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Gravitational Radiation and Gamma-Ray Bursts from Accreting Neutron Stars

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Abstract.
It is well known that hydrodynamic instabilities can be induced in rapidly rotating low magnetic field neutron stars, which accrete mass from a companion in both high and low mass X-ray binaries. The dynamical instability, in particular, takes place when the rotational to potential self-gravitational energy ratio, $\beta \equiv T/|W|$, overcomes a critical value $\beta \simeq 0.2738$. Besides the formation of a bar, spiral arms can also be formed, as well as mass can be ejected. In this paper we argue that after mass ejection from the unstable spinning neutron star, matter goes into the formation of a high-velocity disk-like thick accretion structure, which fragments into blobs driven by gravitational (Jean's) instability. The surrounding matter (blobs) is captured back onto the compact star in a short-scale highly dynamic transient passing through the formation of a disk-collapsed-star system. During the whole system evolution gravitational waves (GWs) in different frequency bands and with distinct waveforms are produced. We here pay attention in particular to two different sources of GWs not previously predicted: the inspiraling of the blobs before crashing the neutron star surface, and the blobs impact themselves. When the blobs impact on the neutron star surface a powerful gamma-ray burst (GRB) can be also produced. We found that during the GRB that we estimate to have an effective temperature of $\simeq 770$ keV and energy of the order of 10^{51} ergs, the characteristic amplitude and signal frequency are $h_c \sim 10^{-20}$ and $f_{gw} \simeq 676$ Hz, respectively, for a source at 10 kpc. Even stronger signals are produced during the inspiraling phase of the blobs ($h \simeq 3.4 \times 10^{-19}$). Prospective detection of these GW bursts by resonant-mass detectors such the TIGAs network and also by interferometric observatories such as LIGO and VIRGO are discussed and found likely.

Key words: gravitational waves – stars: neutron – gamma rays: bursts

1. Introduction

The detection of gravitational waves from astrophysical sources will mark a breakthrough in the history of astronomy (see, e.g., Thorne 1987 and Schutz 1996). Experimental efforts to search for these space-time wrinkles have been under development during the past twenty years (Thorne 1995, 1996). With the advent of technological improvements in several crucial aspects of the detection process we will soon be ready to turn them a reality (Schutz 1996, Thorne 1995, Finn & Chernoff 1993).

In the realm of astrophysics there is a host of possible sources of GWs, namely: inspiral and coalescence of compact binaries, rapidly rotating neutron stars, supernovae, the collapse of a star or star cluster to form a black hole, fall of stars and small black holes into supermassive black hole, ordinary binary stars, among others (see, e.g., Thorne 1995).

It has been recognized that rapidly rotating neutron stars are among the most promising astrophysical sources for the detection of GWs in the bandwidth of the interferometric detectors such as LIGO and VIRGO (Schutz 1996, Thorne 1995, Abramovici et al. 1992, Bradaschia et al. 1990, Brillet 1996, Bonazzola & Mark 1994), and also by the Truncated Icosahedral GW Antennas (TIGAs) (Johnson & Merkowitz 1993, Harry et al. 1996). Rapidly spinning neutron stars have been recently studied up to the onset of the hydrodynamic instability by Houser et al. (1994; hereafter HCS'94) and Lai & Shapiro 1994.

In particular, HCS'94 concluded that $\simeq 4\%$ of the star mass and $\simeq 0.7\%$ of its angular momentum is lost in GWs when the instability sets in. Mass shedding develops a disc-like structure around the star, or more precisely, a torus of dense matter. The subsequent interaction of the

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ejected matter with the compact star and the physical features of this system were not considered in that paper. The evolution of this system is driven by the timescale for fragmentation into clumps, which fall onto the central compact star afterwards.

In a previous publication (Mosquera Cuesta et al. 1998) we discussed the possibility of identifying the systems with "soft gamma-ray repeaters" (SGRs). Although this possibility can not be considered as ruled out, new evidence has emerged on the latter and must be taken into account properly. On the other hand, there is also room for a subset of "classical" GRB to be galactic and to host the kind of systems study here. Independently of the gamma signature, it is quite clear that the processes around the neutron star would constitute a target for GW detectors now in construction.

We here extend the model described in our previous publication and improve it in many aspects, in the sense that the model can afford explanation for highly energetic events. The characteristic GW amplitude and frequency are rederived for the crash of the infalling matter onto the star surface, as well as the GWs generated during the inspiraling of the blobs that precedes the crash.

The remaining of the paper is as follows: In Section 2 we present a discussion of the physics of the model. Section 3 addresses the expected GW emission and the prospects for detection of those systems by a TIGAs "xylophone", as well as by LIGO and VIRGO. Section 4 is devoted to the gamma-ray signatures of the systems.The discussions and conclusions are summarized in Section 5.

2. Physics of the model

Before any detailed description it is worth recalling some of the characteristics of a X-ray binary system that will be useful for our discussion. X-ray binary systems (low-mass x-ray binaries, LMXBs, and high-mass x-ray binaries, HMXBs) consist of a compact object, a neutron star (NS) or black hole (BH), accreting matter from Roche lobe overflowing main sequence or evolved companions. Being the central source a NS, its magnetic field strength and geometry becomes a crucial property, as well as the fashion in which captured material infalls. The whole luminosity, spectral pattern and time variability are influenced by the mass of the compact object and the rate of mass accretion. A magnetic disk disruption is expected to occur for strongly magnetized NS at a distance $\sim 10^3$ NS radii, corresponding to the Afvén radius of the system. For low magnetic field strength NSs the accretion disk can be close to the NS surface. The energy coming from the inner accretion disk and the boundary layer between the disk and star will drive the X-ray emission. The radiation source in the case of a BH, however, comes mainly from the inner disk and stems from viscous heating. Quasi-periodic oscillations (QPO's) and rapid fluctuations may be produced as a consequence of instabilities in the emission region or due to interactions between it and the accretion disk (White et al. 1995).

The scenario, which is going to be analyzed in some detail in the next Sections, postulates that: 1) a low magnetic field ($\sim 10^9 - 10^{10}$ G) neutron star is driven to hydrodynamic instability by the gain of angular momentum received from a primary accretion disk; 2) this disk is fed from the overflown material that comes from the compact star's companion at the first Lagrangian point; 3) as a consequence of the hydrodynamic instability the neutron star ejects material, loosing mass ($\simeq 4\%$) and angular momentum ($\simeq 17\%$), part of which ($\simeq 0.7\%$) is emitted in the form of GWs at frequencies around 4kHz (HCS'94 ; Houser & Centrella 1996; Houser 1998); 4) the newly formed disk rapidly fragments into blobs which start to fall down back to the neutron star driven by the gravitational radiation reaction. The system loses angular momentum due to the emission of GWs. The blob-NS system resembles, except for the slump characteristic scale length, a NS-NS system just before its merging phase. The blobs inspiraling and plunge produces, as shown below, a huge GW amplitude at $\simeq 600 - 700$ Hz; 5) this cluster of fragments falls on the neutron star in the form of needle structures, due to the strong gravitational tidal forces; 6) the collision of these needle structures with the neutron star produces strong GW bursts (peaked) around 600 – 700 Hz and can also produce GRBs; 7) the fall back of the secondary disk (the torus) on the neutron star restores most of the angular momentum the NS endowed before the ejection, placing it close to the hydrodynamic instability again.

2.1. Accretion of the Surrounding Thick Disk onto the Neutron Star Remnant

We assume that the central neutron star has a mass of $M = 1.46 M_{\odot}$. After the hydrodynamical instability, the matter forms a donut-type disc with characteristic dimensions: $\Delta w = 2 \times R_{ns}$ (the disk width; the difference between the external radius R_d, assumed to be the one derived for the final structure in HCS'94 simulations, $R_d \simeq 5 R_{ns}$, and the internal radius, assumed to be the tidal radius, $R_{tide} \simeq 3 R_{ns}$). We also assume that the disc density is near that one of the HCS'94 remnant disc-like structure, i. e., $\rho \simeq 5.7 \times 10^{12} g/cm^3$, see Table 1 for the parameters related to our disk-like structure model. In Table 2 we list the NS model parameters.

Fluid structures, like this accreting disc-type object can undergo *runaway* (see, e.g. Nishida et al. 1996) and/or *Jeans and viscous instability* and, depending on the dynamical conditions, *Rayleigh-Taylor instability.* The time scale for the viscous instability to drive the hydrodynamics of the disc-like structure is rather long to be relevant to the process under scrutiny here (a fact that was emphasized by Nishida et al. 1996). Unfortunately, most of the physics involved in its description is not well-

Table 1. Parameters of our disk-like structure: mass M_d, density ρ_d, width Δw, external radius R_d, tidal radius R_{tide}, bound orbiting radius $R_{orb} \simeq 4.0 R_{ns}$, height-scale ΔH and Afvén radius R_{acc}.

M_d $(M_\odot)$	ρ_d (g/cm^3)	$\Delta\omega$ (cm)	R_d (cm)	R_{tide} (cm)	R_{orb} (cm)	ΔH (cm)	R_{acc} $(R_\odot)$
4.0×10^{-2}	5.7×10^{12}	2.82×10^6	7.05×10^6	4.21×10^6	5.64×10^6	1.4×10^5	1.0×10^3

Table 2. Model parameters: period P, mass M, radius R, angular momentum J and rotational to kinetic energy ratio β for the neutron star.

Parameter	Initial	Final
P (ms)	0.80	0.98
$M_{ns}(M_\odot)$	1.46	1.42
$R_{ns}(cm)$	1.37×10^6	1.41×10^6
J (g cm^2/s)	1.70×10^{49}	1.42×10^{49}
β	0.2738	0.20

understood thus far. So, a clue to get some insight on up to what level it takes part in turning the structure unstable can roughly be inferred by comparing the timescales for both runaway τ_{run} and Jeans τ_{Jeans}, respectively. Provided the system is driven by a combined action of runaway and Jeans' instability planet-like clumps of matter around the central compact body are produced (see, e.g., Frank et al. 1992 for a stability constraint against breaking up into self-gravitating clumps)[1]. The scale length of this clumps follows from the Jeans' wavenumber

$$K_j^2 = \frac{4\pi G\rho_d}{a_d^2} \qquad (1)$$

where K_j is the wave number of the perturbation in the matter, a_d the sound speed in the structure and ρ_d its mass density. Assuming that $a_d \sim 0.1c$, we find $K_j \simeq 7.3 \times 10^{-7}\text{cm}^{-1}$.

The wave number parameter is related to the scale length through $K_j = 2\pi/\lambda$. Then we get $\lambda \simeq 8.6 \times 10^6$cm. We can picture this process as follows: when fragments drop back onto the neutron star surface following ballistic trajectories each blob is distorted into a needle shape (Ramana-Murthy & Wolfendale 1993). This filamentary clump of dense matter firstly hits on star surface with its apiece. A short time elapses until half of the blob impacts on the star surface. The time interval for this collision to occur will be

$$\Delta t_c \approx \left[\frac{(\lambda/2)^2}{GM_{ns}/R_{ns}}\right]^{1/2}, \qquad (2)$$

where in addition to the explicit dependence on physical properties like neutron star mass, radius, etc; the process will also depend on the blob density, temperature and orbital velocity of the surrounding disk of matter around the compact object, through λ.

These clumped structures, despite of being formed through gravitational

instability, are also affected by shock waves and other dissipative processes driving the disk hydrodynamics. Special attention should be paid to the turbulence effects. Because an accurate understanding of the dynamical role of both viscosity and turbulence would require a full numerical computation (which we do not pursue here), we have parameterized them through the parameter β_{acc} (with $0 \leq \beta_{acc} \leq 1$) which tells about the efficiency of both properties in driving the disc evolution.

After losing enough energy and part of its angular momentum through the mechanisms above mentioned, the clumps fall onto the neutron star. The largest clumps should fall first.

It can be shown that the mass of each clump is given by $M_\lambda = \rho_d(\lambda\Delta w\Delta H)$.

In our previous paper (Mosquera Cuesta et al. 1998), we adopted as the time necessary for the blob to fall back into the neutron star (defined as τ_{ff}) $(G\rho)^{-1/2}$. A better approximation is to calculate τ_f based on the general relativistic loss of angular momentum that the blobs undergo while inspiraling around the neutron star. Following Peters (1964), who considers a point-mass approximation, τ_f reads

$$\tau_f = \frac{a_0^4}{4\eta}, \qquad (3)$$

with

$$\eta = \frac{64}{5}\frac{G^3}{c^5}m_1 m_2(m_1 + m_2) \qquad (4)$$

here a_0 is the initial separation between m_1 - m_2 (blob-NS system).

Using the parameters presented in the Tables 1 and 2 we found $\tau_f \simeq 2.5s$, a much larger value than τ_{ff} used by Mosquera Cuesta et al. (1998).

Since

$$M_\lambda = \rho_d(\lambda\Delta w\Delta H) \simeq 1.94 \times 10^{31} g, \qquad (5)$$

then, we have for the effective accreted matter an equivalent rate per year of

$$\dot{M} \approx \frac{\beta_{acc} M_\lambda}{\tau_f} = 8.6 \times 10^4 M_\odot/yr, \qquad (6)$$

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[1] There is a critical dependence of the fragmentation process on the local sound speed in the torus, then it is conceivable even to expect no slumping at all. In that case we will be left with a system fully dominated by the gravitational runaway instability.

where β_{acc} is a measure of the efficiency with which the ejected angular momentum is recovered. We can assume that the parameter $\beta_{acc} \simeq 0.70$ for the case of accretion onto neutron stars [2]. Such an equivalent accretion rate is certainly strong enough so as to force the star not only to radially oscillate but also to make it wobble, and therefore to generate GWs.

2.2. Angular Momentum Recovery

As already mentioned, after the fragmentation of the secondary thick disk (torus) the blobs thus formed fall back into the neutron star, because they lose angular momentum due to the emission of GWs, on a time scale $\tau_f \simeq 2.5s$. In the sequence, the compact body recovers partially the angular momentum lost when it entered the hydrodynamic instability and rotates more quickly.

In Table 2 we show the initial and the final angular momentum of the NS just after the formation of the thick secondary disc. The energy parameter, β, in this case is given by

$$\beta_{stab} \simeq \frac{\mathrm{T}}{|\mathrm{W}|} = \frac{\frac{J^2_{stab}}{2I_{stab}}}{\frac{3}{5}\frac{GM^2_{stab}}{R_{stab}}} \simeq 0.20, \qquad (7)$$

The amount of angular momentum available to the big blobs (which dominate the angular momentum balance) reads

$$\Delta J_{blobs} \simeq \beta_{acc} \times N \times M_\lambda \times V_{orb} \times R_{orb} \qquad (8)$$

where N represents the number of big clumps, $\simeq K_j \times R_{orb} \simeq 4$, $V_{orb} = (GM/4R_{ns})^{1/2} \simeq 0.19c$, the orbital velocity of each clump before being accreted, R_{orb} defines the radius of bound orbiting, $\simeq 4.0R_{ns}$ (taken from the HCS'94 simulations). With our above obtained parameters for the accreted material we get $\Delta J_{blobs} \simeq 1.8 \times 10^{48}$g cm^2 s^{-1}. It is easily shown, following Peters (1964), that half of this angular momentum is carried out by GWs during the blobs inspiraling around the neutron star.

One could argue that such systems could be recurrent. If this is the case the NS should recover the angular momentum lost in the form of GWs, in order to become dynamically unstable again. This is, in principle, possible since angular momentum from the secondary star is continuously being gained by the NS. It can be shown that with accretion rates of $\dot{M} \sim 10^{-8} - 10^{-7} M_\odot/yr$ (Livio 1995) the time scale for recurrence would be $\sim 100 - 1000$ years, at best.

3. GW Emission

We now consider the expected emission of GWs according to this scenario. In particular, we focus on the production of GWs that occurs after the formation of the thick secondary disc, since the precedent phase that starts from a dynamically unstable NS till the formation of the thick disk was considered by HCS'94. Since the model is a "further step" of HCS'94's study, their conclusions concerning the GW production in that phase hold. Using the quadrupole approximation HCS'94 found that the GW characteristic frequency is $f_{gw} \simeq$ 4kHz. The dimensionless amplitude is $h \simeq 4 \times 10^{-19}$ at $\sim$ 10kpc, for a source within the Galaxy, and $h \simeq 2 \times 10^{-22}$ at $\simeq$ 20Mpc, for sources in the Virgo Cluster.

After the formation of the secondary disc, the system produces further GWs via three different processes: a) the inspiraling of the blobs, b) the impact of the blobs with the neutron star surface, and c) the putative precession of the NS (although, $< \theta_{wobble} >= 0$ it is possible that $< \theta^2_{wobble} >\neq 0$).

It is worth mentioning that if our system constitutes a sub-class of the LMXB, there is also an additional source of GWs. Since the dynamics of the evolution of close binaries, is driven by gravitational radiation through angular momentum loss (Paczńsky 1990, King 1995), short period binaries are currently being suggested as interesting sources of GWs (King 1995, Gourgoulhon & Bonazzola 1996). These systems have previously been studied in the context of the so-called *forced gravitational emission* (Wagoner 1984), in which the rate of energy radiated on GWs is self-regulated.

Here we consider in detail the production of GWs, in particular, for two of the possibilities addressed above, namely, during the blob inspiraling phase and during the impact of the blobs with the neutron star surface.

3.1. GW from inspiraling of the blobs

The simplest analysis suggests to consider the inspiraling of the blobs as a scaled-down, short-duration version of the NS-NS merging scenario. Having in mind that this may be an oversimplification of the actual situation (mainly due to the extended character of the blobs, with size $\sim$ orbital radius), we shall proceed to apply the well-known amplitude formula

$$h = 4.1 \times 10^{-22} \times \left(\frac{\mu}{M_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{1/3} \left(\frac{100\,Mpc}{D}\right) \left(\frac{100\,Hz}{f_c}\right)^{1/6} \qquad (9)$$

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[2] Note that this choice guarantees us that the dynamically unstable NS gets rid of sufficient angular momentum so as to become itself secularly unstable. Besides, recall that for the case of accretion onto black holes this $\beta_{acc} \simeq 1$ (Shapiro & Teukolsky 1983). To give physical support to such a value, $\beta_{acc} \simeq 0.70$, it is worth recalling that the black hole-neutron star radius ratio, $R_{BH}/R_{NS} \simeq 3/10$. Such a relation implies that in the case of a neutron star the accretion efficiency must be, at least, a factor $\simeq 0.3$ lower than the black hole efficiency, quoted above.

to our model, where the characteristic GW frequency is $f_{gw} = 2 \times f_{orb} = 2 \times 327 = 654$Hz; which in turn yield a huge amplitude

$$h \simeq 3.4 \times 10^{-19} \tag{10}$$

for a source located within the Galaxy, at ∼ 10 kpc.

3.2. Impact of the Blobs

Concerning the GW emission simultaneous to the impact, first recall that it is the sudden fall of the blobs that triggers the emission of a pulse of GWs during the transition phase to a hydrodynamically stable rotating neutron star. Then, to estimate the GW burst amplitude we can compare the GW flux received on the Earth to the total gravitational luminosity radiated away by the source. Using the relation (Schutz 1996).

$$\frac{c^3}{16\pi G}|\dot{h}|^2 = \frac{1}{4\pi D^2}\frac{\Delta E_{GW}}{\Delta t} \tag{11}$$

where ΔE_{GW} represents the energy flowing into GWs, which is defined as

$$\Delta E_{GW} \sim \Delta L_{GW} \times \Delta t_c, \tag{12}$$

with Δt_c as computed in Section 2.

The gravitational luminosity ΔL_{GW} is given by (Lightman et al. 1975)

$$\Delta L_{GW} \sim \frac{G {M_\lambda}^2 L^4}{5c^5 (\Delta t_c)^6}, \tag{13}$$

The mass of the blob, according to equation 4, is $\mathrm{M}_\lambda = 1.94 \times 10^{31}$ g; the one that triggers the emission of the highest energy photons, and the parameter L is supposed to be the radius of gyration of that mass, $\simeq 4R_{ns}$. Introducing these figures we get for the GW amplitude the value

$$h_c \simeq 8.1 \times 10^{-21}, \tag{14}$$

for a galactic source distance of 10 kpc.

3.3. Detectability of the GW signals

In order to be detected by the new generation of large interferometers and/or the buckyballs Network, the characteristic amplitudes of the processes a), and b) must be larger than the strain burst sensitivity threshold of the detectors for a given frequency. It should be emphasized that while the process of inspiraling a) is a varying-frequency, "chirp" signal, the processes b) would show up as effective GW bursts because of their small duration.

Thus, we have normalized the GW burst signals to their maximum frequency to obtain $h_c = 3.1 \times 10^{-22}(\mathrm{Hz})^{-1/2}$, by dividing by the square root of the characteristic frequency of the GW signal. We have defined for the process b) a GW frequency as the inverse of one-half of the total time elapsed until the entire set of blobs hit the neutron star surface, i.e., $f_{gw} \simeq 1/(4 \times \Delta t_c) = 676$ Hz. This timescale specifies the elapsed time until a "clean" GW signal from the system is settled in. The parameter Δt_c was estimated earlier in connection with the timescale for triggering the GRB.

Then, we conclude that the GW pulses generated in the processes a) and b) are expected to have amplitudes strong enough to be potentially observed by the upcoming LIGO and VIRGO detectors, and buckyball arrays.

4. Gamma-rays Emission

According to the discussion given in the previous Sections, it is clearly expected that the onset of instability in an accreting NS may give rise to bursts of high-energy photons related to the blobs fallback.

It became increasingly clear over the years that gamma-rays transients engulf at least two different classes. The first, "classical" GRBs have been recently demonstrated to be extragalactic. However, a subset of them could still have a galactic origin (Piran 1998). The detection of at least one documented case of a "classical" GRB associated with SN1998bw (Galama et al. 1998) prompted a deep revision of the "standard candle" assumption since the associated energy is many orders of magnitude lower than 10^{51}ergs. A consistent claim for a subset of "classical" GRBs singled out from the majority, and for which a galactic placement (and consequent lower energy) is possible, has been around for some time (see, for example, Belli 1997), although the fraction corresponding to the latter is still unclear.

On the other hand, a class of nearby repeating sources: lower-energy and fast-rising ones ($E_\gamma < 50$ keV), called SGRs has been consistently argued to be singled out from the "classical" sample. Of the four (may be five) SGRs known today at least one was observed to repeat $\simeq 110$ times: SGR 1806-20. Nonetheless, no "classical" γ-ray source has shown convincing evidence for repetitions.

The possibility of spatial and temporal association among astrophysical sources of GWs and the hosts of classical GRBs have been long before conjectured by many investigators (Piran 1998, Janka et al. 1996, Ruffert et al. 1997, Thorne 1996). Kochanek & Piran (1993) have previously pointed out, for example, that the statistics of gamma-ray events should be correlated to the gravitational detection rates for the case of coalescing binaries at cosmological distances.

Concerning our study, the fall of the blobs should trigger a burst of gamma-rays. Its characteristic temperature can be estimated equating the luminosity of accretion (blobs' fall) to the radiation power as

$$\frac{1}{2}G\frac{M_{ns}}{R_{ns}}\beta_{acc}\dot{M}_\lambda = 2\pi R_d^2 \sigma_{SB} T^4; \tag{15}$$

here T and σ_{SB} define the radiation temperature and the Stefan-Boltzmann constant, respectively. We also define

$\dot{M}_\lambda \approx M_\lambda/\tau_f$, where τ_f is the time spent by the blob to fall back on to the neutron star. Using the parameters derived in Section 2, we can obtain for the burst peak temperature, T_{peak}, the value

$$T_{peak} = \left(\frac{G}{4\pi\sigma_{SB}} \frac{\beta_{acc} M_\lambda}{\tau_f} \frac{M_{ns}}{R_{ns}^3} \right)^{1/4} = 2.7 \times 10^{10}\,\mathrm{K}, \quad (16)$$

or equivalently, $T_{peak} \simeq 2.3$MeV. For blackbody models of the emission processes, the effective temperature, $T_{eff} \approx T_{peak}/3$ (Ulmer 1994). Thus, we infer from our model a $T_{eff} \simeq 770$ keV. In deriving this value we have been quite conservative since the Ulmer's definition allows for $T_{eff} \approx T_{peak}/2$ as well (Ulmer 1994).

The association of the systems studied here with a subset of classical GRBs is possible, provided the energy requirement to produced the fireball, and consequently the gamma radiation, be fulfilled. It is easily shown that the kinetic energy of the blobs just before the impact onto the neutron star amount to $\simeq 6 \times 10^{51}$ ergs (approximately one tenth of the initial rotating energy of the NS of our model). Once a significant part of this energy can be converted into gamma radiation, the energy requirement for the present model to account for the GRBs is fulfilled. We recall that some authors argue that putative galactic GRBs would yield energies $< 10^{50}$ erg (see, Ramana-Murthy & Wolfendale 1993, and Fryer et al. 1999).

Apart the energy budget required to produce the GRBs, another very relevant question has to do with the baryon-loading problem, i.e., the confinement of the fireball produced by the baryons. Excessive baryons around the GRB engine would carry energy, in the form of kinetic energy, from the electron/positron/photon fireball. Due to the fact that the system studied here is a rapidly rotating one, thus flattened, the fireball is not significantly confined by the baryons. Another possibility to avoid the baryon loading problem is the putative conversion of baryons into neutrons, whose cross sections with the electrons, positrons, and photons of the fireball is very small as compared to the Thompson cross section σ_{T} (see Fuller et al. 2000 for details).

5. Discussion and Conclusions

In this work we have discussed the post-hydrodynamic instability evolution of a rapidly spinning neutron star. In this picture, the NS accretes from a companion in a low mass X-ray binary. Our aim was to call the attention for a further model and understanding of GW bursts and associated gamma pulses. Particularly, we have shown that the GW pulses (accompanied by gamma-ray events) are expected to have amplitudes strong enough to be potentially observed by the upcoming LIGO and VIRGO detectors, and buckyball arrays. The model has some features that favor the identification of the sources with galactic "classical" GRBs as systems in which dynamical instability is taking place.

Finally, another consequence of our GRB model is that we can expect X-rays quasi-periodic oscillations (QPOs), such those QPOs observed in LMXBs like 4U 1636-536 (Zhang et al. 1996) and 4U 1608-52 (Berger et al. 1996), produced during the last final orbits before the encircling matter hits the star surface. The likely frequencies, f_{QPOs}, would correspond to the orbital frequencies of the innermost stable orbit (which in a Schwarzschild spacetime is $r = 3R_g$, where $R_g \equiv 2\,\mathrm{G}\,M_{remn}/c^2$), namely

$$f_{QPOs} \simeq \left(\frac{GM_{ns}}{4\pi^2 r^3} \right)^{1/2} \left[1 - \left(\frac{R_{ns} c^2}{GM} \right)^{-3/2} j \right] \sim 1\mathrm{kHz}, (17)$$

where $j \equiv (cJ/GM^2)$, and assuming the NS magnetic field strength is sufficiently low. Interesting tests of general relativity in strong gravitational fields might be done in these X-ray binaries if QPO's are present, as argued, for example by Kluźniak et al. (1990) and Kaaret et al. (1997).

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