**PASJ:** Publ. Astron. Soc. Japan **64**, 56, 2012 June 25

# SGRs and AXPs as Rotation-Powered Massive White Dwarfs

Manuel MALHEIRO,[1,4] Jorge A. RUEDA,[1,2] and Remo RUFFINI,[1,2,3]
[1]*Dipartimento di Fisica and ICRA, Sapienza Università di Roma, P.le Aldo Moro 5, I–00185 Rome, Italy*
*ruffini@icra.it*
[2]*ICRANet, P.zza della Repubblica 10, I–65122 Pescara, Italy*
[3]*ICRANet, University of Nice-Sophia Antipolis, 28 Av. de Valrose, 06103 Nice Cedex 2, France*
[4]*Departamento de Física, Instituto Tecnológico de Aeronáutica, CTA, São José dos Campos, 12.228-900, Brazil*

(Received 2012 August 10; accepted 2012 December 11)

## Abstract

SGR 0418+5729 is a "Rosetta Stone" for deciphering the energy source of Soft Gamma Ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs). We present a model based on canonical physics and astrophysics for SGRs and AXPs powered by massive highly magnetized rotating white dwarfs (WDs), in total analogy with pulsars powered by rotating neutron stars (NSs). We predict for SGR 0418+5729 a lower limit for its spin-down rate, $\dot{P} \geq L_{\rm X} P^3/(4\pi^2 I) = 1.18 \times 10^{-16}$, where $I$ is the moment of inertia of the WD. We show for SGRs and AXPs that the occurrence of the glitch and the gain of rotational energy is due to the release of gravitational energy associated to the contraction and decrease of the moment of inertia of the WDs. The steady emission and the outburst following the glitch are explained by the loss of rotational energy of the WDs, in view of the much larger moment of inertia of the WDs, as compared to that of NSs and/or quark stars. There is no need here to invoke the unorthodox concept of magnetic energy release due to the decay of overcritical magnetic fields, as assumed in the magnetar model. A new astrophysical scenario for the SGRs and AXPs associated to Supernova remnants is presented. The observational campaigns of the X-ray Japanese satellite Suzaku on AE Aquarii and the corresponding theoretical works by Japanese groups and recent results of the Hubble Space Telescope, give crucial information for our theoretical model. Follow-on missions of Hubble Telescope and VLT are highly recommended to give further observational evidence of this most fundamental issue of relativistic astrophysics: the identification of the true SGRs/AXPs energy source.

**Key words:** stars: anomalous X-ray pulsars — stars: magnetars — stars: massive fast rotating highly magnetized white dwarfs — stars: soft gamma ray repeaters

## 1. Introduction

Soft Gamma Ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are a class of compact objects that show interesting observational properties (see e.g., Mereghetti 2008): rotational periods in the range of $P \sim (2\text{–}12)$ s, a narrow range with respect to the wide range of ordinary pulsars, $P \sim (0.001\text{–}10)$ s; spin-down rates of $\dot{P} \sim (10^{-13}\text{–}10^{-10})$, larger than ordinary pulsars with $\dot{P} \sim 10^{-15}$; strong outburst of energies of $\sim(10^{41}\text{–}10^{43})$ erg, and for the case of SGRs, giant flares of even large energies $\sim(10^{44}\text{–}10^{47})$ erg, not observed in ordinary pulsars.

The recent observation of SGR 0418+5729 with a rotational period of $P = 9.08$ s, an upper limit of the first time derivative of the rotational period of $\dot{P} < 6.0 \times 10^{-15}$ (Rea et al. 2010), and an X-ray luminosity of $L_{\rm X} = 6.2 \times 10^{31}\,{\rm erg\,s^{-1}}$ promises to be an authentic Rosetta Stone, a powerful discriminant for alternative models of SGRs and AXPs.

If described as a neutron star of $M = 1.4\,M_\odot$, $R = 10$ km and a moment of inertia of $I \approx 10^{45}\,{\rm g\,cm^2}$, which we adopt hereafter as fiducial parameters, the loss of rotational energy of the neutron star,

$$\dot{E}^{\rm NS}_{\rm rot} = -4\pi^2 I \frac{\dot{P}}{P^3} = -3.95 \times 10^{46} \frac{\dot{P}}{P^3}\,{\rm erg\ s^{-1}}\,, \qquad (1)$$

associated to its spin-down rate, $\dot{P}$, cannot explain the X-ray luminosity of SGR 0418+5729, i.e., $\dot{E}^{\rm NS}_{\rm rot} < L_{\rm X}$, excluding the possibility of identifying this source as an ordinary spin-down powered pulsar.

The magnetar model of SGRs and AXPs, based on a neutron star of fiducial parameters, needs a magnetic field larger than the critical field for vacuum polarization, $B_{\rm c} = m_{\rm e}^2 c^3/(e\hbar) = 4.4 \times 10^{13}$ G, in order to explain the observed X-ray luminosity in terms of the release of magnetic energy (see Duncan & Thompson 1992; Thompson & Duncan 1995, for details). However, the inferred upper limit of the surface magnetic field of SGR 0418+5729, $B < 7.5 \times 10^{12}$ G, describing it as a neutron star (see Rea et al. 2010, for details), is well below the critical field challenging the power mechanism based on magnetic field decay purported in the magnetar scenario.

We show that the observed upper limit on the spin-down rate of SGR 0418+5729 is, instead, perfectly in line with a model based on a massive fast rotating highly magnetized white dwarf (see e.g., Paczyński 1990) of mass $M = 1.4\,M_\odot$, radius $R = 10^3$ km, and moment of inertia $I \approx 10^{49}\,{\rm g\,cm^2}$, which we adopt hereafter as fiducial white dwarf parameters. Such a configuration leads for SGR 0418+5729 to a magnetic field of $B < 7.5 \times 10^8$ G. The X-ray luminosity can then be expressed as originating from the loss of rotational energy of the white dwarf, leading to a theoretical prediction for the first time derivative of the rotational period,

$$\frac{L_{\rm X} P^3}{4\pi^2 I} \leq \dot{P}_{\rm SGR\,0418+5729} < 6.0 \times 10^{-15}\,, \qquad (2)$$

where the lower limit is established by assuming that the observed X-ray luminosity of SGR 0418+5729 coincides with the rotational energy loss of the white dwarf. For this specific source, the lower limit of $\dot{P}$ given by equation (2) is $\dot{P}_{\rm SGR\,0418+5729} \geq 1.18 \times 10^{-16}$. This prediction is left to be verified by dedicated scientific missions.

The assumption of massive fast rotating highly magnetized white dwarfs appears to be very appropriate, since their observation has been solidly confirmed in the last years, thanks to observational campaigns carried out by the X-ray Japanese satellite Suzaku (see e.g., Terada 2008; Terada et al. 2008a, 2008b, 2008c, 2008d). The magnetic fields observed in white dwarfs are larger than $10^6$ G all the way up to $10^9$ G (see e.g., Angel et al. 1981; Ferrario et al. 1997; Nalężyty & Madej 2004; Ferrario & Wickramasinghe 2005; Terada et al. 2008c; Külebi et al. 2009). These observed massive fast rotating highly magnetized white dwarfs share common properties with SGRs/AXPs. A specific comparison between SGR 0418+5729 and the white dwarf AE Aquarii (Terada et al. 2008c) is given in section 4.

The aim of this article is to investigate the implications of the above considerations to all observed SGRs and AXPs. The article is organized as follows. In section 2 we summarize the main features of a model for SGRs and AXPs based on rotation powered white dwarfs while, in section 3, we recall the magnetar model. In section 4 we present observations of massive fast rotating highly magnetized white dwarfs. The constraints on the rotation rate imposed by the rotational instabilities of fast rotating white dwarfs are discussed in section 5, and in section 6 we analyze the glitch-outburst connection in SGRs and AXPs. The magnetospheric emission from the white dwarf is discussed in section 7, and the possible connection between SGRs and AXPs with supernova remnants is presented in section 8. In section 9 we address the problem of fiducial parameters of both white dwarfs and neutron stars; in section 10 we summarize conclusions and remarks.

## 2. SGRs and AXPs within the White Dwarf Model

We first recall the pioneering works of Morini et al. (1988) and Paczyński (1990) on 1E 2259+586. This source is pulsating in X-rays with a period of $P = 6.98$ s (Fahlman & Gregory 1981), a spin-down rate of $\dot{P} = 4.8 \times 10^{-13}$ (Davies et al. 1990) and an X-ray luminosity of $L_{\rm X} = 1.8 \times 10^{34}$ erg s$^{-1}$ (Gregory & Fahlman 1980; Hughes et al. 1981; Morini et al. 1988). Specially relevant in the case of 1E 2259+586 is also its position within the supernova remnant G109.1−1.0 with an age estimated to be $t - t_0 = (12–17)$ kyr (Gregory & Fahlman 1980; Hughes et al. 1981).

Paczyński (1990) developed for 1E 2259+586 a model based on a massive fast rotating highly magnetized white dwarf. The upper limit on the magnetic field (see e.g., Ferrari & Ruffini 1969) obtained by requesting that the rotational energy loss due to the dipole field be smaller than the electromagnetic emission of the dipole, is given by

$$B = \left(\frac{3c^3}{8\pi^2}\frac{I}{R^6} P\dot{P}\right)^{1/2}, \qquad (3)$$

where $P$ and $\dot{P}$ are the observed properties; the moment of inertia, $I$, and the radius, $R$, of the object are model-dependent properties. For the aforementioned fiducial parameters of a fast rotating magnetized white dwarf, equation (3) becomes

$$B = 3.2 \times 10^{15} \left(P\dot{P}\right)^{1/2} {\rm G}. \qquad (4)$$

The loss of rotational energy within this model is given by

$$\dot{E}^{\rm WD}_{\rm rot} = -4\pi^2 I \frac{\dot{P}}{P^3} = -3.95 \times 10^{50} \frac{\dot{P}}{P^3} \,{\rm erg\,s^{-1}}\,, \qquad (5)$$

which amply justifies the steady X-ray emission of 1E 2259+586 (see table 3).

A further development for the source 1E 2259+586 came from Usov (1994), who introduced the possibility in a white dwarf close to the critical mass limit, to observe sudden changes in the period of rotation, namely glitches. When the rotation of the white dwarf slows down, centrifugal forces of the core decrease and gravity pulls it to a less oblate shape, thereby stressing it. The release of such stresses leads to a sudden decrease in the moment of inertia and, correspondingly, by the conservation of angular momentum,

$$J = I\Omega = (I + \Delta I)(\Omega + \Delta\Omega) = {\rm constant}\,, \qquad (6)$$

to a shortening of the rotational period and a shrinking of the stellar radius,

$$\frac{\Delta I}{I} = 2\frac{\Delta R}{R} = \frac{\Delta P}{P} = -\frac{\Delta\Omega}{\Omega}\,. \qquad (7)$$

This leads to a change in the gravitational energy,

$$\Delta E_{\rm g} = \frac{GM^2}{R}\frac{\Delta R}{R} \sim 2.5 \times 10^{51} \frac{\Delta P}{P}\,{\rm erg}\,, \qquad (8)$$

which apply as well in the case of solid quark stars (see e.g., Xu et al. 2006; Tong et al. 2011).

The fractional change of period (7) leads to a gain of rotational energy in the spin-up process of the glitch,

$$\Delta E^{\rm WD}_{\rm rot} = -\frac{2\pi^2 I}{P^2}\frac{\Delta P}{P} = -1.98 \times 10^{50} \frac{\Delta P}{P^3}\,{\rm erg}\,, \qquad (9)$$

which is fully explained by the available gravitational energy given by equation (8).

If we turn now to the glitch-outburst correlation, the electromagnetic energy of the bursts in the rotating white dwarf model finds its energetic origin in the release of rotational energy related to the slowing down of the white dwarf rotational frequency. This occurs all the way to the end of the recovery phase, on time scales from months to years. This is most impressively represented e.g., in the case of the glitch-outburst episode of 1E 2259+586 on 2002 June (Kaspi et al. 2003; Woods et al. 2004); see figure 1 for details. We indeed show in section 6 that the change in the moment of inertia of the white dwarf given by equation (7), leading to the release of gravitational energy given by equation (8), and to the rotational energy gain of the white dwarf expressed by equation (9), is sufficient to explain the total electromagnetic energy released in the main burst and in subsequent activity.

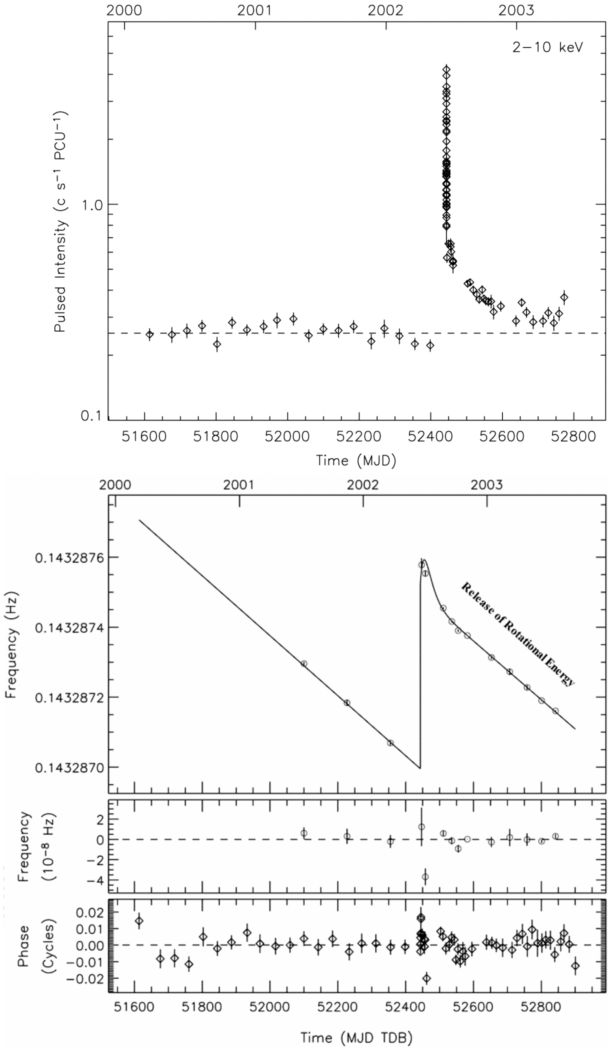

**Fig. 1.** Timing and pulsed emission analysis of the glitch-outburst of 1E 2259+586 on 2002 June (taken from Woods et al. 2004). The observed fractional change of period is $\Delta P/P = -\Delta\Omega/\Omega \sim -4 \times 10^{-6}$ and the observed energy released during the event is $\sim 3 \times 10^{41}$ erg (Woods et al. 2004). Within the white dwarf model from such a $\Delta P/P$ we obtain $\Delta E_{\rm rot}^{\rm WD} \sim 1.7 \times 10^{43}$ erg as given by equation (9), see section 6 for details. We have modified the original figure 7 of Woods et al. (2004) by indicating explicitly where the rotational energy is released after the spin-up, during the recovery phase, by the emission of a sequence of bursts on time scales from months to years (see e.g., Mereghetti 2008).

For the evolution of the period close to a glitch, we follow the parameterization by Manchester and Taylor (1977). The angular velocity, $\Omega = 2\pi/P$, since the glitch time is $t = t_{\rm g}$, until complete or partial recovery, can be described as

$$\Omega = \Omega_0(t) + \Delta\Omega[1 - Q(1 - e^{-(t-t_{\rm g})/\tau_{\rm d}})], \tag{10}$$

where $\Omega_0(t) = \Omega_0 + \dot{\Omega}(t - t_{\rm g})$ is the normal evolution of the frequency in the absence of a glitch, being $\Omega_0$, the frequency prior to the glitch; $\Delta\Omega = -2\pi\Delta P/P^2$ is the initial frequency jump, which can be decomposed in the persistent and decayed parts, $\Delta\Omega_{\rm p}$ and $\Delta\Omega_{\rm d}$, respectively; $\tau_{\rm d}$ is the timescale of the exponential decay of the frequency after the glitch and $Q = \Delta\Omega_{\rm d}/\Delta\Omega = 1 - \Delta\Omega_{\rm p}/\Delta\Omega$ is the recovery fraction, or "healing parameter." For full recovery, we have $Q = 1$, $\Omega(t \gg \tau_{\rm d}) = \Omega_0$, and for zero recovery $Q = 0$, $\Omega(t \gg \tau_{\rm d}) = \Omega_0(t) + \Delta\Omega$. For simplicity, we assume in the following, and especially below in section 6, complete recovery, $Q = 1$.

This mechanism in white dwarfs is similar, although simpler, than that used to explain e.g., glitches in ordinary pulsars (see e.g., Baym & Pines 1971; Shapiro & Teukolsky 1983). The essential difference is that neutron stars are composed of a superfluid core and a solid crust, the latter being the place where starquakes can originate, leading to glitches. A two-component description is then needed; see e.g., Shapiro and Teukolsky (1983). In the present case of a massive rotating white dwarf, such a two-component structure does not exist, and the white dwarf behaves as a single solid system. What is important to stress is that the rotational energy released for $Q \geq 1$ is largely sufficient to explain the bursting phenomena; see section 6 for details.

The crystallization temperature of a white dwarf composed of nuclei $(Z,\ A)$ and mean density, $\bar{\rho}$, is given by (see e.g., Shapiro & Teukolsky 1983; Usov 1994)

$$T_{\rm cry} \simeq 2.28 \times 10^5 \frac{Z^2}{A^{1/3}} \left(\frac{\bar{\rho}}{10^6 {\rm g\ cm^{-3}}}\right)^{1/3} {\rm K}. \tag{11}$$

Thus, assuming an internal white dwarf temperature of $\sim 10^7$ K, we find that the mean density for the crystallization of the white dwarf should be $\sim 2.2 \times 10^7$ g cm$^{-3}$ for $^{12}$C, $\sim 5.2 \times 10^6$ g cm$^{-3}$ for $^{16}$O and $\sim 1.25 \times 10^6$ g cm$^{-3}$ for $^{56}$Fe. Very massive white dwarfs, like the ones we are considering here, have mean densities of $\sim 10^9$ g cm$^{-3}$, and therefore a considerable fraction of their size should in principle be solid at these high temperatures (see also Althaus et al. 2005, 2007). It is worth mentioning that the phase separation of the constituents of CO white dwarfs, theoretically expected to occur in the crystallization process (see Garcia-Berro et al. 1988, for details), has been recently observationally confirmed, thus solving the puzzle of the age discrepancy of the open cluster NGC 6791 (García-Berro et al. 2010).

Under these physical conditions, starquakes leading to glitches in the white dwarf may occur with a recurrence time (see e.g., Baym & Pines 1971; Usov 1994) of

$$\delta t_{\rm q} = \frac{2D^2}{B} \frac{|\Delta P|/P}{|\dot{E}_{\rm rot}|}, \tag{12}$$

where $\dot{E}_{\rm rot}$ is the loss of rotational energy (5), $D = (3/25)\,GM_{\rm c}^2/R_{\rm c}$, $B = 0.33\,(4\pi/3)R_{\rm c}^3 e^2 Z^2\ [\bar{\rho}_{\rm c}/\ (Am_{\rm p})]^{4/3}$; $M_{\rm c}$, $R_{\rm c}$, and $\bar{\rho}_{\rm c}$ are the mass, the radius and the mean density of the solid core, and $m_{\rm p}$ is the proton mass.

For the specific case of 1E 2259+586, Usov (1994) predicted the possible existence of changes of period of $\Delta P/P \approx -(1\text{–}3) \times 10^{-6}$ with a recurrence time between cracks of $\delta t_{\rm q} \approx 7 \times 10^6\,|\Delta P|/P$ yr $\approx$ a few times (1–10) yr. It is impressive that in 2002, indeed, changes on the order of $\Delta P/P \approx -4 \times 10^{-6}$ were observed in 1E 2259+586 (Kaspi et al. 2003; Woods et al. 2004) (see figure 1 for details).

Our aim in the following is to show that this model can also be applied to other SGRs and AXPs. Their entire energetics is explained by the rotational energy loss of fast-rotating magnetized white dwarfs: (1) the X-ray luminosity is well below

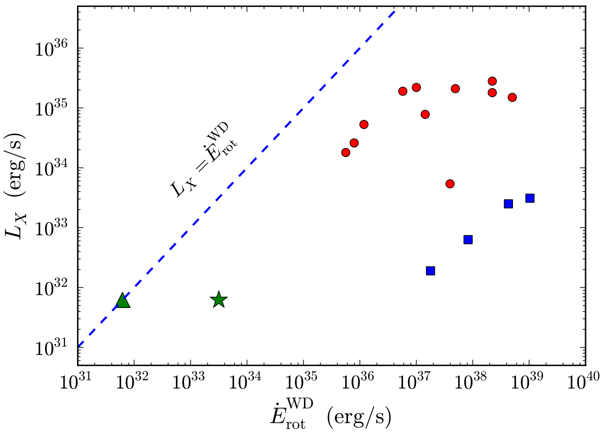

**Fig. 2.** X-ray luminosity, $L_{\rm X}$, versus the loss of rotational energy, $\dot{E}_{\rm rot}$, describing SGRs and AXPs by rotation-powered white dwarfs. The green star and the green triangle correspond to SGR 0418+5729 using, respectively, the upper and the lower limit of $\dot{P}$, given by equation (2). The blue squares are the only four sources that satisfy $L_{\rm X} < \dot{E}_{\rm rot}$ when described as neutron stars (see figure 6 for details).

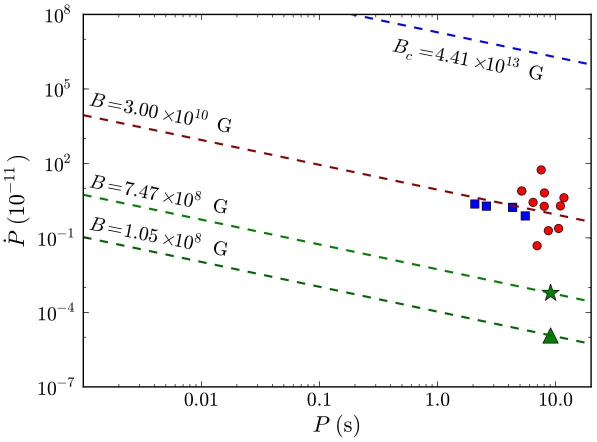

**Fig. 3.** $\dot{P}$–$P$ diagram for all known SGRs and AXPs. The curves of constant magnetic field for white dwarfs given by equation (4) are shown. The blue dashed line corresponds to the critical magnetic field, $B_{\rm c} = m_{\rm e}^2 c^3/(e\hbar)$. The green star and the green triangle correspond to SGR 0418+5729 using, respectively, the upper and the lower limit of $\dot{P}$ given by equation (2). The blue squares are the only four sources that satisfy $L_{\rm X} < \dot{E}_{\rm rot}$ when described as rotation-powered neutron stars (see figure 6 for details).

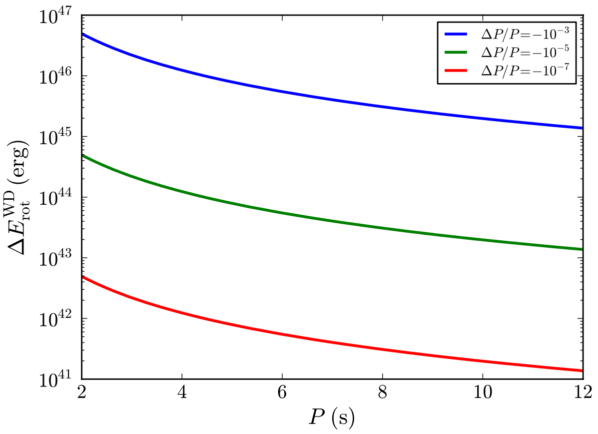

**Fig. 4.** Change in the rotational energy of the white dwarf, $\Delta E_{\rm rot}^{\rm WD}$, given by equation (9) as a function of the rotational period, $P$, in seconds for selected fractional changes of the period, $\Delta P/P$.

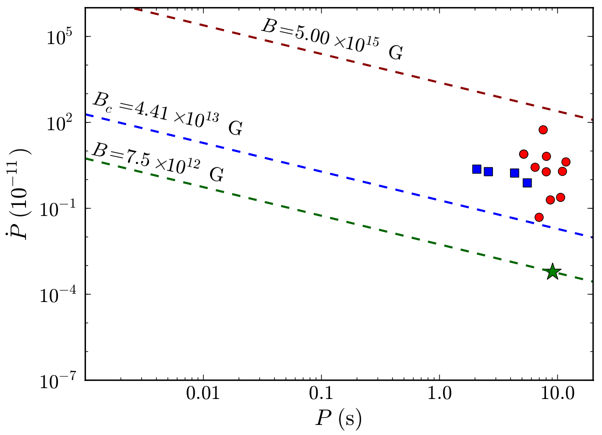

**Fig. 5.** $\dot{P}$–$P$ diagram for all known SGRs and AXPs. The curves of constant magnetic field for neutron stars given by equation (13) are shown. The blue dashed line corresponds to the critical magnetic field, $B_{\rm c} = m_{\rm e}^2 c^3/(e\hbar)$. The green star corresponds to SGR 0418+5729 using the upper limit of $\dot{P}$ given by equation (2). The blue squares are the only four sources that satisfy $L_{\rm X} < \dot{E}_{\rm rot}$ when described as rotation-powered neutron stars (see figure 6 for details).

the rotational energy loss of the white dwarf (see figure 2); (2) in all cases the large magnetic field is well below the critical field for vacuum polarization (see figure 3 and table 3); (3) the energetics of all the bursts can be simply related to the change of rotational energy implied by the observed change of the rotational period (see figure 4, section 5, and table 2).

## 3. SGRs and AXPs within the Magnetar Model

Let us turn to the alternative model commonly addressed as "magnetar" (see e.g., Duncan & Thompson 1992; Thompson & Duncan 1995) based on an ultramagnetized neutron star of $M = 1.4\,M_\odot$ and $R = 10\,$km, and then $I \approx 10^{45}\,$g cm$^2$ as the source of SGRs and AXPs. The limit of the magnetic field obtained from equation (3) becomes

$$B = 3.2 \times 10^{19} \left(P\dot{P}\right)^{1/2}\,{\rm G}, \tag{13}$$

which is four orders of magnitude larger than the surface magnetic field within the fast rotating magnetized white dwarf model (see figure 5).

There are innumerous papers dedicated to this model; for a review covering more than 250 references on the subject see Mereghetti (2008). The crucial point is that in this model there is no role of the rotational energy of the source; the X-ray luminosity is much bigger than the loss of the rotational energy of the neutron star (see figure 6).

Paradoxically, although the bursts appear to be correlated to the presence of glitches in the rotational period, the corresponding increase of change in the rotational energy of

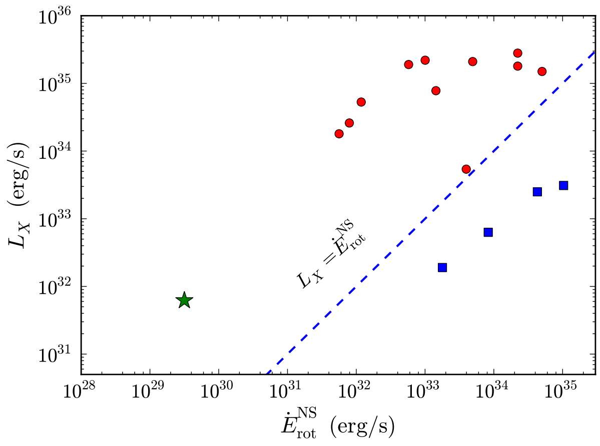

**Fig. 6.** X-ray luminosity, $L_{\rm X}$, versus the loss of rotational energy, $\dot{E}_{\rm rot}$, describing SGRs and AXPs as neutron stars. The green star corresponds to SGR 0418+5729 using the upper limit of $\dot{P}$ given by equation (2). The blue squares are the only four sources with $L_{\rm X} < \dot{E}_{\rm rot}$: 1E 1547.0−5408 with $P = 2.07$ s and $\dot{P} = 2.3 \times 10^{-11}$; SGR 1627−41 with $P = 2.59$ s and $\dot{P} = 1.9 \times 10^{-11}$; PSR J1622−4950 with $P = 4.33$ s and $\dot{P} = 1.7 \times 10^{-11}$; and XTE J1810−197 with $P = 5.54$ s and $\dot{P} = 7.7 \times 10^{-12}$.

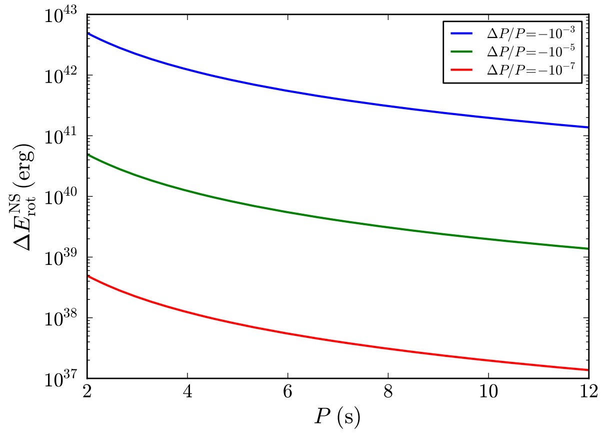

**Fig. 7.** Change in the rotational energy of the neutron star, $\Delta E_{\rm rot}^{\rm NS}$, given by equation (14) as a function of the rotational period, $P$, in seconds for selected fractional changes of period, $\Delta P/P$.

the neutron star,

$$\Delta E_{\rm rot}^{\rm NS} = -\frac{2\pi^2 I}{P^2}\frac{\Delta P}{P} = -1.98 \times 10^{46}\frac{\Delta P}{P^3}\,{\rm erg}, \qquad (14)$$

cannot explain the burst energetic of $\sim (10^{44}$–$10^{47})$ erg. This is a clear major difference between the two models based, respectively, on neutron stars and white dwarfs (see figures 4 and 7 for details).

In magnetars, the value of the rotational period and its first time derivative are only used to establish an upper limit to the magnetic field of the neutron star. In view of the smallness of the moment of inertia of a neutron star with respect to the moment of inertia of a white dwarf, the magnetic field reaches in many cases outstandingly large values of $B \gg B_{\rm c} \sim 4.4 \times 10^{13}$ G; from here the name magnetars (see figure 5). An attempt has been proposed by Duncan and Thompson (1992) and Thompson and Duncan (1995) to assume a new energy source in physics and astrophysics: the magnetic energy in bulk. The role of thermonuclear energy has been well established by physics experiments on the ground as well as in astrophysics to explain the energetics, lifetime, and build-up process of the nuclear elements in main-sequence stars (see e.g., Bethe 1968 and references therein); equally well established has been the role of the rotational energy in pulsars (see e.g., Hewish 1974; Bell & Hewish 1967, and references therein); similarly well established has been the role of gravitational energy in the accretion process into neutron stars and black holes and binary X-ray sources (see e.g., Giacconi 2002; Giacconi & Ruffini 1978 and references therein). In the magnetars instead, it is introduced as an alternative primary energy source not yet tested either in the laboratory (the case of magnetic monopoles) or in astrophysics: a primary energy source due to overcritical magnetic fields.

The mostly qualitative considerations in the magnetar model can be summarized, (see e.g., Ng et al. 2011): in the twisted magnetosphere model of magnetars (Thompson et al. 2002), the observed X-ray luminosity of a magnetar is determined both by its surface temperature and by magnetospheric currents, the latter due to the twisted dipolar field structure. The surface temperature, in turn, is determined by the energy output from within the star due to magnetic field decay, as well as on the nature of the atmosphere and the stellar magnetic field strength. This surface thermal emission is resonantly scattered by the current particles, thus resulting in an overall spectrum similar to a Comptonized blackbody (e.g., Lyutikov & Gavriil 2006; Rea et al. 2008; Zane et al. 2009). In addition, the surface heating by return currents is believed to contribute substantially to $L_{\rm X}$, at least at the same level as the thermal component induced from the interior field decay (Thompson et al. 2002). Magnetar outbursts in this picture occur with sudden increases in the twist angle, consistent with generic hardening of magnetar spectra during outbursts (e.g., Kaspi et al. 2003; Woods et al. 2004; Israel et al. 2007).

It is worth to recall that magnetic-field configurations corresponding to a dipole twisted field have been routinely adopted in rotating neutron stars (see e.g., Cohen et al. 1973). Magnetic field annihilation and reconnection have been analogously adopted in solar physics (see e.g., Parker 1957; Sweet 1958), and also magnetic instabilities have been routinely studied in Tokamak (see e.g., Coppi et al. 1976). These effects certainly occur in magnetized white dwarfs. What is important to stress here is that in none of these systems has the magnetic field been assumed to be the primary energy source of the phenomena, unlike in magnetars.

It is appropriate to recall just a few of the difficulties of the magnetar model in fitting observations, in addition to the main one of SGR 0418+5729 addressed in this article. In particular, e.g.,: (1) as recalled by Mereghetti (2008), “up to now, attempts to estimate the magnetic field strength through the measurement of cyclotron resonance features, as successfully done for accreting pulsars, have been inconclusive”; (2) the prediction of the high-energy gamma-ray emission expected in the magnetars has been found to be inconsistent with the recent observation of the Fermi satellite (see e.g., Tong et al. 2010, 2011); (3) finally, it has been shown to not be a viable attempt to relate magnetars to energy of supernova remnants (see e.g., Allen & Horvath 2004; Ferrario & Wickramasinghe 2006; Vink & Kuiper 2006; Vink 2008) or to the formation of black holes (see e.g., Kasen & Bildsten 2010; Woosley 2010, see however e.g., Patnaude et al. 2009) and of Gamma Ray Bursts (see e.g., Levan et al. 2006; Castro-Tirado et al. 2008; Stefanescu et al. 2008; Bernardini et al. 2009, see however e.g., Goldstein et al. 2011; Rea et al. 2011).

In table 3 we compare and contrast the parameters of selected SGRs and AXPs sources in the magnetar model and in the fast rotating highly magnetized white dwarf model; the larger radius of a white dwarf with respect to the radius of a neutron star of the same mass, $M = 1.4\,M_\odot$, leads to the two models differing on the scale of the mass density, moment of inertia, and rotational energy, which imply a different scale for the surface magnetic fields, leading to a very different physical interpretation of the observations of SGRs and AXPs.

## 4. Observations of Massive Fast Rotating Highly Magnetized White Dwarfs

Some general considerations are appropriate. The white-dwarf model appeals to standard and well-tested aspects of physics and astrophysics. The observation of fast rotating white dwarfs with magnetic fields larger than $10^6$ G all the way up to $10^9$ G has in the mean time been solidly confirmed by observations (see e.g., Angel et al. 1981; Ferrario et al. 1997; Należyty & Madej 2004; Ferrario & Wickramasinghe 2005; Terada et al. 2008c). For a recent and extensive analysis of the magnetic field structure of highly magnetized white dwarfs, see Külebi et al. (2009), and for a catalog[1] and also Kepler et al. (2010).

A specific example is the highly magnetized white dwarf AE Aquarii. The rotational period of this fast rotating magnetized white dwarf, obtained from the sinusoidal pulsed flux in soft X-rays $< 4$ keV (see e.g., Eracleous et al. 1991; Choi & Dotani 2006), has been established to be $P = 33$ s; it is spinning down at a rate of $\dot{P} = 5.64 \times 10^{-14}$. The mass of the white dwarf is $\sim M_\odot$ (de Jager et al. 1994), and the observed temperature is $kT \sim 0.5$ keV. In addition to the soft X-ray component, hard X-ray pulsations were observed with the Japanese satellite Suzaku in 2005 October–November and 2006 October. The luminosity of AE Aquarii, $\sim 10^{31}$ erg s$^{-1}$, accounts for 0.09% of the spin-down energy of the white dwarf (see Terada et al. 2008c for details); the infereed magnetic field of the source is $B \sim 10^8$ G (Ikhsanov & Beskrovnaya 2008).

This white dwarf is one of the most powerful particle accelerators; there has been at least one event of detected TeV emission from this source during its optical flaring activity monitored between 1988 and 1992 (see e.g., Meintjes et al. 1992, 1993; de Jager et al. 1994; Ikhsanov & Biermann 2006; Ikhsanov & Beskrovnaya 2008; Kashiyama et al. 2011). In addition, it shows burst activity in X-rays (Terada et al. 2008c). Although AE Aquarii is a binary system with an orbital period of $\sim 9.88$ hr (see e.g., de Jager et al. 1994), very likely the power due to the accretion of matter is inhibited by the fast rotation of the white dwarf (e.g., Itoh et al. 2006; Terada et al. 2008c).

**Table 1.** Comparison of the observational properties of SGR 0418+5729 and the white dwarf AE Aquarii.*

| | SGR 0418+5729 | AE Aquarii |
|---|---|---|
| $P$ (s) | 9.08 | 33.08 |
| $\dot{P}$ ($10^{-14}$) | $<0.6$ | 5.64 |
| *Age* (Myr) | 24 | 9.4 |
| $L_X$ (erg s$^{-1}$) | $6.2 \times 10^{31}$ | $\sim 10^{31}$ |
| $kT$ (keV) | 0.67 | 0.5 |
| $B$ (G) | $< 7.45 \times 10^8$ | $\sim 10^8$ |
| Pulsed fraction | 0.3 | $\sim$0.2–0.3 |

* For SGR 0418+5729 $P$, $\dot{P}$, and $L_X$ have been taken from Rea et al. (2010). The characteristic age is given by $Age = P/(2\dot{P})$, and the surface magnetic field, $B$, is given by equation (4). The pulsed fraction of SGR 0418+5729 is taken from Esposito et al. (2010) and the one of the white dwarf AE Aquarii from Eracleous et al. (1991) and Choi and Dotani (2006).

Many of the observed physical properties of this white dwarf are very similar to the recently discovered SGR 0418+5729, as we explicitly show in table 1.

Although very fast, AE Aquarii is not the fastest white dwarf observed. The rotational period obtained from the pulsed X-ray emission of RX J0648.0−4418, the white dwarf in the binary system HD 49798/RX J0648.0−4418, is $P = 13.2$ s (Israel et al. 1997). This white dwarf is one of the most massive white dwarfs with $M = 1.28 \pm 0.05\,M_\odot$ (see Mereghetti et al. 2009, for details). Other very massive and highly magnetized white dwarfs are: RE J0317−853 with $M \sim 1.35\,M_\odot$ and $B \sim (1.7\text{–}6.6) \times 10^8$ G (see e.g., Barstow et al. 1995; Külebi et al. 2010b); PG 1658+441 with $M \sim 1.31\,M_\odot$ and $B \sim 2.3 \times 10^6$ G (see e.g., Liebert et al. 1983; Schmidt et al. 1992); and PG 1031+234 with the highest magnetic field $\sim 10^9$ G (see e.g., Schmidt et al. 1986; Külebi et al. 2009). It is interesting to note that the most highly magnetized white dwarfs are massive as well as isolated (see e.g., Należyty & Madej 2004, for details).

## 5. Rotational Instability of White Dwarfs

In order to be stable against the secular instability of the MacClaurin versus Jacobi ellipsoid (Ferrari & Ruffini 1969), the minimal period of a white dwarf with the parameters discussed here is $P_{\rm crit} \sim 0.94$ s. For $P \lesssim P_{\rm crit}$, we would expect very significant emission of gravitational waves due to the transition from the triaxial Jacobi ellipsoids to the axially symmetric MacClaurin ellipsoids. This is well in agreement, and explains the observed long periods of SGRs and AXPs $\gtrsim 2$ s (see figure 8). In the specific case of the source 1E 2259+586, assuming that the supernova remnant G109.1−1.0 and 1E 2259+586 are coeval, we obtain the initial rotational period of the white dwarf in the range $0.94\,{\rm s} < P_0 < 6.8$ s, where the lower limit is given by the bifurcation point between the MacClaurin spheroids and the Jacobi ellipsoids (see e.g., Ferrari & Ruffini 1969); the upper limit is obtained for a constant value of $\dot{P}$. Describing today

---

[1] ⟨http://vizier.cfa.harvard.edu/viz-bin/Cat?J/A%2bA/506/1341⟩.

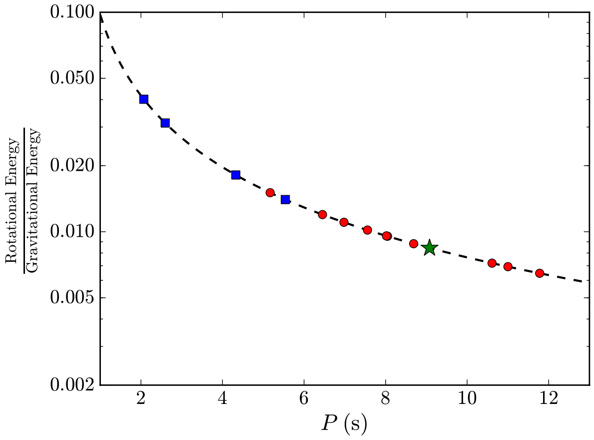

**Fig. 8.** Ratio between the rotational energy and the gravitational energy of a MacClaurin spheroid of $M = 1.4\,M_\odot$ and $R = 10^3$ km as a function of its rotational period, $P$. The rotational period between 2 and 12 s appears to be very appropriate for fast rotating white dwarfs. Fast rotating neutron stars present a much shorter period in the millisecond region. We show on the curve the position of all known SGRs and AXPs. The green star corresponds to SGR 0418+5729. The blue squares are the only four sources that satisfy $L_\mathrm{X} < \dot{E}_\mathrm{rot}$ when described as rotation-powered neutron stars (see figure 6 for details).

1E 2259+586 by a MacClaurin spheroid, we obtain the ratio between the rotational energy and the gravitational energy, $E_\mathrm{rot}/\left|E_\mathrm{grav}\right| \sim 0.011$ (see figure 8), well below the secular instability $\sim 0.14$ and the dynamical instability, $\sim 0.25$ (see Chandrasekhar 1969; Shapiro & Teukolsky 1983, for details).

The above considerations add interest to the recent theoretical analysis of white dwarfs, while taking into account nuclear, weak and electromagnetic interactions within a general-relativistic treatment (Rotondo et al. 2011b). A specially relevant result has recently been obtained (Boshkayev et al. 2011a, 2011b, 2012) by analyzing a white dwarf endowed with mass, angular momentum, and quadrupole moment within the Hartle-Thorne formalism (Hartle 1967; Hartle & Thorne 1968). The rotating white dwarfs have been studied for the new equation of state given by Rotondo et al. (2011a) used to construct the non-rotating configurations by Rotondo et al. (2011b). The critical rotational periods for the onset of the axisymmetric, the mass-shedding and the inverse $\beta$-decay instabilities have been studied in detail. The exact value of the critical period of a white dwarf depends upon the central density of the configuration; rotationally stable white dwarfs exist for rotational periods of $P > P^\mathrm{WD}_\mathrm{min} \sim 0.3$ s. The shortest values are obtained for configurations supported by rotation with critical masses larger than the classical Chandrasekhar limit for non-rotating white dwarfs all the way up to $M_\mathrm{max}$ is $\sim 1.5\,M_\odot$ (see Boshkayev et al. 2011a, 2011b, 2012 for details).

Consequently, also the fastest sources e.g., 1E 1547.0−5408 with $P = 2.07$ s, SGR 1627−41 with $P = 2.59$ s, and PSR J1622−4950 with $P = 4.33$ s, can be safely described as massive fast-rotating white dwarfs, as shown in figure 2.

## 6. Glitches and Outbursts in SGRs and AXPs

The energetic of the observed bursts within the white-dwarf model of SGRs and AXPs can be fully explained by the observed change of period, $\Delta P < 0$ (glitches). In the case of the famous event of 1979 March 5 in the SGR 0526−66 ($P = 8.05$ s), a fractional change in the period of the white dwarf, $\Delta P/P \sim -10^{-4}$ (see figure 4), would be sufficient to explain the energetics of $\sim 3.6 \times 10^{44}$ erg (Mereghetti 2008). Unfortunately, such a change of period could not be observed at that time (see e.g., Mazets et al. 1979), lacking observations of the source prior to the event. Instead, in the case of the flares of 1E 2259+586 on 2002 June ($P = 6.98$ s) and of 1E 1048.1−5937 ($P = 6.45$ s) on 2007 March, observational data are available. For 1E 2259+586, using the observed fractional change of period, $\Delta P/P \sim -4 \times 10^{-6}$ (Woods et al. 2004) (see also figure 1), we obtain within the white-dwarf model a change in the rotational energy, $\left|\Delta E^\mathrm{WD}_\mathrm{rot}\right| \sim 1.7 \times 10^{43}$ erg, to be compared with the measured energy released during the event, $\sim 3 \times 10^{41}$ erg. For the glitch on the 2007 March 26 in 1E 1048.1−5937 with the observed $\Delta P/P \sim -1.63 \times 10^{-5}$, we obtain $\left|\Delta E^\mathrm{WD}_\mathrm{rot}\right| \sim 7.73 \times 10^{43}$ erg, which is strikingly in agreement (and safely superior) with the observed energy released in the event, $4.3 \times 10^{42}$ erg (see e.g., Dib et al. 2009). In the case of super giant flares, there is no clear observational evidence of their association to glitches. However, changes in the moment of inertia of the white-dwarf originating fractional changes in period of order $\Delta P/P \sim -(10^{-5}$–$10^{-3})$ (see figure 4) could explain their large energetics, ranging from $10^{44}$ erg all the way up to $10^{47}$ erg (see e.g., Mereghetti 2008). For the giant flare of SGR 1806−20 on 2004 December 27 (see e.g., Borkowski et al. 2004; Hurley et al. 2005) with an observed energy of $\sim 10^{46}$ erg, there is a gap in the timing data of the source between 2004 October and 2005 March (see Mereghetti et al. 2005; Tiengo et al. 2005). The observed rotational period of SGR 1806−20 after 2005 March is not consistent with the expected rotational period obtained from the spin-down rate, $\dot{P} = 5.5 \times 10^{-10}$; instead, this is consistent with $\dot{P} = 1.8 \times 10^{-10}$. The change in the rotational period has been attributed to "global reconfigurations of the neutron-star magnetosphere" (see e.g., Tiengo et al. 2005). Within the white-dwarf model, such burst activity is consistent with a glitch with a fractional change of period $\sim -3 \times 10^{-3}$. All of the above discussion is summarized in table 2 and figures 1 and 4.

In all of the above cases, the gain in the rotational energy in the glitch is much larger than the energy observed in the flaring activities following the glitches. This means that there is ample room to explain these glitch-outburst events in a large range of recovery fractions, $Q$. It appears to be appropriate to systematically monitor the $Q$ factors for all glitches in SGRs and AXPs.

It is interesting that PSR J1846−0258, $P = 0.3$ s, experienced in 2006 June a radiative event with an estimated isotropic energy of $\sim (3.8$–$4.8) \times 10^{41}$ erg (Kumar & Safi-Harb 2008). Assuming that such an event was triggered by a glitch in the neutron star, one obtains an associated fractional change of period $\Delta P/P \sim -(1.73$–$2.2) \times 10^{-6}$, as given by equation (14). Indeed, as shown by Kuiprt and Hermsen (2009), the outburst emission was accompanied by a large glitch, $\Delta P/P \sim -(2.0$–$4.4) \times 10^{-6}$, in perfect agreement with

**Table 2.** Glitches and Outbursts of some SGRs and AXPs within the white dwarf model.

| | SGR 0526−66 | 1E 2259+586 | 1E 1048.1−5937 | SGR 1806−20 |
|---|---|---|---|---|
| Date | 1979 March | 2002 June | 2007 | 2004 March December |
| Observed energy (erg) | $3.6 \times 10^{44}$ | $3 \times 10^{41}$ | $4.2 \times 10^{42}$ | $\sim 10^{46}$ |
| $\lvert \Delta P \rvert / P$ | $1.2 \times 10^{-4}$ (predicted) | $4.24 \times 10^{-6}$ (observed) | $1.63 \times 10^{-5}$ (observed) | $3 \times 10^{-3}$ (predicted) |
| Predicted energy (erg) | $3.6 \times 10^{44}$ | $1.7 \times 10^{43}$ | $7.7 \times 10^{43}$ | $\sim 10^{46}$ |

* The predicted values of $|\Delta P|/P$ are calculated with equation (9) assuming $\left|\Delta E_{\rm rot}^{\rm WD}\right|$ equals the observed energy of the burst event. The predicted values of the energy released in the burst event is calculated with equation (9) using the observed fractional change of rotational period $|\Delta P|/P$.

the theoretical prediction given by the loss of rotational power after the spin-up of the neutron star without advocating any magnetar phenomena. This fact reinforces the idea that PSR J1846−0258 is not a magnetar, but an ordinary rotationally powered neutron star, also in line with the recent suggestions by Kuiprt and Hermsen (2009) and Rea et al. (2010).

## 7. Magnetosphere Emission from White Dwarfs

We return now to the structure of the magnetosphere of the white-dwarf model for SGRs and AXPs. In order to obtain an agreement between the observed X-ray luminosity and the X-ray spectral distribution, it is necessary that only a part of the surface of the white dwarf has to be an X-ray emitter.

We can define a dimensionless filling factor,

$$\mathcal{R} = \frac{L_{\rm X}}{4\pi R^2 \sigma T^4}, \tag{15}$$

where $\sigma$ is the Stefan-Boltzmann constant and $T$ is the temperature of the source. This factor gives an estimate of the effective area of X-ray emission, and consequently information about the structure of the magnetic field from the surface of the object. It is interesting that this factor for the white dwarf is in the range of $10^{-6}$–$10^{-5}$ (see table 3), quite similar to that of the Sun, $\mathcal{R}_\odot = L_\odot^{\rm X}/(4\pi R_\odot^2 \sigma T_\odot^4) \approx (7.03 \times 10^{-8}$–$1.2 \times 10^{-6})$, in the minimum $L_\odot^{\rm X} = 2.7 \times 10^{26}\,{\rm erg\,s^{-1}}$ and in the maximum $L_\odot^{\rm X} = 4.7 \times 10^{27}\,{\rm erg\,s^{-1}}$ of solar activity, respectively (see e.g., Peres et al. 2000; Judge et al. 2003). This should be expected by the general argument involving the conservation of flux in the transition from a highly magnetized main-sequence star to a white dwarf. A magnetic field on the order of $\sim 10^9\,$G on the surface of these white dwarfs must clearly have a filamentary structure in the range of $\mathcal{R} \sim 10^{-6}$–$10^{-5}$.

In the specific case of SGR 0418+572, such an $\mathcal{R}$ factor is $\sim 10^{-9}$, which is of the same order as that of the white dwarf AE Aquarii, as can be seen from table 1 by comparing the values of $L_{\rm X}$ and $kT$, which are the quantities involved in equation (15).

At times, the presence of an $\mathcal{R}$ factor has been interpreted as originating from a spot-like radial emission of the radiation from the surface of the white dwarf. If one were to assume that the radiation occurs radially beamed and occurring just from the surface either of the neutron star or the white dwarf, spot radiation would lead to a pulsed fraction of the emission flux, $\sqrt{1/n \sum_{i=1}^{n} (y_i - \bar{y})^2}/\bar{y} \sim 1$, where $n$ is the number of phase bins per cycle, $y_i$ is the number of counts in the $i$th phase bin and $\bar{y}$ is the mean number of counts in the cycle (see e.g., Esposito et al. 2010, for details about this definition). This problem, which seems to be in contradiction with the observations of pulsed fractions $< 1$ in SGRs and AXPs (see e.g., Esposito et al. 2010), would be equally severe for both neutron stars and white dwarfs (see e.g., table 1).

It is appropriate to recall that all of the SGRs and AXPs within a rotating white-dwarf model have magnetic fields in the range of $10^8\,{\rm G} \lesssim B \lesssim 10^{11}\,{\rm G}$ (see table 3). It is quite natural to assume that the X-ray emission should be linked to the presence of the magnetic field. It is worth noting that the modeling of the physics and the geometrical structure of the magnetic field and of the magnetospheres is a most active field of current research. As shown by Romani and Watters (2010), the morphology of the pulses as well as of the light curves strongly depend on many model parameters, e.g., special and general relativistic effects, the viewing angle, the magnetic moment-spin axis angle, the spin axis-line of sight angle, the specific location of the emission zone, and the adopted magnetospheric model including possible corrections due to deviations from a pure dipolar structure.

From the broad sinusoidal pulsed flux of SGRs/AXPs (see e.g., Mereghetti 2008), we know that the pulsed fraction is less than one, and that the luminosity differs remarkably from a spiky one. We then find it natural to assume that the emission comes from an area covering the white-dwarf surface with a very marked filamentary structure. Similar considerations for neutron-star magnetospheres have been purported e.g., by Michel and Dessler (1981); Michel (1983), giving evidence of magnetospheric activity from the pole all the way up to the equator; also see the most interesting case of pair-production activities in the magnetosphere of a rotating white dwarf, considered for the transient radio source GCRT J1745−3009 by Zhang and Gil (2005). Moreover, such structures are regularly observed in the Sun and in the Earth Aurora. Explicit sinusoidal pulsed flux in soft X-rays ($< 4\,$keV) has been observed in AE Aquarii (see e.g., Eracleous et al. 1991; Choi & Dotani 2006); and also see figure 6 in Mereghetti et al. (2011) for similar sinusoidal pulsed emission of the white dwarf RXJ 0648.0−4418 with a rotational period of $P = 13.2\,$s. For all of the above sources, a filamentary structure of the magnetic field is clearly expected.

We do not discuss here the issue of the spectral features within the white-dwarf model. The aim of this article is just to point out that all of these problems can be addressed with merit, starting from the rotational energy of a rotating white dwarf, rather than the magnetic of energy of a magnetar. The spectrum of the persistent emission of SGRs and AXPs for

**Table 3.** SGRs and AXPs as white dwarfs and neutron stars.

| | SGR 1806−20 | SGR 0526−66 | SGR 1900+14 | SGR 0418+5729 |
|---|---|---|---|---|
| $P$ (s) | 7.56 | 8.05 | 5.17 | 9.08 |
| $\dot{P}$ ($10^{-11}$) | 54.9 | 6.5 | 7.78 | $<6.0 \times 10^{-4}$ |
| *Age* (kyr) | 2.22 | 1.97 | 1.05 | $24.0 \times 10^{3}$ |
| $L_{\mathrm{X}}$ ($10^{35}\,\mathrm{erg\,s^{-1}}$) | 1.50 | 2.1 | 1.8 | $6.2 \times 10^{-4}$ |
| $kT$ (keV) | 0.65 | 0.53 | 0.43 | 0.67 |
| $\dot{E}_{\mathrm{rot}}^{\mathrm{WD}}$ ($10^{37}\,\mathrm{erg\,s^{-1}}$) | 50.24 | 4.92 | 22.24 | $3.2 \times 10^{-4}$ |
| $B_{\mathrm{WD}}$ ($10^{9}\,\mathrm{G}$) | 206.10 | 73.18 | 64.16 | 0.75 |
| $\mathcal{R}_{\mathrm{WD}}$ ($10^{-5}$) | 0.65 | 2.06 | 4.07 | $2.4 \times 10^{-4}$ |
| $\dot{E}_{\mathrm{rot}}^{\mathrm{NS}}$ ($10^{35}\,\mathrm{erg\,s^{-1}}$) | 0.502 | 0.05 | 0.22 | $3.2 \times 10^{-6}$ |
| $B_{\mathrm{NS}}$ ($10^{14}\,\mathrm{G}$) | 20.61 | 7.32 | 6.42 | 0.075 |
| $\mathcal{R}_{\mathrm{NS}}$ | 0.065 | 0.21 | 0.41 | $2.4 \times 10^{-5}$ |
| | 1E 1547−54 | 1E 1048−59 | 1E 1841−045 | 1E 2259+586 |
| $P$ (s) | 2.07 | 6.45 | 11.78 | 6.98 |
| $\dot{P}$ ($10^{-11}$) | 2.32 | 2.70 | 4.15 | 0.048 |
| *Age* (kyr) | 1.42 | 3.79 | 4.50 | 228.74 |
| $L_{\mathrm{X}}$ ($10^{35}\,\mathrm{erg\,s^{-1}}$) | 0.031 | 0.054 | 2.2 | 0.19 |
| $kT$ (keV) | 0.43 | 0.62 | 0.38 | 0.41 |
| $\dot{E}_{\mathrm{rot}}^{\mathrm{WD}}$ ($10^{37}\,\mathrm{erg\,s^{-1}}$) | 103.29 | 3.97 | 1.01 | 0.056 |
| $B_{\mathrm{WD}}$ ($10^{9}\,\mathrm{G}$) | 22.17 | 42.22 | 70.71 | 5.88 |
| $\mathcal{R}_{\mathrm{WD}}$ ($10^{-5}$) | 0.07 | 0.028 | 8.16 | 0.49 |
| $\dot{E}_{\mathrm{rot}}^{\mathrm{NS}}$ ($10^{35}\,\mathrm{erg\,s^{-1}}$) | 1.03 | 0.040 | 0.010 | $5.62 \times 10^{-4}$ |
| $B_{\mathrm{NS}}$ ($10^{14}\,\mathrm{G}$) | 2.22 | 4.22 | 7.07 | 0.59 |
| $\mathcal{R}_{\mathrm{NS}}$ | 0.007 | 0.0028 | 0.82 | 0.049 |

* The rotational period $P$, the spin-down rate $\dot{P}$, the X-ray luminosity $L_{\mathrm{X}}$ and the temperature $T$ have been taken from the McGill online catalog at www.physics.mcgill.ca/∼pulsar/magnetar/main.html. The characteristic age is given by $Age = P/(2\dot{P})$, the loss of rotational energy $\dot{E}_{\mathrm{rot}}$ is given by equations (5) and (1) and the surface magnetic field is given by equations (4) and (13) for white dwarfs and neutron stars respectively. The filling factor $\mathcal{R}$ is given by equation (15).

energies of $<10\,\mathrm{keV}$ is well fitted either by the superposition of a blackbody and a high-energy tail, or by a single blackbody or a double blackbody (see e.g., Mereghetti 2008). Such a spectral feature is clearly already evidenced for rotating white dwarfs; following the work of Terada et al. (2008c). In addition to the thermal modulation in the softer X-ray band, spiky pulsations like the ones of pulsars have been observed by the Suzaku satellite in the hard X-ray band of over 4 keV in the white dwarf AE Aquarii. The X-ray spectrum requires an additional hard X-ray component on the well-known thermal emissions with temperatures of 0.5 and 2.9 keV. Combined with results from timing analyses, spectral shapes and flux, it was there concluded that the hard X-ray pulsations should have a non-thermal origin, for example, possible Synchrotron emission with sub MeV electrons. The claim of the first discovery of a white dwarf equivalent to a neutron star pulsar was there made. In view of the possible evidence of very high energy emission in the TeV region observed during the optical flares of AE Aquarii (see e.g., de Jager et al. 1994; Ikhsanov & Biermann 2006; Ikhsanov & Beskrovnaya 2008; Terada et al. 2008c, 2008d; Kashiyama et al. 2011, and references therein), it would be important to have observations by INTEGRAL and Fermi of a rotating magnetized white dwarf in the 20–200 keV band in order to establish further analogies between fast rotating highly magnetized white dwarfs and magnetar candidates.

More specifically, for the source SGR 0418+5729 and its interpretation as a white dwarf, a crucial result has recently been obtained by Durant, Kargaltsev, and Povlov (2011). We first recall the observed range of temperatures of massive isolated white dwarfs: $1.14 \times 10^{4}\,\mathrm{K} \leq T \leq 5.52 \times 10^{4}\,\mathrm{K}$; (see table 1 in Ferrario et al. 2005). From the broad band Hubble Space Telescope imaging of the field of SGR 0418+5729, the upper limits of the black body surface temperature, $T < 3.14 \times 10^{4}\,\mathrm{K}$ and $T < 1.18 \times 10^{4}\,\mathrm{K}$ in the *F110W* and *F606W* filters, can be established for a radius of $R = 10^{8}\,\mathrm{cm}$. In this respect it is also worth recalling the optical observations of AXP 4U 0142+61 of Hulleman, van Kerkwijk, and Kullkarni (2000). The photometric results of the field of 4U 0142+61 at the 60-inch telescope on Palomar Mountain are in agreement with a $1.3\,M_{\odot}$ white dwarf with a surface temperature of $\sim 4 \times 10^{5}\,\mathrm{K}$ (see Hulleman et al. 2000, for details). These results are, therefore, fully consistent with the SGR/AXP white-dwarf model, and follow-on missions of Hubble and VLT are strongly recommended.

## 8. The Connection with Supernova Remnants

We would like to address the special issue of the supernova remnants energetics and their association with SGRs and AXPs. A firm association between SGRs/AXPs and supernovae has been purported by Gaensler et al. (2001) in the cases of 1E 1841−045 (SNR G27.4+0.0, Kes 73), AX J1845.0−0258 (SNR G29.6+0.1), and 1E 2259+586 (SNR G109.1−1.0, CTB 109). Also see Gelfand and Gaensler (2007) for the possible association of 1E 1547.0−5408 (SNR G327.24−0.13). What is of interest for us here is the special issue of the energetics of the supernova remnant and the presence of an SGR or an AXP.

Paczyński (1990), in the case of AXP 1E 2259+586, attempted to explain the supernova remnant by assuming the merger of a binary system of an ordinary white dwarf of mass $\sim$ (0.7–1) $M_{\odot}$, based on models by Iben and Tutukov (1984) and Paczyński (1985), leading both to the formation of a fast rotating white dwarf, and to the supernova remnant. Recent simulations of white dwarf-white dwarf mergers (see e.g., Pakmor et al. 2010) show that mergers of (0.8–0.9 $M_{\odot}$) produce supernova events, generally not very efficient energetically, well below the observed explosion energy of $\sim 7.4 \times 10^{50}$ erg of the supernova remnant G109.1−1.0, associated with 1E 2259+586 (see e.g., Sasaki et al. 2004).

In the intervening years much more has been understood about the process of gravitational collapse and the composition of the material surrounding neutron stars and black holes, both from pulsar observations and Gamma Ray Bursts. Fascinating evidence for the presence of planets around pulsars in supernova remnants has been established (see e.g., Konacki et al. 1999; Hansen 2002; Konacki & Wolszczan 2003). Similarly, the presence of a many body process of gravitational collapse has been evidenced for Gamma Ray Bursts (see e.g., Ruffini 2009).

In view of the above, we advance a possible scenario in which the SGRs/AXPs and the supernova remnant originate from a very close binary system composed of a white dwarf and a companion late evolved star, close to the process of gravitational collapse. The collapse of the companion star, either to a neutron star or to a black hole, leads to mass loss that can unbind the original binary system. Three possible cases can occur (see e.g., Ruffini 1973): if the loss of mass in the supernova explosion is $M_{\rm loss} < M/2$, $M$ being the total mass of the binary, the system remains bound; (2) if $M_{\rm loss} \sim M/2$, then the system becomes unbound and the white dwarf is expelled at nearly orbital motion velocity; and (3) if $M_{\rm loss} \gg M/2$ the white dwarf is kicked out with very high runaway velocities. Only in the first case will the object lie at the center of the supernova remnant. For a review on the evolution of binary systems see Stairs (2004), and for a detailed treatment of the problem of runaway velocities from supernova explosions see Tauris and Bailes (1996) and Tauris and Takens (1998).

The white dwarf in this picture does not participate in either the gravitational collapse or in the formation of the supernova remnant; it can have a period, and the lifetime is determined essentially by prior evolution of the binary system. This explains the disagreement between the age of the supernova remnant and the characteristic age of the SGR/AXP when inferred by a neutron-star model. In the case of large kick velocities, the runaway white dwarf can collide with the surrounding material in the supernova remnant, and very likely also with planets. Such collisions may well casue changes in the moment of inertia of the white dwarf, and consequently in its rotational period, leading to glitches and burst activity.

In the above context it is appropriate to recall the pioneering work of Katz (1996) on explaining the super-Eddington luminosities in the flaring episodes of SGRs and AXPs as originating in the accretion process of planetary fragments, particularly the important role of the magnetic confinement of an $e^{+}e^{-}$ pair plasma. The model explains the observed self-absorbed thermal spectrum of flares and their loose dependence on their luminosity. Katz (1996) has shown that the infall of planetary fragments may lead to a continuous injection of energy to the magnetosphere, which leads to magnetic confinement of the source if the magnetic field satisfies

$$B > \sqrt{\frac{2L}{cR^2}} = 2.6 \times 10^{7} \sqrt{\frac{L_{41}}{R_8^2}}\ {\rm G}, \tag{16}$$

where $L_{41}$ is the luminosity in units of $10^{41}$ erg s$^{-1}$ and $R_8$ is the radius of the source in units of $10^{8}$ cm.

In the case when the radiation is not being continuously resupplied, but is initially contained within the volume of $\sim 4\pi R^3/3$, the minimum magnetic field for confinement is given by

$$B > \sqrt{\frac{6L\tau}{R^3}} = 2.45 \times 10^{8} \sqrt{\frac{L_{41}\tau_{0.1}}{R_8^3}}\ {\rm G}, \tag{17}$$

where $\tau_{0.1}$ is the time $\tau$ during which the source is radiating at a luminosity $L$, in units of 0.1 s. The fiducial values for $L$ and for $\tau$ were chosen here to be typical of the bursting activity of SGRs/AXPs (see e.g., Mereghetti 2008). The above two bounds for the magnetic field are indeed in line with the surface magnetic fields obtained in this paper; see figure 3 for details. Thus, the super-Eddington luminosities observed in the outbursts can be well explained within the white-dwarf model, and there is no need to introduce the huge magnetic fields of the magnetar model (Paczynski 1992; Thompson & Duncan 1995).

## 9. On the Fiducial Neutron Star and White Dwarf Parameters in Light of Recent Theoretical Progress

Before concluding, we would like to introduce a word of caution concerning the fiducial values adopted for both the neutron star and the white dwarf in the above Sections. In the intervening years, much more has been learned concerning the equation of state, and on a more complex description of the structure parameters of both white dwarfs and neutron stars.

The equations of equilibrium of neutron stars, traditionally based on the Tolman-Oppenheimer-Volkoff equations, have been superseded by an alternative formulation based on the general-relativistic Thomas-Fermi conditions of equilibrium within the Einstein–Maxwell equations (Rueda et al. 2011). Correspondingly, the above values of $(I/R^6)^{1/2}$ in equation (3) estimated in the fiducial parameters, leading to equation (13), can in fact acquire values in the range of $0.44 \lesssim (I/R^6)^{1/2}/(I_{\rm f}/R_{\rm f}^6)^{1/2} \lesssim 0.56$, where subscript ‘f’ stands for the fiducial parameter. This range corresponds to the range of masses $0.5 \lesssim M/M_{\odot} \lesssim 2.6$ (Belvedere et al.

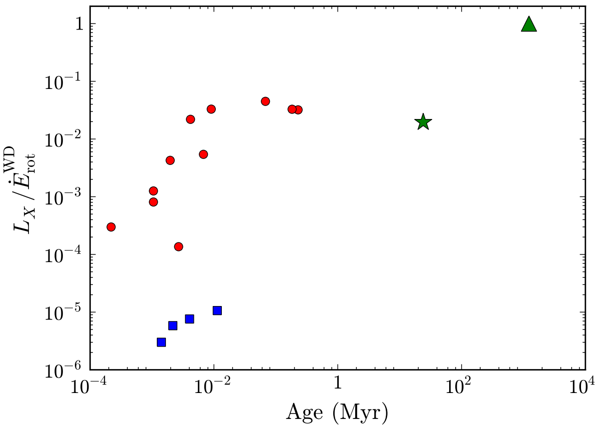

**Fig. 9.** Ratio between the observed X-ray luminosity, $L_{\rm X}$, and the loss of rotational energy, $\dot{E}_{\rm rot}$, describing SGRs and AXPs by rotation-powered white dwarfs. The green star and the green triangle correspond to SGR 0418+5729 using, respectively, the upper and lower limits of $\dot{P}$ given by equation (2). The blue squares are the only four sources that satisfy $L_{\rm X} < \dot{E}_{\rm rot}$ when described as rotation-powered neutron stars (see figure 6 for details).

2011). Correspondingly, the magnetic field is in the range of $0.44 \lesssim B/B_{\rm f}^{\rm NS} \lesssim 0.56$, where $B_{\rm f}^{\rm NS}$ is given by equation (13).

Similar considerations apply for the white dwarf case. General-relativistic white dwarfs taking into account nuclear, weak and electromagnetic interactions have recently been constructed (Rotondo et al. 2011b) following the new equation of state for compressed nuclear matter given by (Rotondo et al. 2011a). The case of rotating white dwarfs in general relativity has been studied by Boshkayev, Rueda, and Ruffini (2011a, 2011b) and Boshkayev et al. (2012). It has been found that white dwarfs can be as fast as $P_{\rm min}^{\rm WD} \sim 0.3$ s and as massive as $M_{\rm max} \sim 1.5\,M_{\odot}$; see section 5 for details. For example, a white dwarf of $M = 1.44\,M_{\odot}$ rotating with period of $P = 3.2$ s will have an equatorial radius of $R_{\rm eq} \sim 3604$ km, a polar radius of $R_{\rm p} \sim 2664$ km, and a moment of inertia $I \sim 2.9 \times 10^{49}\,{\rm g\,cm}^2$. In this case we will have $(I/R^6)^{1/2}/(I_{\rm f}/R_{\rm f}^6)^{1/2} \sim 0.01$, and therefore $B/B_{\rm f}^{\rm WD} \sim 0.01$, where $B_{\rm f}^{\rm WD}$ is given by equation (4).

This issue is particularly relevant to studying the four sources in figure 6. These sources can definitely be explained within a unified framework of rotating white dwarfs with all of the other SGRs and AXPs. In view of the parameters recently obtained, they may also be interpreted as being regular neutron stars with a barely critical magnetic field. For these sources an option remains open for their interpretation as white dwarfs or neutron stars. A more refined analysis will clarify the correctness of the two possible interpretations both, in any case, alternative to the magnetar model.

## 10. Conclusions and Remarks

Recent observations of the source SGR 0418+5729 cast a firm separatrix in comparing and contrasting the two models for SGRs and AXPs based, respectively, on an ultramagnetized neutron star and on a white dwarf. The limit on the magnetic field derived in the case of a neutron star, $B = 7.5 \times 10^{12}$ G, makes it not viable as an explanation based on the magnetar model both from a global energetic point of view and from the undercritical value of the magnetic field. In the white-dwarf model, the picture is fully consistent. It is interesting that the rotational-energy loss appears to approach the value of the observed X-ray luminosity with time (see figure 9) as the magnetospheric activity settles down.

The description of SGR 0418+5729 as a white dwarf predicts the lower limit of the spin-down rate, $\dot{P}$, given by equation (2); the surface magnetic field field is, accordingly to equation (4), constrained by $1.05 \times 10^8\,{\rm G} < B_{\rm SGR\,0418+5729} < 7.47 \times 10^8$ G (see figure 3). The campaign of observations launched by the Fermi and Agile satellites will soon address this issue and settle in the near future this theoretical prediction.

The characteristic changes of the period, $\Delta P/P \sim -(10^{-7}$–$10^{-3})$, and the relating bursting activity of $\sim (10^{41}$–$10^{46})$ erg in SGRs and AXPs can be well explained in term of the rotational energy released after the glitch of the white dwarf. It is also appropriate to recall that fractional changes on scales of $|\Delta P|/P \lesssim 10^{-6}$ are also observed in pulsars, and are routinely expressed in terms of the release of rotational energy of the neutron star, without appealing to any magnetars phenomena; e.g., the glitch/outburst activity experienced in June 2006 by PSR J1846−0258 (see section 6).

In the magnetar model the dipole field is invoked to explain the period and the slowing down of the star, leading to enormous magnetic fields of $\sim 10^{14}$–$10^{15}$ G; see e.g., figure 5. The steady emission as well as the transient activity needs an additional explanation due to the decay of strong multipolar magnetic fields (see e.g., Tong et al. 2011, and references therein). In the case of a model based on quark stars, a second component represented by an accretion disk around the star is also required to explain the energetics, without appealing to ultra-strong magnetic fields (Xu et al. 2006; Tong et al. 2011). In the case of the model based on a rotating magnetized white dwarf, we show that the occurrence of the glitch, the associated sudden shortening of the period, as well as the corresponding gain of rotational energy, can be explained by the release of gravitational energy associated with a sudden contraction and decrease of the moment of inertia of the white dwarfs, consistent with the conservation of angular momentum. The energetics of the steady emission as well as that of the outbursts following the glitch can be simply explained in term of the loss of rotational energy, in view of the moment of inertia of the white dwarfs, much larger than that of neutron stars or quark stars; see equations (8) and (9).

Observations of massive fast rotating highly magnetized white dwarfs by dedicated missions as the one leadered by the X-ray Japanese satellite Suzaku (see e.g., Terada et al. 2008c) has led to a confirmation of the existence of white dwarfs sharing common properties with neutron star pulsars, and hence they are called white-dwarf pulsars. The theoretical interpretation of the high-energy emission from white-dwarf pulsars will certainly help to understand SGR and AXP phenomena (see e.g., Kashiyama et al. 2011).

We have given evidence that all SGRs and AXPs can be interpreted as being rotating white dwarfs, provided that the rotational period satisfies $P > P_{\rm min}^{\rm WD} \sim 0.3$ s.

Concerning the rotational period of SGRs and AXPs, it becomes interesting to confront our general-relativistic results on uniformly rotating white dwarfs (Boshkayev et al. 2011a, 2011b, 2012) with the interesting work of Ostriker and Bodenheimer (1968) on differentially rotating Newtonian white dwarfs.

Regarding magnetized white dwarfs, the coupling between the rotation and Rayleigh-Taylor instabilities arising from chemical separation upon crystallization may have an important role in building the magnetic field of the white dwarf (E. García-Berro et al. in preparation).

We encourage observational campaigns from space and ground for gaining understanding about the most fundamental issue of relativistic astrophysics: identification of the SGRs/AXPs energy source.

We are grateful to the referee for clear formulations of a number of fundamental issues, which we have addressed and solved. We are also thankful for a careful reading of the manuscript and many positive suggestions. We are grafeful for interesting discussions on this subject to E. García-Berro, Jorge Horvath, Jeremiah Ostriker, José Pacheco, Yukikatsu Terada, and Vladimir Usov, as well as to all participants of the IRAP Erasmus Mundus Ph. D. School “From Nuclei to White Dwarfs to Neutron Stars” held at Les Houches, France, 2011 April. Manuel Malheiro acknowledges the hospitality and support of ICRANet, and the Brazilian agency FAPESP (fellowship BPE 2010/0558-1 in the thematic project 2007/03633-3) for the financial support.

*Note added after submission*: We stress here the most recent observations of PSR J1841−0500 with a rotation period of $P = 0.9$ s. This pulsar is located at only $4'$ from the AXP 1E 1841−045,[2] associated with the supernova remnant Kes 73 (see Camilo et al. 2011, for details). Such a discovery represents clear observational support for predicting the binary scenario that we introduced in section 8, leading to an SGR/AXP, a supernova remnant and an additional neutron star or black hole. Deep searches for radio pulsations in the vicinities of other sources, AX J1845.0−0258, associated with SNR G29.6+0.1, 1E 2259+586, associated with SNR G109.1−1.0 (CTB 109), and 1E 1547.0−5408, associated to SNR G327.24−0.13, are highly recommended.

---

[2] The properties of 1E 1841−045 can be found in the fourth column of the lower half of table 3.

## References

Allen, M. P., & Horvath, J. E. 2004, ApJ, 616, 346

Althaus, L. G., García-Berro, E., Isern, J., & Córsico, A. H. 2005, A&A, 441, 689

Althaus, L. G., García-Berro, E., Isern, J., Córsico, A. H., & Rohrmann, R. D. 2007, A&A, 465, 249

Angel, J. R. P., Borra, E. F., & Landstreet, J. D. 1981, ApJS, 45, 457

Barstow, M. A., Jordan, S., O’Donoghue, D., Burleigh, M. R., Napiwotzki, R., & Harrop-Allin, M. K. 1995, MNRAS, 277, 971

Baym, G., & Pines, D. 1971, Ann. Phys., 66, 816

Bell, S. J., & Hewish, A. 1967, Nature, 213, 1214

Belvedere, R., Pugliese, D., Rueda, J. A., Ruffini, R., & Xue, S.-S. 2011, Nucl. Phys. A., 883, 1

Bernardini, F., et al. 2009, A&A, 498, 195

Bethe, H. A. 1972, in Physics, Nobel Lectures Vol. 4 (Amsterdam: Elsevier Pub. Co.), 215

Borkowski, J., Gotz, D., Mereghetti, S., Mowlavi, N., Shaw, S., & Turler, M. 2004, GCN Circ., 2920

Boshkayev, K., Rueda, J. A., & Ruffini, R. 2011a, Int. J. Mod. Phys. E, 20, 136

Boshkayev, K., Rueda, J. A., & Ruffini, R. 2011b, in Proc. From Nuclei to White Dwarfs to Neutron Stars, ed. A. Mezzacappa & R. Ruffini (Singapore: World Scientific) in press

Boshkayev, K., Rueda, J. A., Ruffini, R., & Siutsou, I. 2012, ApJ submitted (arXiv:1204.2070)

Camilo, F., Ransom, S. M., Chatterjee, S., Johnston, S., & Demorest, P. 2012, ApJ, 746, 63

Castro-Tirado, A. J., et al. 2008, Nature, 455, 506

Chandrasekhar, S. 1969, Ellipsoidal Figures of Equilibrium (New Haven, CT: Yale University Press)

Choi, C.-S., & Dotani, T. 2006, ApJ, 646, 1149

Cohen, R. H., Coppi, B., & Treves, A. 1973, ApJ, 179, 269

Coppi, B., Pellat, R., Rosenbluth, M., Rutherford, P., & Galvao, R. 1976, Soviet J. Plasma Phys., 2, 961

Davies, S. R., Wood, K. S., & Coe, M. J. 1990, MNRAS, 245, 268

de Jager, O. C., Meintjes, P. J., O’Donoghue, D., & Robinson, E. L. 1994, MNRAS, 267, 577

Dib, R., Kaspi, V. M., & Gavriil, F. P. 2009, ApJ, 702, 614

Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9

Durant, M., Kargaltsev, O., & Pavlov, G. G. 2011, ApJ, 742, 77

Eracleous, M., Patterson, J., & Halpern, J. 1991, ApJ, 370, 330

Esposito, P., et al. 2010, MNRAS, 405, 1787

Fahlman, G. G., & Gregory, P. C. 1981, Nature, 293, 202

Ferrari, A., & Ruffini, R. 1969, ApJ, 158, L71

Ferrario, L., Vennes, S., Wickramasinghe, D. T., Bailey, J. A., & Christian, D. J. 1997, MNRAS, 292, 205

Ferrario, L., & Wickramasinghe, D. 2006, MNRAS, 367, 1323

Ferrario, L., & Wickramasinghe, D. T. 2005, MNRAS, 356, 615

Ferrario, L., Wickramasinghe, D., Liebert, J., & Williams, K. A. 2005, MNRAS, 361, 1131

Gaensler, B. M, Slane, P. O., Gotthelf, E. V., & Vasisht, G. 2001, ApJ, 559, 963

Garcia-Berro, E., Hernanz, M., Isern, J., & Mochkovitch, R. 1988, Nature, 333, 642

García-Berro, E., et al. 2010, Nature, 465, 194

Gelfand, J. D., & Gaensler, B. M. 2007, ApJ, 667, 1111

Giacconi, R. 2003, in the Nobel Prizes 2002, ed. T. Frängsmyr (Stockholm: Almgvist & Wiksell), 111

Giacconi, R., & Ruffini, R. 1978, Physics and astrophysics of neutron stars and black holes (Amsterdam: North Holland Publishing Co.)

Goldstein, A., et al. 2011, ApJ submitted (arXiv:1101.2458)

Gregory, P. C., & Fahlman, G. G. 1980, Nature, 287, 805

Hansen, B. M. S. 2002, in ASP Conf. Ser., 263, Stellar Collisions, Mergers and their Consequences, ed. M. M. Shara (San Francisco: ASP), 221

Hartle, J. B. 1967, ApJ, 150, 1005

Hartle, J. B., & Thorne, K. S. 1968, ApJ, 153, 807

Hewish, A. 1992, in Nobel Lectures in Physics 1971–1980, ed. S. Lundgvist (Singapore: World Scientific), 174

Hughes, V. A., Harten, R. H., & van den Bergh, S. 1981, ApJ, 246, L127

Hulleman, F., van Kerkwijk, M. H., & Kulkarni, S. R. 2000, Nature, 408, 689

Hurley, K., et al. 2005, Nature, 434, 1098
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Ikhsanov, N. R., & Beskrovnaya, N. G. 2008, arXiv:0809.1169
Ikhsanov, N. R., & Biermann, P. L. 2006, A&A, 445, 305
Israel, G. L., Campana, S., Dall'Osso, S., Muno, M. P., Cummings, J., Perna, R., & Stella, L. 2007, ApJ, 664, 448
Israel, G. L., Stella, L., Angelini, L., White, N. E., Kallman, T. R., Giommi, P., & Treves, A. 1997, ApJ, 474, L53
Itoh, K., Okada, S., Ishida, M., & Kunieda, H. 2006, ApJ, 639, 397
Judge, P. G., Solomon, S. C., & Ayres, T. R. 2003, ApJ, 593, 534
Kasen, D., & Bildsten, L. 2010, ApJ, 717, 245
Kashiyama, K., Ioka, K., & Kawanaka, N. 2011, Phys. Rev. D, 83, 023002
Kaspi, V. M., Gavriil, F. P., Woods, P. M., Jensen, J. B., Roberts, M. S. E., & Chakrabarty, D. 2003, ApJ, 588, L93
Katz, J. I. 1996, ApJ, 463, 305
Kepler, S. O., Kleinman, S. J., Pelisoli, I., Peçanha, V., Diaz, M., Koester, D., Castanheira, B. G., & Nitta, A. 2010, in AIP Conf. Ser., 1273, 17th European White Dwarf Workshop, ed. K. Werner & T. Rauch (New York: AIP), 19
Konacki, M., Lewandowski, W., Wolszczan, A., Doroshenko, O., & Kramer, M. 1999, ApJ, 519, L81
Konacki, M., & Wolszczan, A. 2003, ApJ, 591, L147
Külebi, B., Jordan, S., Euchner, F., Gänsicke, B. T., & Hirsch, H. 2009, A&A, 506, 1341
Külebi, B., Jordan, S., Nelan, E., Bastian, U., & Altmann, M. 2010b, A&A, 524, A36
Kumar, H. S., & Safi-Harb, S. 2008, ApJ, 678, L43
Levan, A. J., Wynn, G. A., Chapman, R., Davies, M. B., King, A. R., Priddey, R. S., & Tanvir, N. R. 2006, MNRAS, 368, L1
Liebert, J., Schmidt, G. D., Green, R. F., Stockman, H. S., & McGraw, J. T. 1983, ApJ, 264, 262
Lyutikov, M., & Gavriil, F. P. 2006, MNRAS, 368, 690
Manchester, R. N., & Taylor, J. H. 1977, Pulsars (San Francisco: W. H. Freeman)
Mazets, E. P., Golentskii, S. V., Ilinskii, V. N., Aptekar, R. L., & Guryan, Iu. A. 1979, Nature, 282, 587
Meintjes, P. J., De Jager, O. C., Raubenheimer, B. C., Brink, C., Nel, H. I., North, A. R., & Visser, B. 1993, in Proc. of 23rd Int. Cosmic Ray Conf., Vol. 1, ed. D. A. Leahy et al. (Singapore: World Scientific), 338
Meintjes, P. J., Raubenheimer, B. C., de Jager, O. C., Brink, C., Nel, H. I., North, A. R., van Urk, G., & Visser, B. 1992, ApJ, 401, 325
Mereghetti, S., Tiengo, A., Esposito, P., La Palombara, N., Israel, G. L., & Stella, L. 2009, Science, 325, 1222
Mereghetti, S. 2008, A&AR, 15, 225
Mereghetti, S., et al. 2005, ApJ, 628, 938
Mereghetti, S., La Palombara, N., Tiengo, A., Pizzolato, F., Esposito, P., Woudt, P. A., Israel, G. L., & Stella, L. 2011, ApJ, 737, 51
Michel, F. C. 1983, ApJ, 266, 188
Michel, F. C., & Dessler, A. J. 1981, ApJ, 251, 654
Morini, M., Robba, N. R., Smith, A., & van der Klis, M. 1988, ApJ, 333, 777
Należyty, M., & Madej, J. 2004, A&A, 420, 507
Ng, C.-Y., et al. 2011, ApJ, 729, 131
Ostriker, J. P., & Bodenheimer, P. 1968, ApJ, 151, 1089
Paczyński, B. 1985, in Cataclysmic Variables and Low-Mass X-ray Binaries, ed. D. Q. Lamb & J. Patterson (Dordrecht: Reidel), 1
Paczyński, B. 1990, ApJ, 365, L9
Paczynski, B. 1992, Acta Astron., 42, 145
Pakmor, R., Kromer, M., Röpke, F. K., Sim, S. A., Ruiter, A. J., & Hillebrandt, W. 2010, Nature, 463, 61
Parker, E. N. 1957, Phys. Rev., 107, 830
Patnaude, D. J., Loeb, A., & Jones, C. 2010, New Astron., 16, 187
Peres, G., Orlando, S., Reale, F., Rosner, R., & Hudson, H. 2000, ApJ, 528, 537
Rea, N., et al. 2010, Science, 330, 944
Rea, N., Jonker, P. G., Nelemans, G., Pons, J. A., Kasliwal, M. M., Kulkarni, S. R., & Wijnands, R. 2011, ApJ, 729, L21
Rea, N., Zane, S., Turolla, R., Lyutikov, M., & Götz, D. 2008, ApJ, 686, 1245
Romani, R. W., & Watters, K. P. 2010, ApJ, 714, 810
Rotondo, M., Rueda, J. A., Ruffini, R., & Xue, S.-S. 2011a, Phys. Rev. C, 83, 045805
Rotondo, M., Rueda, J. A., Ruffini, R., & Xue, S.-S. 2011b, Phys. Rev. D, 84, 084007
Rueda, J. A., Ruffini, R., & Xue, S.-S. 2011, Nucl. Phys. A, 872, 286
Ruffini, R. 1973, in Black Holes, ed. C. Dewitt-Morette & B. S. Dewitt (New York: Gordon & Breach), 451
Ruffini, R. 2009, in Proc. 12th Marcel Grossmann Meeting on General Relativity, ed. T. Damour et al (Singapore: World Scientific)
Sasaki, M., Plucinsky, P. P., Gaetz, T. J., Smith, R. K., Edger, R. J., & Slane, P. O. 2004, ApJ, 617, 322
Schmidt, G. D., Bergeron, P., Liebert, J., & Saffer, R. A. 1992, ApJ, 394, 603
Schmidt, G. D., West, S. C., Liebert, J., Green, R. F., & Stockman, H. S. 1986, ApJ, 309, 218
Shapiro, S. L., & Teukolsky, S. A. 1983, Black holes, white dwarfs, and neutron stars: The physics of compact objects (New York: Wiley-Interscience)
Stairs, I. H. 2004, Science, 304, 547
Stefanescu, A., Kanbach, G., Słowikowska, A., Greiner, J., McBreen, S., & Sala, G. 2008, Nature, 455, 503
Sweet, P. A. 1958, in IAU Symp. No. 6, Electromagnetic Phenomena in Cosmical Physics, ed. B. Lehnert (Cambridge: Cambridge University Press), 123
Tauris, T. M., & Bailes, M. 1996, A&A, 315, 432
Tauris, T. M., & Takens, R. J. 1998, A&A, 330, 1047
Terada, Y. 2008, Astron. Her., 101, 526
Terada, Y., et al. 2008a, PASJ, 60, 387
Terada, Y., et al. 2008b, in AIP Conf. Ser., 1085, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian et al. (New York: AIP), 689
Terada, Y., et al. 2008c, PASJ, 60, 387
Terada, Y., et al. 2008d, Adv. Space Res., 41, 512
Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255
Thompson, C., Lyutikov, M., & Kulkarni, S. R. 2002, ApJ, 574, 332
Tiengo, A., Esposito, P., Mereghetti, S., Rea, N., Stella, L., Israel, G. L., Turolla, R., & Zane, S. 2005, A&A, 440, L63
Tong, H., Song, L. M., & Xu, R. X. 2010, ApJ, 725, L196
Tong, H., & Xu, R. X. 2011, Int. J. Mod. Phys. E, 20, 15
Usov, V. V. 1994, ApJ, 427, 984
Vink, J. 2008, Adv. Space Res., 41, 503
Vink, J., & Kuiper, L. 2006, MNRAS, 370, L14
Woods, P. M., et al. 2004, ApJ, 605, 378
Woosley, S. E. 2010, ApJ, 719, L204
Xu, R. X., Tao, D. J., & Yang, Y. 2006, MNRAS, 373, L85
Zane, S., Rea, N., Turolla, R., & Nobili, L. 2009, MNRAS, 398, 1403
Zhang, B., & Gil, J. 2005, ApJ, 631, L143