ENERGETICS OF THE SUPERFLARE
FROM SGR1806-20 AND A POSSIBLE
ASSOCIATED GRAVITATIONAL WAVE
BURST

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Abstract

We discuss in this Letter the energetics of large gamma-ray superflares observed from Soft-Gamma Repeater sources. The last recorded event has in fact ruled out some models for the energy release. For the first time actual information about a possible associated gravitational wave emission may be gathered from the LIGO data, even in the case that most of the energy was emitted in gamma-rays. Even upper limits on the amplitude of the latter $h$ at the expected frequency $f_c \leq 2 kHz$ may be useful to further constrain the remaining mechanisms.

1 Introduction

A small class of compact objects, the so-called Soft Gamma Repeaters, has recently attracted the attention of astrophysicists again. The few members of the class are now thought to be highly magnetized neutron stars (or magnetars, [1]), in spite that not all observed features fit so easily in this picture [2]. In steady state SGRs emit small quasi-thermal bursts with an associated temperature of $\sim 10 keV$. This
steady phase is probably of short duration, since the total number in the galaxy may not be larger that \( \sim 5 - 10 \) objects. Interestingly, a quake-like pattern, similar to the terrestrial earthquakes, has been found in the time series [3] and therefore the idea that crust cracking was responsible for the observed behavior was put forward.

While the steady behavior of these sources is quite interesting, and not yet fully understood, more spectacular events definitely associated with them challenge the ingenuity of the researchers. These are the superflares, sudden events releasing a large amount of energy observed to occur once in three out of the four firmly known sources, namely SGR 0526-66, SGR 1900+14 and SGR 1806-20. The existence and nature of superflares may reveal something fundamental about these sources. We focus in this note on the energy budget quest of these events, with possible implications for the existing gravitational (GW) wave experiments.

2 Free-energy sources of superflares

One of the most important and primary issues is the very source of the released energy (see Table 1, Column 3 for the inferred isotropic equivalent values). An interpretation in terms of the magnetar model has been advanced, involving a large-scale reconnection/untwisting of the magnetosphere. This kind of model seems to fit the observed features (rise time, spectral features and decay) quite well [4]. However, and even if a high magnetic field is involved, there are a few alternatives for the source of free energy which may be worth considering for the sake of comparison and further study.

The first one is some kind of phase transition at high density. Depending on parameters, and also on the detailed dynamics in which matter undergoes a phase transition, a huge amount of energy may be released simply by a mechanical readjustment of the star [5]. Those calculations arrive at an upper limit to the released energy of the order of \( \Delta E = W(\delta R/R) \), where \( W \) is the original binding energy of the star and \( \delta R/R \) is the fractional change in the radius. Numbers as high as \( 10^{53} \text{ erg} \) seem possible, although not all this released energy will be funnelled in a definite channel and must be shared (see below). Another picture [6] invokes a more complicated and exotic structure at high density to produce the superflares spaced in time, while the
“active” phase results in between. Admittedly, there is a high degree of speculation in structured quark matter that has not been settled over the years [7, 8, 9].

A new version of this picture (an exotic solid quark phase which occupies most of the interior of the "neutron" star [10, 11]) has been recently proposed as a likely source of free energy. In these models, condensation of quarks in position space competes with the celebrated momentum space features (CFL and analogues). This solid may crack whenever sufficiently strained, releasing an elastic energy of the order of \( \Delta E = 10^{47}(\mu/10^{32} \text{erg cm}^{-3})(\theta_{max}/10^{-3})(R/10 \text{ km})^3 \text{ erg} \), assuming a high value of the shear modulus as appropriated for the exotic solid [10, 11], a maximum strain \( \theta_{max} \sim 10^{-3} \) and essentially all the star as a solid body participating in the process. Stresses may be caused by spindown, which is unlikely for these slow rotators with periods \( \sim \text{ seconds} \), or by magnetic fields [12, 13]. A simple estimation of the field necessary to fulfill the condition of cracking can be made balancing the magnetic and solid stresses, yielding the lower limit \( B > 2.5 \times 10^{15}(\mu/10^{32} \text{ erg cm}^{-3})(\theta_{max}/10^{-3})(B_c/10^{15} \text{ G})^{-1} \text{ G} \). We see that, even if a high magnetic field could be ultimately confirmed, its role in superflares would not be automatically established. Solid quark stars quakes are good candidates to give rise to an interesting experimental signal (next Section).

Alternatively, another more exotic kind of free energy may be a source, namely the "burning" of neutron matter to strange matter [14]. This ultimate source of free energy arises if the energy per baryon number unit of three-flavor quark matter happens to be lower than the same quantity in the confined hadronic phase, and if further astrophysical conditions are met to trigger the conversion of a neutron star well after its birth, analogously to models of GRBs [15]. There is plenty of free energy available from this process, since the conversion is expected to release \( \sim 10 \text{ MeV} \) per baryon number unit, adding up to \( \Delta E = 10^{52}(\epsilon/10 \text{ MeV})(N_B/10^{57}) \text{ erg} \) for a solar-mass star. When and how this energy is employed depends on the details of the process [14]. A mechanical readjustment of the star with release of additional energy may follow the conversion and play a role [16]. Needless to say, the observation of a second superflare from the same source would rule out this possibility.

From a general point of view we may classify these few sources of free energy as "mechanical" (first two cases), "chemical" (strange
matter hypothesis), and "external" (magnetospheric hypothesis, see also Refs. 17 and 18 for an alternative accretion models also falling in this category). It should be emphasized that only the last superflare observed from the source SGR 1806-20 firmly excludes models based on conventional crust seismology, since the energy detected in gammarays alone exceeds the total elastic energy of any reasonable model crust. Even if we allow a substantial beaming factor $\sim 0.1$, thus reducing the released energy, these models are in trouble to explain superflares, even more if recurrence is ever observed in any of the sources and particularly the recent SGR1806-20. In other words, if superflares are due to solid cracking, the latter should be exotic. The detailed lightcurves can be a powerful tool to check the details of specific models.

Table 1. Superflares from SGRs and detectability of associated GW

| Object      | Date      | $E_\gamma$ (erg) | D (kpc) | Maximum $\eta$ |
|-------------|-----------|------------------|---------|----------------|
| SGR 0526-66 | 1979 Mar 5| $6 \times 10^{44}$ | 50      | $2 \times 10^{-3}$ |
| SGR 1900+14 | 1998 Aug 27| $2 \times 10^{44}$ | 15      | 0.01            |
| SGR 1806-20 | 2004 Dec 27| $3.5 \times 10^{46}$ | 10      | 4.8             |

3 Gravitational waves from SGR superflares

Another exciting feature of the last superflare is the possibility of searching with good prospects for the first time an associated gravitational wave (GW) burst. Technically, this kind of analysis is akin to the search of associated bursts to the nearby GRB030329 [19]. One of the main advantages over "blind" searches is that the time and position of the source (though not the relative orientation of the emission pattern) are well-known, facilitating the analysis.

The "mechanical" models have been explored as sources of GW in a number of papers [5, 13], and the general results seems to be that the sharing of the released energy should favor the ultimate dissipation as heat via radial oscillations [20] for slow rotators. However, since the the total energy is huge, even a 1% or so being emitted in GW is still
a very large number and should suffice, in principle, for a detection at the present sensitivities with high signal-to-noise ratios. In these models, however, one finds difficult to understand why the total energy budget (mainly carried by the radiation) appears to be so reduced respect to the calculated values, by factors $O \sim 10^{-6}$ or so. If, in turn, the values of Table 1 for the total energy are adopted, then the actual GW energy would be reduced accordingly, and the prospects for its detection vanish.

To the best of our knowledge, no specific calculation of GW emission has been performed for quaking solid stars as described by Zhou et al. [11] as yet. The main reason for a higher total energy release, perhaps up to $\Delta E \sim 10^{47}$ erg can be attributed to a higher value of the shear modulus $\mu$, which in turn allows to match the energy in gamma-rays (Table 1) and also to expect quite naturally $\Delta E \sim E_\gamma$ on purely theoretical grounds. Thus, the model could be considered to have a right energy scale and enough energy in GW to be detected with the state-of-the-art experiments.

The GW expected from the propagation of a conversion neutron $\rightarrow$ strange matter is strongly asymmetric in presence of moderate magnetic fields, and therefore some GW signal is expected [21], with a yet uncertain strength. The details of this model of a superflare have been discussed in Lugones et al.[14], as already noted. The overall prospects seem encouraging for a positive detection. The same considerations apply to the model presented in Mosquera Cuesta et al. [17], even though the evidence for accretion-powered SGRs has not been found so far [22].

Ioka [23] has performed a detailed calculation of the magnetospheric energy release model, with the result that the changing deformation (increase in the moment of inertia) may result in GW emission via the excitation of star oscillations. The simplest estimates indicate about $10^{47}$erg in GW, practically the same number than the exotic solid quake model expectation. This stresses the need of further study of the temporal and spectral differences predicted by both models.

On general grounds, one can resort to the simplest and roughest estimate for the GW emission, largely independent of the model as long as the energy release is quick enough (thus giving rise to a burst of GW). The signal-to-noise ratio can be expressed in terms of the basic quantity $E_\gamma$ if we write $\Delta E = E_\gamma/\eta$. The quantity $\eta$ relating both energies could be smaller than 1 (if heat generation is inefficient), or
larger than 1 (most of the energy coming out in gamma-rays), as suggested above. The signal-to-noise ratio for a broadband interferometer reads

\[
\frac{S}{N} = 10^5 \eta^{-1/2} \left( \frac{E_\gamma}{M_\odot c^2} \right)^{1/2} \left( \frac{1 \text{ kHz}}{f_c} \right)^{3/2} \left( \frac{10 \text{kpc}}{r} \right)
\]

where \( f_c \sim 2 \text{kHz} \) is the characteristic frequency of the signal, assumed to correspond to the lowest quadrupolar mode of the star oscillation, and \( r \) is the distance to the source [24]. Requiring \( S/N \geq 3 \) as a minimum criterion for detection within a short time interval around the superflare yields the limits on the parameter \( \eta \) quoted in the last column of Table 1 (the LIGO team uses a much conservative criterion, \( S/N \geq 8 \) in their analysis). As is stands, the last superflare from the source SGR 1806-20 is the only event which could be detected even if the energy seen in gamma-rays carried away most of the release.

\section{Conclusions}

We have briefly discussed some of the issues related to the observed superflares from SGR sources. In particular, the well-documented event of 2004 Dec 27 from the source SGR 1806-20 has restricted the number of viable models because of the involved energetics [4, 25].

Another relevant question is whether detectable GW emission accompanies the gamma superflare. As it stands, the giant superflare from SGR 1806-20 may be used to probe essentially all available models in this respect, whereas the former events, in addition of not being monitored, could only have probed models in which the energy put in GW was overwhelming. Thus, a careful search has to be performed in the data around 1 kHz, this frequency being dependent on the equation of state above nuclear matter densities. Our conclusions are in line with other works, including the latest [26, 27] which specifically discussed the sources and detection strategies prior to the last recorded event.

Note added in proof: after the acceptance of this work, we became aware of a paper by Drago, Pagliara and Berezhiani (gr-qc/0405145) in which mini-collapses of rapidly spinning-down hybrid stars are shown to produce GW bursts, a scenario perfectly compatible with our statements in the general discussion.
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