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Strange-pulsar evolution and soft γ-repeaters

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ABSTRACT

Soft γ-repeaters are puzzling sources which produce γ-transients, and which have been tentatively identified as a separate subclass from sources which produce 'classical' γ-bursts. We sketch the features of a model for soft γ-repeaters based on the evolutionary history of strange pulsars. It is shown that the main features of soft γ-repeaters can be explained by strange-pulsar evolution.

Key words: dense matter – elementary particles – stars: peculiar – pulsars: general – gamma-rays: bursts.

1 INTRODUCTION

The astrophysics of γ-ray transients has progressively become a very active arena for theorists and observers in recent years. As an outstanding example, facilities like the BATSE and COMPTEL experiments on board the *Compton Observatory* (see, for example, Fishman et al. 1992 and Schönfelder et al. 1992) are releasing high-quality data which will enable us to make improvements to future theoretical models. Among these cosmic phenomena, particularly remarkable is the recent discovery of the repeating sources now identified as soft γ-repeaters (hereafter SGR), which seem to form a different class from the more ubiquitous sources of 'classical' γ-ray bursts (Golenetskii, Ilyinskii & Mazets 1984; Laros et al. 1987). As discussed in Norris et al. (1989), the features that distinguish SGR as a different family are:

(a) stochastic recurrence patterns and short repetition times;
(b) average duration strongly peaked at ~ 0.1 s;
(c) almost invariant spectral shapes with output power at $E \approx 30$ keV;
(d) lack of substantial spectral evolution, and
(e) very rapid rise and decay time-scales, unresolved in most cases.

So far only three sources of soft γ-bursts (hereafter SGB) have been positively identified in the sky. On the basis of the similitude of the events (suggesting a 'standard candle' mechanism), Norris et al. (1989) have derived distance ratios which are consistent with galactocentric locations for the sources $1806-20$ and $1900+14$ and an LMC site for $0526-66$. They have further argued that the features (a)–(e) may be explained by seismic activity in compact stars. It should be stressed that all the data taken from the *KONUS*, *Solar Maximum Mission* and *International Cometary Explorer* experiments can be explained in terms of the three quoted sources only.

If the association with distant compact stars is real, then objects must very rarely become SGR and/or the lifetime in this 'active' phase must be very short. This constraint can be formally stated as

$$\tau_A < 500 \text{ yr } f_{\rm SGR}^{-1} \tag{1}$$

(Kouveliotou et al. 1989), where $f_{\rm GSR}$ is the fraction of the whole population which becomes a SGR. On the other hand, the idea of quake-induced γ-ray bursts is not new (Pacini & Ruderman 1974; Tsygan 1975; Fabian, Icke & Pringle 1976; Muslimov & Tsygan 1986; Epstein 1988; Blaes et al. 1989); by assuming a 'standard' hadronic composition (i.e. n, p, e^-), it has long been suggested that *classical* bursts may originate in this fashion, but that *soft* bursts probably do not, since many features (including recurrence time-scales) fall far short of what is needed to fit SGRs. For example, it is difficult to accommodate a quake era compatible with the constraint of equation (1) from Coulomb lattice cracking in the stellar crust. Instead, a large number of sources with a long repetition time-scale has been suggested from theoretical considerations.

The *internal* structure of a compact star is one of the most uncertain branches of stellar physics. Not only has the actual state of the 'normal' matter raised major debates (on superfluid phases, neutron crystallization and so on), but there are several plausible alternatives for the composition at supranuclear densities (pion and kaon condensates, quark cores, etc.). Motivated by an entirely different question, we have recently explored an even more radical departure from 'standard' pulsar models. The idea that the cold form of quark matter known as *strange matter* (Farhi & Jaffe 1984; Witten 1984) is stable and plays a decisive role in the explo-

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sions in which pulsars are thought to be born (Benvenuto & Horvath 1989) required that an attempt be made to explain the full pulsar phenomenology (Benvenuto & Horvath 1990; Benvenuto, Horvath & Vucetich 1990), which is a formidable and as yet unfinished task. We shall discuss in this paper the features of a model for SGR based on this so-called strange-pulsar structure.

The plan of this paper is as follows. In Section 2 we discuss the role of interactions between Q_α hadrons in dense matter. Estimates of the observable features resulting from such interactions are presented in Section 3, together with the possible link with γ-ray transients. Section 4 is devoted to the seismology of the stellar models. In Section 5 some points about the propagation of seismic waves and the production of a SGB are made. Section 6 contains a brief account of the expected temporal features of the model. Finally we give some conclusions in Section 7, which may be considered a summary of the weaknesses and strengths of this scenario.

2 QUARK-ALPHA MATTER IN STRANGE PULSARS

The structure of the putative strange-pulsar models has been addressed by Benvenuto et al. (1990) (see Benvenuto, Horvath & Vucetich 1991 for a review). As explained in Section 1, these stellar models can be considered as an attempt to introduce a component that can give a more realistic phenomenologic behaviour (including *glitches*) than that expected from homogeneous strange stars. The key new physical ingredient is the introduction of an (also hypothetical) 18-quark state to the strange-matter picture. This state is termed the 'quark-alpha' (Q_α) after Michel (1988) (see also Terazawa 1989 for discussion of this state), and may be expected to be bounded and stable. With this inclusion, the formerly undifferentiated strange-star interior becomes onion-like, and its dynamical behaviour is currently being explored. The feature that interests us most here is the existence of a new type of baryonic solid (denoted 'Q_α solid' in fig. 1 of Benvenuto & Horvath 1990) located above the strange-matter liquid core. As we shall see below, its physical features are adequate to provide a possible site for SGB generation.

In earlier work (Benvenuto & Horvath 1990; Benvenuto et al. 1990), the Q_α matter was modelled as a hard-sphere system, because no substantial residual interactions were foreseen for these particles. However, since Q_αs are hadrons, at some level a weakly attractive interaction (in addition to the strongly repulsive ones which are represented by the hard core) should be present. This can be understood by recalling the close analogy with a bosonic ^{4}He system, although the interactions obviously have different origins and strengths. A schematic diagram for the dominating Q_α–Q_α two-quark exchange (with pionic quantum numbers) is presented in Fig. 1.

An appropriate expression for the associated potential (in fact the simplest choice) is an effective two-pion-exchange Yukawa form

$$V(r) = -\alpha_s^2 \left(\frac{m_n}{m_q}\right)^2 \frac{e^{-r/\lambda}}{r^2}, \qquad (2)$$

where $\alpha_s^2 \simeq 10$ is a strong interaction coupling constant, m_n and m_q are the masses of the nucleon and the Q_α ($\simeq 5$ GeV) respectively, and $\lambda \equiv (2\, m_\pi)^{-1}$ is the range of the interaction expressed in natural units.

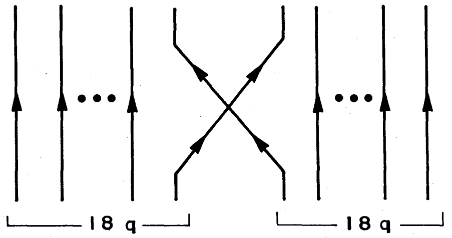

Figure 1. Two-quark exchange interaction generating an attractive tail of the Q_α–Q_α potential.

Clearly, such an attractive tail does not have any important consequences for the structure of the star, but the effect on the evolutionary history may be drastic. We shall address this point in the next section.

3 PHASE TRANSITIONS IN STRANGE PULSARS

A pure hard-sphere system at high densities and low temperatures shows a fluid–fcc solid phase transition at a value $n_q a^2 = 0.25$ (where n_q is the particle number density and a the scattering length ~ 1.7 fm; see Benvenuto & Horvath 1990). It is, however, clear that the solid arises because the hard cores 'cage' the particles at high densities. Provided that an attractive interaction like that of equation 2 is present, the system should further crystallize when the temperature is low enough and thermal energies are dominated by the attractive energy. A quantitative criterion for the onset of this transition may be formulated in terms of the dimensionless parameter Γ defined as

$$\Gamma = \alpha_s^2 \left(\frac{m_n}{m_q}\right)^2 \frac{e^{-\langle r\rangle/\lambda}}{\langle r\rangle^2\, T}, \qquad (3)$$

with $\langle r\rangle = (3/4\pi n_q)^{1/3} \simeq 1.2$ fm the mean interparticle separation. Detailed calculations (Slattery, Doolen & DeWitt 1980) show that crystallization occurs when $\Gamma \geq 170$, so the melting temperature T_m is

$$T_m \simeq 5 \times 10^7\ \mathrm{K} \qquad (4)$$

for the Q_α solid. In a stellar interior, such a value of the physical temperature T can be related to a redshifted surface temperature (Horvath, Benvenuto & Vucetich 1991) of $T_S^\infty \simeq 10^5$ K, which is in itself indicative of a relatively old compact object (recall that X-ray observations of pulsars have established upper limits to T_S^∞ in this range only for characteristic ages $\tau \geq 10^6$ yr, if at all; see Shibazaki & Lamb 1989 and references therein).

When crystallization of a region occurs, a latent heat of the order of

$$|Q| \simeq T_m N \qquad (5)$$

is released inside the star. Here N stands for the number of particles which crystallize. Previous calculations have given a total Q_α solid mass of $\simeq 2 \times 10^{-2}$ M$_\odot$ (Benvenuto & Horvath 1990), hence $N \simeq 4 \times 10^{55}$. Assuming that all the solid crystallizes at once, equations (4) and (5) therefore show that as much as 10^{47} erg may be suddenly released and radiated away. The fraction of the energy finally radiated in γ-rays, denoted $\eta|Q|$, depends on the emissivity in the neutrino channels, the elastic response of the warm material, etc., and cannot be reliably estimated, but we may expect $\eta \ll 1$. We also note that, in analogy with well-known laboratory phase transitions, crystallization of the *whole* solid is not automatically guaranteed and may indeed develop as a gradual process depending on several microscopic features of the material.

We suggest that this sudden release of energy should be associated with strong γ-ray transients, as in the famous 1979 March 5 event (Cline et al. 1982). Although there is still considerable controversy over the association of this event with the supernova remnant N49 in the Large Magellanic Cloud (LMC), it has been argued that there is no fatal evidence against an extragalactic origin at $\simeq 55$ kpc (Norris et al. 1989). As is well known, an isotropic γ-burst for this event at a LMC distance implies a lower bound to the energy release in γ-rays of $E_\gamma \geq 5\times 10^{44}$ erg. In the framework of the crystallization scenario, only a low efficiency of $\eta \simeq 10^{-2}$ for converting the latent heat into γ-rays is needed to fulfill this requirement. Furthermore, it is now possible to address in some detail the idea (Norris et al. 1989) that the 1979 March 5 event triggered an 'active' interval of the source 05266 − 66. The source of the activity, as we shall show below, should be identified with the release of elastic energy by starquakes.

4 STRANGE-PULSAR SEISMOLOGY

First, we estimate the total energy per particle $E/N|_\mathrm{c}$ due to the attractive interactions in the crystalline solid phase. Following Schiff (1973), this contribution is calculated by convoluting the potential with the spatial distribution function $g(r/a)$ over the whole volume:

$$E/N|_\mathrm{c} = \frac{1}{2}\, n_Q \int g(r/a)\, V(r)\, \mathrm{d}^3 r. \tag{6}$$

Assuming a simple analytical expression $g(r/a) = \cos^2(\pi r/a)$, the integral is easily performed to give

$$E/N|_\mathrm{c} = 4\pi^3 \alpha_\mathrm{s}^2 n_\mathrm{q} \left(\frac{m_\mathrm{n}}{m_\mathrm{q}}\right)^2 \left(\frac{\lambda^3}{a^2}\right) \times \exp(-a/2\lambda) \left(1 + 4\pi^2 \frac{\lambda^2}{a^2}\right)^{-1} \tag{7}$$

Inserting the same numerical values used above into equation (7), it is concluded that an energy of $\sim 10^{49}$ erg is stored in the solid. Of course, not all the energy is available to power the seismic events, but rather a fraction of it corresponding to the spin-down generated strain, namely

$$E_\mathrm{s} = \epsilon\, \sigma\, V_\mathrm{SOL}, \tag{8}$$

where $\sigma V_\mathrm{SOL} \equiv E/N|_\mathrm{c} N$ (σ being the stress and V_SOL the volume of the solid) and ϵ is the star oblateness. Because the crystal is relatively fragile to cracking (see below), ϵ should not be significantly different from the oblateness at the epoch of crystallization ϵ_0. In the one-parameter formulation of Pines & Shaham (1972), ϵ_0 can be found by minimizing the energy of the star and takes the value

$$\epsilon_0 \simeq \frac{I_0 \Omega^2}{4A} \simeq 10^{-3}, \tag{9}$$

with $I_0 \simeq 10^{45}$ g cm^2 the total moment of inertia, $A = -(1/5)E_\mathrm{GRAV}$ (E_GRAV being the total gravitational energy) and Ω the angular velocity of the star (taken to be $\simeq 5$ rad s^{-1}, appropriate for an old pulsar). Thus we can express the total strain energy as

$$E_\mathrm{s} = 10^{43} \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{\sigma V_\mathrm{SOL}}{10^{48}\ \mathrm{erg}}\right) \mathrm{erg}. \tag{10}$$

The above discussion on the available elastic energy tacitly assumes that plastic flow does not occur and a brittle response of the material is the actual behaviour. It is known from laboratory crystals that the transition between these two regimes is achieved at a temperature $T_\mathrm{B} \simeq 0.1\ T_\mathrm{m}$ in a quite abrupt fashion (taking only a small temperature interval of $\simeq 10^{-2}\ T_\mathrm{m}$). The identification of old pulsars as SGB sources would then require a quite rapid cooling of the star if an appreciable E_s is to be stored without a plastic flow release. Thus we are led to suggest that the early photon cooling era (Tsuruta 1986), which is characterized by a steep slope of T as a function of the star age τ, may be the epoch at which crystallization occurs. We note that in most cooling calculations $\tau \geq 10^6$ yr for the onset of this era and thus our previous assumptions are probably justified.

As in the work of Tsygan (1975), we picture the active phase of a SGR as the time interval where successive 'cracks' reduce the original uniform crystal to a network of regions with relatively small stresses between them. In this period, essentially the full amount of E_s in equation (10) will be released, reducing the oblateness ϵ to the point where quakes are no longer possible.

The seismic behaviour is better expressed by introducing the dimensionless strain θ, defined as

$$\sigma = 3\mu\theta. \tag{11}$$

It is known from laboratory samples that the maximum strain θ_MAX does not appreciably exceed 10^{-3} (Ruderman 1991). Each quake reduces the stress by means of jumps of order $\Delta\theta < \theta_\mathrm{MAX}$ and releases energy of about

$$E_R \simeq 10^{41} \left(\frac{\Delta R}{10^5\ \mathrm{cm}}\right) \left(\frac{R}{10^6\ \mathrm{cm}}\right)^2 \left(\frac{\mu}{5\times 10^{31}\ \mathrm{erg\ cm^{-3}}}\right) \times \left(\frac{\theta}{10^{-3}}\right) \left(\frac{\Delta\theta}{10^{-5}}\right) \mathrm{erg}, \tag{12}$$

where ΔR is the thickness of the crystal and all the quantities have been scaled to fiducial values. We see that, provided an efficient conversion to γ-rays is possible, the energy requirements for typical SGB are met in principle.

It is also important to note that the total number of ϵ-reducing quakes N_q can be expressed (Ruderman 1991) in terms of $\Delta\theta$ and the periods P_on, P_off which limit the quake era. We expect from equation (1) a P_off value comparable to P_on; in terms of $\delta P/P \equiv (P_\mathrm{off} - P_\mathrm{on})/P_\mathrm{on}$, we therefore estimate

$$N_\mathrm{q} \simeq 10^2 \left(\frac{\Delta\theta}{10^{-5}}\right)^{-1} \left(\frac{\delta P/P}{10^{-3}}\right), \tag{13}$$

which compares favourably, for example, with the number of events detected from SGR 1806 − 20 (Norris et al. 1989), which is thought to have finished its active period. However, given the state of the art of the models, we have not made any attempt to address the temporal bunching of the events, which could be significant, as suggested by the observations of SGR 1910 + 14 (Kouveliotou et al. 1989).

5 GENERATION OF A SGB

A 'deep focus' starquake like the ones described in the former section can produce a SGB in two ways: (a) by means of a shock focused on to the surface layers (Fabian et al. 1976); or (b) by shaking the frozen magnetic field lines, which in turn radiate. Possibility (a) is an effective means of transmitting the released energy, although it appears difficult to avoid substantial X-ray emission after the burst itself, which is not observed (a way out could be provided by a sufficiently low heat transfer time-scale). Lacking more reliable knowledge of the elastic interior, we should bear this in mind as a viable possibility. The alternative is production of the burst from Alfvén waves in the surface, which requires a relative perturbation of the magnetic field:

$$\delta B/B \simeq 1.5\times10^{-3}\left(\frac{B}{10^{11}\ G}\right)\left(\frac{L}{10^{42}\ \mathrm{erg\ s^{-1}}}\right)^{1/2} \qquad (14)$$

(Blaes et al. 1989). With this scaling, we obtain a relative perturbation of the surface magnetic field $\delta B/B\sim10^{-3}$ for a typical SGB. Detailed models show how these amplitudes are related to the propagation of shear waves in the outer crust dominated by a Coulomb lattice, but at this point it is important to note that the strange-pulsar models cannot be simply described by this kind of calculation. The main reason for this is that 'deep focus' starquakes originate at much larger depths (~1 km) than do crustquakes, and the liquid Q_α phase above the solid cannot transmit shear waves ($\mu=0$). Thus any perturbation perpendicular to the propagation should be maintained by magnetic rigidity in the liquid Q_α region, and it is not clear to what extent we should pursue such a possibility. A much more likely alternative is that *longitudinal* waves can carry the perturbations, a possibility addressed by Tsygan (1975). However, a comparatively small amount of the total energy is shared by these modes and this may conflict with the naive energetic estimates given above. Nevertheless, it can be stated that a relative *internal* displacement ξ/R of a few centimetres is enough to excite appreciable Alfvén luminosities (equation 14) from the radiating surface. This is a modest requirement for the proposed starquake mechanism.

The fate of the Alfvén waves in the magnetosphere which finally produce the SGB is still less certain (see Blaes et al. 1989 for a discussion). Above the stellar surface, there is no difference between a conventional and a strange-pulsar model, and the results of studies of this region can be adopted without reservations.

6 THE RISE, DAMPING AND THE X-RAY PAUCITY

Provided that an efficient mechanism for the transmission of the energy exists, the rise time of the SGB should be determined by the propagation of the waves in the solid. An appropriate value for shear modes is

$$\tau_R \simeq \Delta R(\rho_q/\mu)^{1/2} \simeq 10^{-4}\ \mathrm{s}, \qquad (15)$$

consistent with the observations (compressional modes set a τ_R which does not differ much from the value quoted in equation 15).

The damping mechanism is, however, a more delicate problem. Electromagnetic damping is not likely to be effective since its associated time-scale $\tau_{\mathrm{em}}\simeq10^3$ s (Muslimov & Tsygan 1986) is much longer than the average duration of 0.1 s for a SGB. The same is also true for gravitational damping (Tsygan 1975; Fabian et al. 1976). We are left with viscous damping, which is not expected to be important for stellar *crusts*, which produce the Alfvén radiation. Deep motions can, however, be effectively damped by the bulk viscosity of the strange-matter core (Wang & Lu 1984; Sawyer 1989) and the solid shell. It is conceivable that an effective coupling to B of the Coulomb crust and the deep structure determines the damping of the bursts. Of course, this need not be true for the 1979 March 5 event, where $L\gg L_{\mathrm{SGR}}$ and the emission lasted for several seconds.

Finally, we would like to stress that the internal constitution of a strange-pulsar model may have a built-in mechanism for avoiding the presence of substantial X-radiation. Since Q_α are bosons, the neutrino emissivities are not Pauli-blocked and reactions like Q_α-Q_α or Q_α-n scattering may be significant cooling channels. To see how this works, let us parametrize the luminosity in terms of a typical pionic luminosity

$$L=\eta\ 10^{46}\left(\frac{T}{10^9\ \mathrm{K}}\right)^6\ \mathrm{erg\ s^{-1}} \qquad (16)$$

(Maxwell et al. 1977). Ignoring all the other neutrino reactions, the time-scale for cooling the star to the original temperature is estimated to be $\Delta t=E_R/L$. If we require Δt to be less than, say, 10 s, even a value of $\eta\ll1$ suffices to get rid of the heat by neutrino emission. We conclude that a modest emissivity of the Q_α matter could explain the X-ray paucity constraint.

7 CONCLUSIONS

We have discussed in this work the features of strange-pulsar models in the context of their likely role as sources of soft γ-bursts. A summary of this scenario follows.

(i) Because of residual interactions, there is a crystallization of the Q_α solid inside old stars ($\tau\sim10^6$ yr) which releases a total energy of $|Q|\simeq10^{47}$ erg. It is this, we suggest, that produces events like the 1979 March 5 burst, which radiated at least 5×10^{44} erg in γ-rays if the source was located in the LMC (see, however, Felten 1981 for arguments against an LMC location of the source).

(ii) The 'superburst' events, being a signature of the phase change, open the burster era identified with the cracking of the crystal down to a stellar configuration in which the oblateness ϵ drops below its minimum value compatible with starquakes. This produces $N_{\mathrm{q}}\simeq100$ (equation 13), each event releasing about 10^{41} erg (equation 12), in agreement with previous observations, and gives a prediction of $\tau_A\simeq$ few yr.

(iii) Conversion of the quake energy to the final γ-burst may occur by means of a shock wave or Alfvén radiation, although it should be stressed that each mechanism has its own difficulties which are hard to evaluate.

(iv) Rise times are consistent with observations, but the damping is quite problematic. It may be related to the viscosity of the exotic matter. The X-ray paucity constraint is associated with the neutrino luminosity of the Q_α layer which quickly removes the generated heat (note that a preliminary version of this scenario in Horvath 1992 erroneously attributed this feature to a low thermal conductivity of the Q_α shell, which is in fact an excellent conductor of heat).

The observation of another 1979 March 5-like event followed by SGB activity would provide a strong case for this type of model. Indeed, a very recent observation of a multipulse soft emission by the BATSE team seems to indicate that the source 1900+14 has become active again; a thorough analysis of the data may help to refine the model. Indirect evidence of the internal composition of the pulsars, such as determinations of the surface temperatures and oscillation modes, may also yield important clues about the viability of the model.

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