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NATURE AND NURTURE: A MODEL FOR SOFT GAMMA-RAY REPEATERS

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ABSTRACT

During supernova explosions, strange stars with almost bare quark surfaces may be formed. Under certain conditions, these stars could be rapidly spun down by the torque exerted by the fossil disks formed from the fallback materials. They may also receive large kicks and hence have large proper-motion velocities. When these strange stars pass through the spherical "Oort" comet cloud formed during the presupernova era, they will capture some small-scale comet clouds and collide with some comet-like objects occasionally. These impacts can account for the repeating bursts as observed from the soft gamma repeaters. According to this picture, it is expected that SGR 1900+14 will become active again during 2004–2005.

Subject headings: accretion, accretion disks — dense matter — gamma rays: bursts — pulsars: general — stars: neutron

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are two groups of enigmatic sources. They share the following properties: (1) They all have long rotation periods (clustered within 5–12 s) and large spin-down rates (see, e.g., Mereghetti & Stella 1995 and Kouveliotou et al. 1998, 1999). (2) Most of them are associated with supernova remnants, indicating that they are young objects (for reviews, see Hurley 1999 and Mereghetti 1999). (3) No optical, infrared, or radio counterparts have been identified (e.g., Eikenberry & Dror 2000; Lorimer & Xilouris 2000). (4) They all have soft persistent pulsed X-ray emission with luminosities of $L_X \sim 10^{35}$–10^{36} ergs s^{-1}, well in excess of the spin-down energy of these sources (e.g., see Thompson 2000 for a review). The main difference between both types of objects is that SGRs show occasional soft gamma-ray bursts while AXPs do not. It is also found that SGRs usually have larger proper-motion velocities than AXPs according to their relative positions with respect to the cores of their supernova remnants (Hurley 1999). The main characteristics of the SGR bursts include the following: (1) Most of the bursts have super-Eddington luminosities with $L_b \sim 10^{38}$–10^{42} ergs s^{-1}. (2) The fluence distribution of the bursts is a power law, and there is no correlation between the burst intensity and the time intervals between the bursts (Gögüs et al. 1999, 2000). (3) Two giant flares have been detected from SGR 0526−66 (the 1979 March 5 event) and SGR 1900+14 (the 1998 August 27 event), which share some common properties (see Thompson 2000 for a review). (4) Most bursts have soft spectra with characteristic energy around 20–30 keV.

The popular model for SGRs and AXPs is the magnetar model, which can account for almost all the phenomena listed above (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996; Thompson 2000). However, the differences between SGRs and AXPs are not straightforwardly interpreted since these objects are not intrinsically different objects within the magnetar picture. It also remains unclear how some other issues—e.g., the nonsystematic discrepancy between the characteristic ages derived assuming dipolar spin-down and the ages of the associated supernova remnants, no clear positive dependence between L_X and the polar surface field strength B_p, etc.—can be properly addressed. On the other hand, a fossil disk accretion model for AXPs recently emerges from the independent studies by Chatterjee et al. (Chatterjee, Hernquist, & Narayan 2000; Chatterjee & Hernquist 2000) and Alpar (1999, 2000). The neutron stars in such a scenario have normal magnetic fields, similar to the Crab pulsar. The model can interpret the AXP phenomenology well, but the bursts from the SGRs are difficult to interpret. On observational grounds, Marsden et al. (2000) observed that the SGRs and the AXPs are located in a much denser environment than the normal pulsars. They hence argue that the peculiar behaviors of the SGRs and AXPs may be due to their "nurture" from the environment rather than due to their special "nature" (i.e., magnetars) as compared with the normal pulsars. However, no plausible idea was proposed to connect the "nurture" to the phenomenology of these sources, especially the bursting behavior of the SGRs.

In this Letter, we attempt to propose a model to understand the bursting behavior of the SGRs without introducing the magnetar idea. We propose that the central objects of the SGRs are "bare" strange stars with normal magnetic fields (10^{12}–10^{13} G). We assume that these strange stars are born directly from supernova explosions from some massive progenitors and they have experienced a spin-down history as that having been proposed for the AXPs within the fossil disk model (Chatterjee et al. 2000; Alpar 2000). According to this model, some fallback materials from the supernova ejecta will form a fossil disk around the strange star. The SGRs/AXPs are just such strange/neutron stars that have experienced the "propeller" phase ($r_c \ll r_m < r_l$) and are now in the "tracking" phase ($r_c \lesssim r_m < r_l$) when infall of the materials onto the surface is possible and the star is X-ray bright. Here r_l, r_m, and r_c are the light cylinder, the magnetospheric radius, and the corotating radius, respectively. In our picture, AXPs may be still neutron stars. We will attribute the SGR bursts to their occasional collisions with some comet-like objects in the dense environment of the SGRs. We will show how various SGR properties as reviewed above could be accounted for within this picture. Our model differs from some other strange star SGR models (e.g., Alcock, Farhi, & Olinto 1986b; Cheng & Dai 1998; Dar & de Rujula 2000).

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2. THE MODEL

Strange stars (Haensel, Zdunik, & Schaeffer 1986; Alcock, Farhi, & Olinto 1986a) are hypothetical objects based on the assumption that strange quark matter is more stable than nuclear matter (Witten 1984; Farhi & Jaffe 1984). Although the existence of such stars is still subject to debate, some evidence in favor of strange stars has recently been collected (e.g., Li et al. 1999a, 1999b; Titarchuk & Osherovich 2000). Strange stars can either be bare or have normal matter crusts (Alcock et al. 1986a). They can be formed directly during or shortly after some supernova explosions when the central density of the proto–neutron stars is high enough to induce phase conversion (e.g., Dai, Peng, & Lu 1995; Xu, Zhang, & Qiao 2000). If a strange star is born directly from a supernova explosion, it is likely that the star might be almost bare (Xu et al. 2000). Some radio pulsars may be such strange stars with exposed bare quark surfaces (Xu, Qiao, & Zhang 1999).

There are three main motivations for us to choose (bare) strange stars rather than neutron stars to interpret the SGRs. (1) A prominent feature of the SGR bursts is their super-Eddington luminosities. This feature has been regarded as a strong support to the magnetar model, since superstrong magnetic fields may considerably suppress the Thompson cross section and consequently raise the Eddington limit to several orders of magnitude higher (Paczyński 1992; Thompson & Duncan 1995). However, the luminosities of the most luminous events, e.g., the initial spike of the March 5 event with $L \sim 10^{44}$ ergs s^{-1}, are still above the enhanced Eddington limit. An important merit of bare strange stars is that they are not subject to the Eddington limit at all since the bulk of the star (including the surface) is bound via strong interaction rather than gravity (Alcock et al. 1986a). This presents a clean interpretation of the super-Eddington luminosities of the SGRs, as long as the impacts are not in the polar cap region where the accretion flow from the fossil accretion disk is channeled. (2) As criticized by Thompson & Duncan (1995), the impacting model for neutron stars suffers the baryon contamination problem. The impact may load too much baryonic matter to cause adiabatic dilution of photons in an expanding fireball to energies well below the hard X-ray and gamma-ray band. A bare strange star can naturally evade such a criticism, since the infall matter will be essentially converted into strange quark matter within a very short period of time ($\sim 10^{-7}$ s; Dai et al. 1995) when they penetrate into the star. A newborn bare strange star may have a very thin normal matter atmosphere (Xu et al. 2000), which is far less than the amount required to pollute the fireball. (3) Observationally, SGRs tend to have larger proper-motion velocities (~ 1000 km s^{-1}) than normal pulsars and AXPs. Although we do not attempt to propose a detailed "kick" theory in the present Letter, we note that the formation of a strange star rather than a neutron star may potentially pose some possibilities to interpret the large proper-motion velocities of SGRs. Present kick theories invoke either hydrodynamically driven or neutrino-driven mechanisms (Lai 2000). For the former, the kick arises from presupernova *g*-mode perturbations amplified during the core collapse, leading to asymmetric explosion (Lai & Goldreich 2000). We note that the formation of a strange star is a two-step process, i.e., the formation of a proto–neutron star and phase conversion. Neutrino emission in the second step could be significantly asymmetric since the phase conversion may be off-center as a result of the initial density perturbation (D. Lai 2000, personal communication). An off-center transition condition may be also realized in the presence of an electron-neutrino–degenerate gas in a proto–neutron star (Benvenuto & Lugones 1999). Thus, the phase transition process may give an additional kick to achieve a higher velocity. More detailed investigations are desirable to verify these proposals.

We now describe the model in more detail. We assume that the progenitor of a strange star is surrounded by a huge spherical comet cloud that is similar to the Oort cloud in the solar system. They may be formed during the formation of the massive star and have almost finished gravitational relaxation. Since the progenitor of a strange star should have a mass larger than 10 $M_\odot$, we expect that the radius of the Oort cloud in the progenitor system may be 1 order of magnitude larger than the solar value ($\sim 2 \times 10^{13}$ km Weissman 1990), i.e., $r_{\rm O} \sim 2 \times 10^{14}$ km. Supernova explosion blast waves will not destroy these comet clouds (Tremaine & Zytkow 1986). The luminous UV/optical emission from the progenitor is also unlikely to evaporate the comets. Although the radiation flux received by the Oort cloud comets of the massive star should be about a factor of 30 higher than that received by the solar Oort cloud comets, the existence of copious "Kuiper Belt" comets in the solar system (which is 4 orders of magnitude closer to the Sun than the Oort cloud) hints that comets can withstand shining with much higher luminosities. The influence of nearby stars may also not be prominent because of the same reason, even if SGRs are associated with luminous star clusters (e.g., Vrba et al. 2000). Using the typical proper-motion velocity of the SGRs, $V_{\rm SGR} \sim 10^3$ km s^{-1}, and the typical supernova remnant age, $t_{\rm SGR} \sim 10^4$ yr, the distance that an SGR has traveled since its birth, is $r \sim 3 \times 10^{14}$ km, remarkably consistent with the distance of the Oort cloud $r_{\rm O}$. Thus, the age clustering of the SGRs near 10^4 yr is simply owing to this being the age when a lot of impacts are available. The lack of bursts from the AXPs may be due to their much smaller proper-motion velocities and probably also their different nature, i.e., neutron stars. Although SGR 1806−20 has a smaller projected proper-motion velocity ($V_\perp \sim 100$ km s^{-1}), we assume that it has a similar velocity as other SGRs, with a large velocity component along the direction of the line of sight. The capturing rate could be estimated as $\dot{N} \sim \pi(2GM_*/V_{\rm SGR}^2)^2 V_{\rm SGR} n_c$, where n_c is the number density of the comets within the Oort cloud. To produce a bursting rate of 1 yr^{-1}, n_c is required to be $\sim(10^{-22}$ to $10^{-23})$ km^{-3}. This is about 4 orders of magnitude higher than the inferred comet number density in the solar Oort cloud [$\sim(10^{-26}$ to $10^{-27})$ km^{-3}; Weissman 1990], but about 3–4 orders of magnitude lower than the inferred number density in the Kuiper Belt of the solar system [$\sim(10^{-18}$ to $10^{-20})$ km^{-3}; Weissman 1990]. Keeping in mind that the mass density of the Oort cloud and the number density of the comets may be enhanced as a result of accretion from the dense environment in the supernova remnants (Marsden et al. 2000) and that the number density quoted for the solar system might be a lower limit (Weissman 1990), the required n_c may be not unreasonable. Some SGRs have a more frequent bursting rate. This may be due to the strange star having captured a denser small-scale comet cloud.

When the strange star passes through its Oort cloud, it may capture some small-scale clouds and make them circulate around it within its rest frame,[6] and the comets within the cloud will be occasionally accreted onto the strange star surface. The different bursting luminosities (or more precisely the different energies for different bursts) correspond to different masses of the impacting objects. During each impact, the energy released

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[6] The fossil disk around the star may also be a perturber of the comets, which may enhance the chances of captures.

is a sum of the gravitation energy and the phase conversion energy. The former has an efficiency of $\eta_{\rm grav} = GM/(Rc^2)$, which is ∼20.6% for typical strange star parameters, and the latter has an efficiency of $\eta_{\rm conv} = \Delta\epsilon/(930\ {\rm MeV})$, where $\Delta\epsilon$ is the energy per baryon released during the phase conversion. The value of $\Delta\epsilon$, which depends on unknown QCD parameters (e.g., MIT bag constant, strange quark mass, and the coupling constant for strong interaction), is rather uncertain. Some recent calculations (e.g., Bombaci & Datta 2000) show that $\Delta\epsilon \sim 100$ MeV may be reasonable, and we will adopt this value for indicative purpose. The deviation of this value from the exact value is not important since this only reflects slightly different required comet masses. We thus get $\eta_{\rm conv} \sim 11\%$. Assuming that about one-half of the energy will be brought away by neutrinos, the total gamma-ray emission efficiency is $\eta_\gamma \sim (\eta_{\rm grav} + \eta_{\rm conv})/2 \sim 16\%$. Thus, the repeating bursts with $L_b \sim 10^{38}$–10^{42} ergs s^{-1} and typical bursting time ∼0.1 s correspond to the comet masses within the range of $7 \times (10^{16}$–$10^{20})$ g. These are reasonable values for comet masses. The so-called giant flare requires an object (an asteroid or a comet) with a mass of several 10^{24} g. Considering that the giant flares are rather rare, it is reasonable to suppose that such large objects may exist in some dense clouds. Notice that all the luminosities quoted above are derived under the assumption of isotropic emission. For impacting events discussed here, during which the emission is anisotropic, the required comet masses may be lowered by a factor of 10–100. There is no mass distribution data available for the solar comets, but we expect that the distribution should be a power law (see also Pineault & Poisson 1989). This is because the stars, which also belong to a gravitationally self-organized system but in a larger scale, have a well-known Salpeter's power-law mass distribution.[7] The bursting intervals depend on the spatial distribution of the comets within their orbits; thus, there should be no correlations between the luminosity of a burst and the waiting time before or after this burst. All these are in excellent agreement with the statistics of the SGR bursts (Gügüs et al. 1999, 2000). Adopting the typical comet mass as the lowest value of the power-law distribution, the comet number density inferred above gives a total comet mass of about 0.1 $M_\odot$, not unreasonable, for the same reasons discussed before.

When a comet falls into the strange star magnetosphere, it will endure tidal distortion and compression so that it is an elongated dense solid object when it reaches the strange star surface (Colgate & Petschek 1981). Because they are globally neutral solid bodies, these comets will not be channeled to the polar cap regions where the asymptotic accretion flow from the fossil disk takes place. This ensures the super-Eddington luminosity emission from a bare strange star. The large Coulomb barrier above the bare quark surface (Alcock et al. 1986a) will not prevent the object from penetrating into the quark core. The rising rate of the energy released from the falling object is similar to the rising rate of the density from a vacuum to solid iron (Howard, Wilson, & Barton 1981; Katz, Toole, & Unrul 1994), so that the rising time of the bursts could be of submillisecond to millisecond order, consistent with the observations of the giant flares (Hurley et al. 1999). The duration of the hard spike observed in the giant flares corresponds to the continuing infall time of the object, which is on the order of 0.1–1 s (e.g., Katz et al. 1994). The August 27 giant flare from SGR 1900+14 has slightly smaller total energy but both longer rising time and longer duration of the initial spike than the March 5 event of SGR 0526−66. This may be understood by assuming that the falling object of the March 5 event is an asteroid while that of the August 27 event is a comet, both with a similar mass. During an impact, both gravitational energy and phase transition energy will be released in a sufficiently short period of time. Since there is no baryon contamination for a bare strange star, the energy will be mainly released as photons and neutrinos. Soon an optically thick pair fireball will form via processes such as γ-γ (Thompson & Duncan 1995) and γ-E (Usov 1998) near a bare quark surface. The magnetic field will confine this pair plasma, and the soft fading tail of the giant flares can be due to contraction of this pair bubble (Thompson & Duncan 1995; Katz 1996). For the accretion case discussed here, the energy deposited into the pair bubble is continually supplied, which is different from the abrupt release case in the magnetar model. Thus, the required magnetic field for confinement is less demanding, i.e., $B > (2L_b/R^2c)^{1/2} = 8 \times 10^{10} G L_{44}^{1/2} R_6^{-2}$ (Katz 1996). The trapped pair plasma has a characteristic temperature of $T \sim 23$ keV, and the emergent spectrum is roughly a blackbody with absorption, which is almost independent on the size of the impacting object (Katz 1996). All these match the SGR phenomenology well.

Sometimes the accreting matter is not solid, but is an ionized plasma. In such cases, the effect of the large Coulomb barrier should be carefully investigated. The kinetic energy of a proton when it is accreted onto the strange star surface is $E_k \sim Gm_pM/2R \sim 100$ MeV. However, when materials are accreted as fluid, it is possible that the kinetic energy will be radiated away via heat before hitting the surface. In the accretion column, the scale of the shock wave zone is dependent on the accretion rate. It is found that when the accretion luminosity is less than $\sim 4 \times 10^{36}$ ergs s^{-1}, the deceleration of the accreting fluid can be neglected (Basko & Sunyaev 1976). This is true for SGRs and AXPs since the quiescent X-ray luminosities of these objects are only 10^{35}–10^{36} ergs s^{-1}. The Coulomb barrier of a bare strange star is $E_C = \frac{3}{4}V_q \sim 15$ MeV, where $V_q^3/3\pi^2 \sim 20$ MeV is defined as the quark charge density inside the quark matter (Alcock et al. 1986a). Thus, the accreting fluid, including that from the fossil disk, can also penetrate into the strange quark core. This ensures the bare strange star picture conjectured in this Letter. The accreted matter at the polar cap will undergo phase transition and release some extra energy. It is unclear whether the slightly harder spectra of the quiescent emission of the SGRs with respect to the AXPs is caused by phase transition (we suppose AXPs to be neutron stars). The enigmatic precursor of the August 29 event of SGR 1900+14 (Ibrahim et al. 2000) may be due to infall of an extended ionized cloud that is followed by a solid object.

Depending on the impacting angles during the captures, the small-scale comet clouds may have various orbital periods and eccentricities so that the precipitation onto the star surface is expected to be periodic, especially when the comets are clustered into a clump in the orbit rather than being spread over the orbit. In fact, SGR 0526−66 has been reported to have a 164 day period in bursts (Rothschild & Lingenfelter 1984). Its present quiescence may be because the previous comet cloud has been depleted as a result of many cycles of precipitations. If it becomes active again, a different period is expected since it may have captured a different cloud. SGR 1900+14, on the other hand, has experienced three active periods: during 1979 (Mazets et al. 1981), 1992 June–August (Kouveliotou et al. 1993), and 1998 May–1999 January (Gögüs et al. 1999). The active periods are short, and the interval between the first two

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[7] Observationally the giant flares belong to the high end of the power-law fluence distributions.

is roughly twice of that between the last two (about 6 yr). This makes us suspect a 6 yr period for SGR 1900+14 activity. According to this picture, there should be some bursts in 1986. But this is within the "detection gap" of the SGR bursts when there is no gamma-ray mission in space before BATSE was launched. *Thus, we expect that SGR 1900+14 should become active again during 2004–2005.* This will give a definite test to our model. SGR 1806−20 activity does not have a clear periodicity. However, a plausible 733 day period is found from its timing residual (Woods et al. 2000). This might be due to comets being spread almost over the whole orbit and the spin-down of the strange star being perturbed by this comet orbit.

In our model, a fossil disk is assumed to interpret the spin-down behavior and the quiescent emission. It is expected that emission (especially during the bursts) should have some interactions with the disk with certain optimal geometric configurations. The chance to see such interactions should be small due to the small size of the disk. The 6.4 keV emission line from the August 19 burst of SGR 1900+14 (Strohmayer & Ibrahim 2000) may be due to the disk's reprocessing of the bursting emission.

3. DISCUSSION

In this Letter, we propose that the peculiar behaviors of the SGRs are due to both their nature (bare strange stars) and their nurture (the Oort cloud in the dense environment). Instead of invoking the magnetar hypothesis, we adopt the strange star hypothesis to interpret some interesting features of the SGRs. It is worth pointing out that the periodic activity does not depend on the nature of the central star. Although some authors argue that the bursting phenomenology (e.g., super-Eddington luminosity) can be also interpreted by colliding comets with a neutron star (e.g., Katz 1996), we think that a bare strange star is a cleaner interpretation due to the reasons discussed above. An important criterion to differentiate our model from the magnetar model is the activity period. If SGR 1900+14 will be turned on again in 2004, the magnetar model is then not favored, since it may be hard to find a mechanism to trigger the magnetic field decay instabilities periodically. If it turns out that some problems (e.g., super-Eddington luminosity, baryonic contamination, and large proper-motion velocity) are not solvable within the neutron star impacting model, the bursts from SGR 1900+14 in time then provide support to the strange star hypothesis and will bring profound implications for fundamental physics.

According to this picture, there might be some other bare strange stars that may also have super-Eddington bursts when they collide with comet-like objects. However, they must have passed through the Oort cloud and/or in a much less dense environment, so the chance to detect repeating bursts is rare. Single bursting events are possible, and they may account for a small portion of the short, soft bursts in BATSE data. The association of SGR 1806−20 with a radio plerion may not be compatible with the present picture, but recent results indicate that the nonthermal radio core of the supernova remnant G10.0−0.3 may be associated with another luminous blue variable rather than with the SGR (Hurley 1999).

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