An origin for the main pulsation and overtones of SGR1900+14 during the August 27 (1998) superoutburst

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ABSTRACT
The crucial observation on the occurrence of subpulses (overtones) in the Power Spectral Density of the August 27 (1998) event from SGR1900+14, as discovered by BeppoSAX (Feroci et al. 1999), has received no consistent explanation in the context of the competing theories to explain the SGRs phenomenology: the magnetar and accretion-driven models. Based on the ultra-relativistic, ultracompact X-ray binary model introduced in the accompanying paper (Mosquera Cuesta 2004a), I present here a self-consistent explanation for such an striking feature. I suggest that both the fundamental mode and the overtones observed in SGR1900+14 stem from pulsations of a massive white dwarf (WD). The fundamental mode (and likely some of its harmonics) is excited because of the mutual gravitational interaction with its orbital companion (a NS, envisioned here as point mass object) whenever the binary Keplerian orbital frequency is a multiple integer number \( m \) of that mode frequency (Pons et al. 2002).

Besides, a large part of the powerful irradiation from the fireball-like explosion occurring on the NS (after partial accretion of disk material) is absorbed in different regions of the star driving the excitation of other multipoles (Podsiadlowski 1991, 1995), i.e., the overtones (fluid modes of higher frequency). Part of this energy is then reemitted into space from the WD surface or atmosphere. This way, the WD lightcurve carries with it the signature of these pulsations inasmuch the way as it happens with the Sun pulsations in Helioseismology. It is shown that our theoretical prediction on the pulsation spectrum agrees quite well with the one found by BeppoSAX (Feroci et al. 1999). A feature confirmed by numerical simulations (Montgomery & Winget 2000).

Key words: Binaries: close — stars: individual (SGR 1900+14) — stars: neutron — stars: white dwarfs — stars: oscillations — gamma-rays: theory — relativity

1 THE AUGUST 27 (1998) EVENT AND MAGNETAR MODEL: CONCORDANCE OR CRISIS

The lightcurve of the spectacular superoutburst from SGR 1900+14 in August 27, 1998 exhibited a stable pulsation with period 5.16s (Hurley 1999a,b,c; Murakami et al. 1999; Mazets et al. 1999; Feroci et al. 1999). Since the modulation frequency is in the range of the other three SGRs studied before, Kouveliotou et al. (1999) and Hurley et al. (1999a,b,c) concluded that the observations provide strong support to the Duncan & Thompson (1992); Thompson & Duncan (1995,1996) magnetar model for SGRs. They claimed that the observed spindown rate of the pulse period, \( \dot{P} = 1.1 \times 10^{-10} \text{ss}^{-1} \), may be explained by emission of dipolar radiation from an NS endowed with a very strong magnetic field \( B \sim (2 - 8) \times 10^{14} \text{G} \), a characteristic magnetic field strength inferred also from the spin down of the pulse period \( P = 7.47 \text{s} \) of SGR 1806-20 (Kouveliotou et al. 1998).

Despite the rough agreement between the SGR1900+14 on August 27, 1998 observations and the theoretical prediction of the magnetar picture, problems for this model came together with that apparent success. On the one hand, it is clear that there is an overall consistency between the observations and the magnetar model. However, it is also clear that the simple “giant dipole” dynamics is not unique in explaining the spindown history of the objects, and in fact several problems with that picture are already present when dealing with ordinary, low-field pulsar cousins. Among them we can quote the values of the few measured braking indexes (which do require modifications from the canonical dipole spindown model) and the mismatch between characteristic and dynamical-historical ages in the case of some PSR-SN associations. Actually, the presence of ordinary pulsars in the high-\( P \), high-\( \dot{P} \) “magnetar” region remains puzzling (Manchester 2000), and an interpretation of the SGR-AXPs in terms of high (but sub-Schwinger) fields is in principle possible (Allen & Horvath 2000).

On the other hand, it seems that a single population can not account...
for both ordinary and magnetar objects (Regimbau & de Freitas Pacheco 2001).

The event GRB980827 was also detected by BeppoSAX (Feroci et al. 1999). These observations led to the discovery of an extremely regular interpulse set in the X-ray data of GRB980827 event from SGR 1900+14 (see Fig.1). The interpulses appear separated in time \( \approx 1 \text{s} \) in between, with no lag. This behavior, Feroci et al. (1999) advanced, is unexpected and quite difficult to explain in the magnetar framework. According to the magnetar model for SGRs, global seismic oscillations (Duncan 1998), pure shear deformation-induced toroidal modes (standards labelled as \( T_\nu \)) with no radial components, i.e., \( n = 0 \) overtones, are expected to be produced in association with the onset of a new recurrence of a “soft” \( \gamma \)-ray repeater. According to Duncan (1998); “... these toroidal modes are easy to excite via starquakes because the restoring force is determined uniquely by the weak Coulomb forces of the crustal ions. However, overtones are not allowed because that would require far too much energy so as to allow for the extremely short period (\( \leq 1 \text{ms}, \) or lower) NS oscillations to be excited”. An energy that the crust cracking mechanism cannot provide (de Freitas Pacheco 1998).

In overall, the simplest and neatest interpretation of that observations is that the subpulses in the lightcurve (Power Spectral Density) of the burst from GRB980827 are overtones of the fundamental frequency \( f_0 = 0.194 \text{Hz} \) (Feroci et al. 1999). As shown below, we may be actually detecting the whole WD pulsation spectrum, up to 19 harmonics (Feroci et al. 1999). The importance of having a large part of the pulsational spectrum of the object can not be overstated. The main purpose of this Letter is to address this issue. We show that a self-consistent interpretation for the fundamental mode of pulsation and the harmonics discovered by Feroci et al. (1999) could be constructed invoking the excitation of WD pulsational \( p - \text{modes} \) driven by tidal-heating (Pons et al. 2002) plus the irradiation (Podsiadlowski 1991) triggered by supercritical accretion onto its orbital NS partner in an X-rays ultracompact ultra-relativistic binary (see a more detailed discussion on this model in the accompanying paper by Mosquera Cuesta 2004a).

2 THE WD EXCITATION ENERGY SOURCE: TIDAL HEATING PLUS \( \gamma \)-IRRADIATION

The basis of the ultra-relativistic compact binary model for SGRs (Mosquera Cuesta 2004a), is that during rather sparse catastrophic epochs (\( \Delta T_{\text{SGRs}} \leq 10\text{yr} \)) the WD starts to transfer mass onto a low-magnetized (\( B \sim 10^{12} \text{G} \)) rapidly rotating millisecond (ms) massive NS (\( \sim 2M_\odot \)). This process develops via the formation of a thick dense massive accretion disk (TDD) very close to the innermost stable circular orbit around the NS. The disk becomes unstable due to gravitational runaway or Jeans instability, partially slumps and inspirals onto the NS. The abrupt supercritical mass accretion onto the NS releases a quasi-thermal powerful \( \gamma \)-ray burst (GRB), a fireball to say. A parcel of the accretion energy illuminates with hard radiation (\( \gamma - \text{rays} \)) the WD, additionally perturbing its hydrostatic equilibrium. The WD absorbs this huge energy at its interior and atmosphere,\(^1\) This irradiation excites other \( p \)-modes of the WD oscillation spectrum, the overtones, since it already pulses at its fundamental mode because of the tidal interaction of the binary (see Table I).

The abrupt supercritical accretion also perturbs the NS hydrostatic equilibrium which drives it into non-radial nonaxisymmetric oscillations that produces GWs due to excitation of the NS fluid modes (see Mosquera Cuesta et al. 1998). Further, the remaining part of the TDD might be the neighbour environment (\( \sim 100\text{km from the NS} \)) where matter carried by the fireball can nucleosynthetise to produce the noticeable iron \( \text{Fe}^{56} \) line discovered by Strohmaier & Ibrahim (2000) during the GRB980827 giant outburst. This possibility is explored in a forthcoming communication (Mosquera Cuesta, Duarte & de Freitas Pacheco, in preparation). (We address the reader to the related paper by Mosquera Cuesta 2004a, for a full description of the interacting relativistic compact binary here pictured).

| Table I. First few radial (l=0) and nonradial (l\neq 0) modes for a 1.05 M\odot WD model (Temperature =12000 K). Columns 1, 2, 4 and 5, represent the l-value, radial overtone value n, period (s) and frequency (Hz), as computed by Montgomery & Winget (1999). |
| l \hspace{0.5cm} n \hspace{0.5cm} P \hspace{0.5cm} P \hspace{0.5cm} Freq. [Hz] |
| 0 1 \hspace{0.5cm} 0.66121 \hspace{0.5cm} 5.416 \hspace{0.5cm} 0.1846 |
| 0 2 \hspace{0.5cm} 1.87364 \hspace{0.5cm} 1.911 \hspace{0.5cm} 0.5322 |
| 0 3 \hspace{0.5cm} 2.80941 \hspace{0.5cm} 1.275 \hspace{0.5cm} 7.7845 |
| 0 4 \hspace{0.5cm} 3.69229 \hspace{0.5cm} 0.970 \hspace{0.5cm} 1.0310 |
| 0 5 \hspace{0.5cm} 4.54111 \hspace{0.5cm} 0.789 \hspace{0.5cm} 1.2680 |
| 1 1 \hspace{0.5cm} 1.39589 \hspace{0.5cm} 2.566 \hspace{0.5cm} 0.8998 |
| 1 2 \hspace{0.5cm} 2.33949 \hspace{0.5cm} 1.531 \hspace{0.5cm} 0.6532 |
| 1 3 \hspace{0.5cm} 3.23226 \hspace{0.5cm} 1.108 \hspace{0.5cm} 0.9025 |
| 1 4 \hspace{0.5cm} 4.09340 \hspace{0.5cm} 0.875 \hspace{0.5cm} 1.1430 |
| 2 0 \hspace{0.5cm} 0.99360 \hspace{0.5cm} 3.604 \hspace{0.5cm} 0.2774 |
| 2 1 \hspace{0.5cm} 1.85472 \hspace{0.5cm} 1.931 \hspace{0.5cm} 0.5179 |
| 2 2 \hspace{0.5cm} 2.73775 \hspace{0.5cm} 1.308 \hspace{0.5cm} 0.7644 |
| 2 3 \hspace{0.5cm} 3.60567 \hspace{0.5cm} 0.993 \hspace{0.5cm} 1.0068 |
| 2 4 \hspace{0.5cm} 4.45214 \hspace{0.5cm} 0.804 \hspace{0.5cm} 1.2431 |
| 3 0 \hspace{0.5cm} 1.24455 \hspace{0.5cm} 2.878 \hspace{0.5cm} 0.3475 |
| 3 1 \hspace{0.5cm} 2.17168 \hspace{0.5cm} 1.649 \hspace{0.5cm} 0.6064 |
| 3 2 \hspace{0.5cm} 3.06016 \hspace{0.5cm} 1.170 \hspace{0.5cm} 0.8545 |
| 3 3 \hspace{0.5cm} 3.92616 \hspace{0.5cm} 0.912 \hspace{0.5cm} 1.0963 |
| 3 4 \hspace{0.5cm} 4.76880 \hspace{0.5cm} 0.751 \hspace{0.5cm} 1.3316 |

\( 1 \) The author truly thanks Prof. J. Horvath (IAG-USP/Brazil) for enlightening discussions on these issues.

\( 2 \) Podsiadlowski (1991; and references therein) has discussed this process for irradiated main sequence and evolved stars, where the companion expands to a new state of thermal equilibrium, which provides a new mechanism to drive mass transfer onto the NS. This alters the binary evolution, and may bring a new evolutionary stage during which the orbital period increases, leading to larger orbital period during and at the end of the mass transfer. Although the WD in this relativistic binary is a degenerate compact star with an atmosphere, we believe a similar behavior should also take place in it, since the new thermal timescale, \( \Delta T_{\text{WD}} \), is comparable to the heat (\( \gamma \)-rays) diffusion time in the outer layers.
of pulsating ZZ-Ceti WDs in surveys, those models also provide the spectrum of pulsations of the short period pressure-driven (p-mode) pulsations.

Any perturbation of the hydrostatic equilibrium of a canonical WD will grow on its dynamical timescale

$$\tau_{\text{dyn}} \sim (G_\text{WD} \rho_\text{WD})^{-1/2} \sim 5.16 \text{ s} \left(\frac{4 \times 10^6 \text{ g cm}^{-3}}{\rho_\text{WD}}\right)^{1/2}.$$  \hspace{1cm} (1)

The WD normal mode spectrum ($p$-modes) is obtained from the radial wavenumber $k_r$ defined by (Montgomery & Winget 1999)

$$k_r^2 = \frac{1}{\sigma^2 c_s^2} \left(\sigma^2 - L_l^2\right) \left(\sigma^2 - N^2\right)$$  \hspace{1cm} (2)

with $\sigma$ the mode angular frequency and $c_s$ the sound speed in the star material. Here the squared Lamb/acoustic frequency is defined

$$L_l^2 = l(l + 1) \frac{c_s^2}{r^2}$$  \hspace{1cm} (3)

where $r$ is the radial variable, and $N^2$ the Brunt-Väisälä frequency. For $p$-modes:

$$\sigma^2 > L_l^2, N^2,$$  \hspace{1cm} (4)

and

$$\sigma \sim \frac{k_r \pi}{\int_{r_2}^{r_1} \frac{dr}{c_s}}$$  \hspace{1cm} (5)

where $r_2$, $r_1$ are the inner and outer turning points, respectively, at which $k_r = 0$ for a given $\sigma$.

Montgomery & Winget (1999) studied the pulsational modes of a massive WD ($M_{\text{WD}} \sim 1.1M_\odot$) which possess a hydrogen atmosphere of about $M_{\text{WD}}^\text{env} \sim 10^{-6}M_\odot$, with and without core-crystallization. The full spectrum of one of their numerical models is displayed in Table I, and a selected subset is displayed in Table II\(^3\) to compare with BeppoSAX observations (Feroci et al. 1999).

### 3 DISCUSSIONS

#### 3.1 The WD required mass

If we use the picture being introduced here to explain the pulsation discovered in GRB980827 (Hurley 1999a; Kouveliotou 1999a; Murakami et al. 1999; Feroci et al. 1999), it is easy to see that the WD mass (see Table 3) needed to produce pulsations with timescale

\(^3\) A curious note on this result is that it exhibits the same number of overtones as the one Feroci et al. (1999) found in the GRB980827 data from SGR1900+14.

#### 3.2 SGRs spindown rate

Moreover, the SGR 1900+14 spindown determined by Kouveliotou et al. (1999) and the pulse period increase found by Murakami et al. (1999); Marsden, Rothschild & Lingenfelter (1999); Harding, Contopoulos & Kazanas (1999) may be explained as follows: because the WD is a gravothermal system, as soon as it loses mass (when overflowing its Roche lobe) its negative specific heat forces it to expand until a new dynamical equilibrium radius is found. Then, the next stage of pulsation should occur with a slightly lower period compared to the previous one (secular increase). As a result, the pulse period increases. However, the interplay between the WD thermal cooling during the post-outburst reemission (which implies post-burst shrinking) and tidal heating via gravitational interaction with the NS (which implies pre-burst expansion) may lead to a slight up-down-up change in the fundamental mode of pulsation. This processes may help to understand the observed tiny changes in the SGR 1900+14 period: near superoutburst it is a bit longer, while in quiescence it shortens.

Thus, the rate of variation of the viscously attenuated pulsation time, $\tau_{\text{pulse}} = 5.16 \text{ s}$, divided by the timescale $\tau_{\text{dyn}} \sim 10^3 \text{ yr}$ needed to dissipate via wave-leakage for radial modes\(^4\) the ab-

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\(^4\) Physical support for the figures that have been used here comes from the detailed numerical calculations of pulsation periods for DA and DB
Table 3. SGRs observed pulsation periods and inferred masses for the WD in the binary model.

| SGR     | P [s] | Mass [M⊙] |
|---------|-------|-----------|
| 1900+14 | 5.16  | 1.1       |
| 0526-66 | 8.1   | 0.70      |
| 1806-20 | 7.47  | 0.80      |
| 1627-41 | 6.7   | 0.95      |

In our view this is the origin of those important time variations. Discrepancies might be caused by the differences in the WD model used (see Table 1). We stress that in a realistic star the overtone frequencies depend on the WD matter EOS and the degree of core crystallization. Changes in pulsation (fundamental) periods of a few percent are expected to occur once lattice crystallization onsets while the harmonics (overtones) remain almost unchanged (Montgomery & Winget 1999).

3.3 X-ray emission during quiescent, pre- and post-burst

What about X-ray emission and pulsation in long-term quiescence, pre- and post-burst? A number of viable processes may explain why SGRs glow in hard X-rays over some months before and after undergoing dramatic transients such as GRB980827 in SGR 1900+14, as well as the long-term quiescent emission: 1) changes in the gravitational potential at each orbital revolution (Podsiadlowski 1991, 1995), 2) crust cracking driven by the WD strong magnetic field (analogously to the NS case, see de Freitas Pacheco 1998), and 3) plate tectonics (Rothschild, Marsden & Lingenfelter 2001) induced by any or both the mechanisms just listed.

In this paper, as a first approach, we shall focus our discussion on this issue in the context of the scenario number 2) above. The remaining possibilities will be addressed elsewhere. This key property can be explained if we suppose that the quiescent soft X-rays luminosity \( L_X^{\text{GRS}} \sim 10^{35} \) erg s\(^{-1}\) (Kouveliotou et al. 1999) is powered by the release of WD crustal elastic energy\(^5\), inasmuch as in the current picture of magnetars (de Freitas Pacheco 1998). In this case, we get

\[
\frac{B_{\text{surf}} B_{\text{core}}}{8\pi\mu_0} \times 4\pi R_{\text{WD}}^2 \times \Delta R_{\text{WD}} \geq L_X^{\text{GRS}} \times \tau
\]

where \( \tau \sim 10^4 \) yr is the system lifetime since its formation, \( B_{\text{surf}} \sim 10^9 \) G WD crustal magnetic field, as in the super magnetised WD: RE J0317-853, \( M = 1.35 \), \( P = 725 \) s (Wickramasinghe & Ferrario 2000), and \( B_{\text{core}} \sim 10^{15} \) G is the WD core magnetic field. This yields a WD crust thickness: \( \Delta R_{\text{WD}} \sim 70 \) km\(^6\). The crust-cracking induces shear stresses which dissipate energy causing excitation of WD oscillation modes quite similar to the NS case (de Freitas Pacheco 1998, and references therein)\(^7\). We thus emphasize that the conclusion by Mazets et al. (1999): “... the processes accounting for emission of the narrow initial pulse and the long pulsating tail in both SGR 0526-66 and 1900+14 are separated in the source not only on time but in space...”, is realized in the picture introduced here, i.e., the NS releases the superoutburst while the WD the subsequent tail of pulsations via the mechanism invoked above.

4 CONCLUSIONS

As a summary, the NS low magnetization in this model leads SGR1900+14 (and perhaps all SGRs) under the pulsar death line making it undetectable as a binary radio pulsar, a viewpoint confirmed by Xilouri et al. (1998). Overall, since several SGRs are enshrouded by intervening galactic dust and gaseous nebulae (SNe remnants: Gaensler et al. 2001), optical observations of the suggested hot WD (\( \sim 12000 \) K) may render a breakthrough. This fact makes it a systematic high resolution search for such optical (or infra-red) counterparts of SGRs a timely and promising task. In this line, we remark that Ackerlof et al. (2000) have pursued optical follow-ups of SGRs over 10 outbursts: 8 events from SGR1900+14 and 2 events from SGR 1806-20. Although a careful search for new or variable sources in the view field of those SGRs was performed, no optical counterparts were seen down to \( m_V \sim 15 \). Thus the search for such SGRs counterparts remains, and perhaps VLA, GEMINI or KECK observations in the K-band could unravel them. On the other hand, it will be extremely relevant if the propeller model of Marsden, Rothschild & Lingenfelter (2001) and Alpar (1999, 2000) could provide a clean explanation for the observed spectrum of pulsational modes. This may help to discriminate among the SGRs accretion models through future observations.

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\(^6\) Note that this thickness is nearly equal to the Earth’s asthenosphere height scale. These scaling similarities (including the WD radius) may suggest a plate tectonics strikingly similar to that observed on our planet. Some suggestions in this direction have been put forward by Cheng et al. (1995), but they were associated to NS plate tectonics rather than to a WD, which in many respects is alike our planet.

\(^7\) We add to this mechanism that is possible for the (ms)NS rotation energy: \( E_{\text{spin}} \sim I_{\text{NS}} \Omega_{\text{NS}}^2 \sim 3 \times 10^{35} \) erg s\(^{-1}\) to play some role in driving the X-rays emission and pulsation during these stages due to its irradiation onto the WD, although the tidal interaction must be the dominant source.
An origin for the main pulsation and overtones of SGR1900+14...

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