximum avail-
able unipolar potential drop across the polar cap reads

$$\Phi_{\text{max}} = \frac{2\pi^2 B_p R_{\text{WD}}^3}{c^2 \rho_2} = 3.9 \times 10^{10} \, V \frac{B_{p,9} R_{\text{WD},8.7}}{(P/77 \, \text{min})^{-2}}$$

The maximum energy of the electrons accelerated in this potential drop is

$$\gamma_e M = e \Phi_{\text{max}} / me^2 = 7.6 \times 10^4 B_{p,9} R_{\text{WD},8.7} (P/77 \, \text{min})^{-2}.$$  

The potential drop is about 2 orders of magnitude smaller than that in radio pulsars.

The surface layer of white dwarfs is composed of a non-degenerate electron gas and possibly an ionic lattice (Shapiro & Teukolsky 1983). The lattice melting temperature is $T_m \sim 8.8 \times 10^5 \, K$ ($\rho / 10^2 \, \text{ergs cm}^{-3}$)$^{1/3} (Z/12)^{5/3}$, where $\rho$ 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 anti-parallel rotator, i.e., $\Omega \cdot \mathbf{B} < 0$, where $\Omega$ and $\mathbf{B}$ are the vectors for the rotational and magnetic axes, the polar cap region is populated with positively charged particles. In a co-rotating magnetic white dwarf magnetosphere, whether or not the surface can provide a free ionic lattice, the composition in the WD surface layer, the cohesive energy is $\Delta \epsilon_c = e \Phi_{\text{max}} / me^2$.$ \sim 10^3$. So only photons far in the Rayleigh-Jeans branch would be resonantly scattered in the rest frame of the electrons. The typical resonant IC photon energy (Zhang et al. 1997) is

$$\epsilon_{\gamma, \text{IC}} \sim \gamma_e B_9(580 \gamma_{e,4.7} B_{p,9}) \, \text{keV},$$

which is slightly larger than the electron rest energy $mc^2 = 511 \, \text{keV}$, but does not meet the pair production threshold.

$$\epsilon_{\gamma} = \epsilon_{\gamma, \text{IC}} = \min(\gamma_e 2.8 kT, \gamma_e mc^2) = \min(18 \, \text{GeV}, \gamma_{e,4.7} B_{p,9} / 26 \, \text{GeV}).$$

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

\[ l_e = (\sigma_{IC} n_{ph})^{-1} = 2.8 \times 10^9 \text{ cm} \ T_{1.5}^{-3} \ \sigma_{IC}^{-1} \ \sigma_T^{-1}, \tag{4} \]

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

\[ l_{ph} = \chi \rho \left( \frac{B_q}{B_p} \right) \left( \frac{2mc^2}{e\gamma} \right) \sim \max(1.7 \times 10^8 \text{ cm} \ \rho_9 B_{p,9}^{-1} \gamma_e^{-1} T_{4.5}^{-1}, 1.2 \times 10^8 \text{ cm} \ \rho_9 B_{p,9}^{-1} \gamma_e^{-1} l_{ph}), \tag{5} \]

where \( \chi \sim 1/15 \) has been used, \( B_q = m_e^2 c^3/e\hbar = 4.4 \times 10^{-3} \) G is the critical magnetic field, \( m_e, c, e, \) and \( \hbar \) are fundamental constants with their conventional meanings. Equation (5) applies when \( l_{ph} \ll R_{WD} \) 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 \( R_{WD} \) and \( l_{ph} \) is comparable to \( R_{WD} \). This means that the condition for copious pair production is not satisfied (which is defined by the condition \( (l_e + l_{ph}) < R_{WD} \) for a space charge limited flow (Arons & Scharlemann 1979), and the white dwarf is below the so-called pair “death line” in the \( P - B_p \) plane in analogy of radio pulsars (Ruderman & Sutherland 1975; Zhang et al. 2000; Hibschman & Arons 2001; Harding & Muslimov 2002; Harding et al. 2002). This explains why GCR T1745-3009 is dormant under normal conditions, i.e. before and after the observed 5 pulsing cycles.

A crucial point is that GCR T1745-3009 lies not deep below the death line, and can probably emerge out of the graveyard under some circumstances. From Eqs.(4) and (5), we can see that \( l_e \) sensitively depends on \( T \), and \( l_{ph} \) depends on both \( \rho \) and \( B_p \). Since we have witnessed regularly enhanced sunspot activities 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 star-spots 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 the temperature is raised by at least a factor of 3, \( l_e \) (Eq.[4]) is greatly reduced to be (much) shorter than \( R_{WD} \). Plenty of gamma-rays (with typical energy 26 GeV) are generated. In the meantime, stronger (say \( B_p \sim 10^9 \) G), more curved (say, \( \rho \sim 10^8 \) cm) magnetic field structures emerge, so that \( l_{ph} \) also becomes much smaller than \( R_{WD} \). The IC \( \gamma \)-rays 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 min pulse duration, i.e.

\[ \frac{R_e}{R_{WD}} = \left( \frac{10 \ 2\pi \sin \alpha}{\frac{77}{3}} \right)^2 \frac{R_e}{R_{WD}} \approx 3300 \left( \frac{P}{77 \text{ min}} \right)^{10^{-1}} \tag{6} \]

where \( \alpha \) 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 (5 periods for GCR T1745-3009), 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 time scale is different from the solar case. The complexity of magnetic fields may be arisen from a convective surface layer of the white dwarf (Steffen et al. 1995) or 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 & DETECTABILITY

The spin down energy loss rate of GCR T1745-3009 could be estimated as

\[ \dot{E} = \frac{(2\pi)^4 B^2_p R^6_{WD}}{6c^3 P^4} \]

\[ = 3.3 \times 10^{26} \text{ erg s}^{-1} B_{p,9}^2 R_{WD,8.7}^6 \left( \frac{P}{77 \text{ min}} \right)^{-4}. \tag{7} \]

This is not a particularly energetic engine compared with normal pulsars. The 0.33 GHz radio flux at the flare is \( \sim 1.67 \text{ Jy} \). The condition that the radio luminosity does not exceed the spindown luminosity can be derived as

\[ d < 0.8 \text{ kpc} (\Delta \Omega_{-2})^{-1/2} B_{p,9} R_{WD,8.7}^3, \tag{8} \]

where \( \Delta \Omega \) is the unknown solid angle of the radio emission, which for a slow rotator like GCR T1745-3009, is conceivable to be as small as 0.01. Given the uncertainties of \( \Delta \Omega, B_p \) and \( R_{WD} \), the galactic center distance (\( \sim 8.5 \text{ kpc} \)) is not ruled out, although the source could be much closer.

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

\[ F_{\gamma/X}^{max} \approx \frac{\dot{E}}{\Delta \Omega D^2} \]

\[ = 4.8 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \]

\[ \times (\Delta \Omega)^{-1} B_{p,9}^2 R_{WD,8.7}^6 \left( \frac{P}{77 \text{ min}} \right)^{-4} \left( \frac{D}{8.5 \text{ kpc}} \right)^{-2}. \tag{9} \]

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

If \( B_p = 10^9 \) G, the expected spin down rate is

\[ \dot{P} = \frac{\dot{E} P^3}{4\pi^2 l_{WD}} = 8.2 \times 10^{-15} B_{p,9}^2 R_{WD,8.7}^6 T_{50}^{-1} \left( \frac{P}{77 \text{ min}} \right)^{-1}, \tag{10} \]
where $I_{WD} \sim 10^{50}$ g cm$^2$ is the moment of inertia of the white dwarf. Even with long term monitoring, such a small spindown rate is difficult to measure.

The apparent optical/IR magnitude of a white dwarf at a distance of 8.5 kpc is $\sim (27-30)$. Extinction would further suppress the optical flux. Deep IR exposure 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 therefore suggests the discovery of such a new type of pulsating, occasionally radio-loud, strongly magnetized white dwarfs. The study of this object and future more objects (if discovered) would also shed light on the poorly understood coherent radio emission mechanism (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 become active again occasionally if strong sunspot-like magnetic fields emerge into their polar cap regions. These transient radio pulsars are awaiting being discovered.

We thank S. R. Kulkarni for drawing our attention to this new phenomenon, D. Lai and J. Dyks for helpful discussion. This work is supported by NASA NNG04GD51G (BZ and JG) and by grant 1 P03D 029 26 of the Polish State Committee for Scientific Research (JG).

REFERENCES

Arons, J. & Scharlemann, E. T. 1979, ApJ, 231, 854
Brinkworth, C. S., Marsh, T. R., Morales-Rueda, L., Maxted, P. F. L., Burleigh, M. R. & Good, S. A. 2005, MNRAS, 357, 333
Ferrario, L., Venne, S., Wickramasinghe, D. T., Bailey, J. A. & Christian, D. L. 1997, MNRAS, 292, 205
Gil, J. & Mitra, D. 2001, ApJ, 550, 383
Goldreich, P. & Julian, W. H. 1969, ApJ, 157, 869
Harding, A. K. & Muslimov, A. G. 1998, ApJ, 508, 328
——. 2002, ApJ, 568, 862
Harding, A. K., Muslimov, A. G. & Zhang, B. 2002, ApJ, 576, 366
Hilschman, J. A. & Arons, J. 2001, ApJ, 554, 624
Hulleman, F., van Kerkwijk, M. H. & Kulkarni, S. R. 2000, Nature, 408, 689
Hyman, S. D., Lazio, J. W., Kassim, N. E., Paul, S. R., Markwardt, C. B. & Yusef-Zadeh, F. 2005, Nature, 434, 50
Jones, P. B. 1986, MNRAS, 218, 477
Kawaler, S. D. 2004, in Stellar Rotation, Proc. of IAU Sym. No. 215 (Nov 11-15, 2002, Cancun, Yucatan, Mexico), 561
Kijak, J. & Gil, J. 2003, A&A, 397, 969
Kulkarni, S. R. & Phinney, E. S., 2005, Nature, 434, 28
Lai, D. 2001, Rev. Mod. Phys., 73, 629
Maxted, P. F. L., Ferrario, L., Marsh, T. R. & Wickramasinghe, D. T. 2000, MNRAS, 315, L41
Melrose, D. 2004, in IAU Symp. 218, Young Neutron Stars and Their Environments, ed. F. Camilo & B. M. Gaensler (San Francisco: ASP), 349
Mestel, L. & Ruderman, M. A. 1967, MNRAS, 136, 27
Muslimov, A. G. & Tsygan, A. I. 1992, MNRAS, 255, 61
Muslimov, A. G., Van Horn, H. M. & Wood, M. A. 1995, ApJ, 442, 758
Paczyński, B. 1990, ApJ, 365, L9
Ruderman, M. & Sutherland, P. G. 1975, ApJ, 196, 51
Shapiro, S. L. & Teukolsky, S. A. 1983, Black holes, white dwarfs and neutron stars: the physics of compact objects. A Wiley-Interscience Publication, John Wiley & Sons
Steffen, M., Ludwig, H.-G. & Freytag, B. 1995, A&A, 300, 473
Sturrock, P. A., 1971, ApJ, 164, 529
Turrolla, R., Possenti, A. & Treves, A. 2005, ApJ, 628, L49
Uskov, V. V. 1993, ApJ, 410, 761
Uskov, V. V. & Melrose, D. B. 1996, ApJ, 464, 396
Wickramasinghe, D. T. & Ferrario, L. 2000, PASP, 112, 873
Zhang, B., Harding, A. K. & Muslimov, A. G. 2000, ApJ, 531, L135
Zhang, B., Qiao, G. J., Lin, W. P. & Han, J. L. 1997, ApJ, 478, 313
Zhu, W. W. & Xu, R. X. 2005, astro-ph/0504251