ON THE NATURE OF SOFT GAMMA-RAY REPEATERS

BING ZHANG
Astronomy & Astrophysics Department, Pennsylvania State University, USA

ABSTRACT. Soft gamma-ray repeaters (SGRs) and Anomalous X-ray pulsars (AXPs) are generally accepted to be magnetars. Recently, Zhang, Xu & Qiao (2000, ApJ, 545, L127) proposed an alternative viewpoint about the nature of the SGRs (and AXPs). In this picture, SGR bursts are attributed to the impacts of some comet-like objects with the central bare strange star. Here I briefly review this model, and confront it with the detailed observations of SGRs/AXPs. A comparison to the magnetar model is also presented. Some theoretical issues concerning the nature of the SGRs (and AXPs) are discussed.

1. An impacting model for SGRs

Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are distinct among other astrophysical objects in several aspects. 1. They are peculiar among the categories they were originally belong to: SGRs are anomalous among the normal gamma-ray bursts, and AXPs are anomalous among the normal X-ray pulsars. 2. These two groups of objects emerging from two distinct astrophysical branches share many common properties (they are also different in some aspects, though). 3. The nature of these objects, as discussed below, is very likely to be exotic, either a neutron star with ultrahigh magnetic fields (a magnetar), or a “neutron star” with exotic interior (a strange star or a hybrid star), or even a combination of the both. Any successful theory should address both the similarities and the discrepancies between SGRs and AXPs.

A well-accepted model for SGRs/AXPs is the magnetar model (see Thompson 2001 for a review). A “nurture” model for the AXPs, which invokes accretion from a fossil accretion disk, is also prevailing (e.g. Chatterjee et al. 2000), but no attempt was made to interpret SGR bursts within this model. Recently, we (Zhang, Xu & Qiao 2000, hereafter ZXQ00) proposed a “nurture + nature” model for SGRs. There are three independent assumptions in this model: 1. plenty of comets exist in the “Oort Cloud” of the massive progenitor of the SGR host, and they occasionally impact the SGR host when the host passes through the Oort Cloud; 2. a fossil accretion disk is formed after the supernova explosion, and accretion from this disk onto the surface of the SGR host is responsible for the long-term spindown behavior of the SGR; 3. Stars composed with strange quark matter, i.e., strange stars, exist in nature, and they are the SGR hosts. A detailed description about how these assumptions can account for the SGR phenomenology is presented in ZXQ00. Here I only highlight two relevant issues: 1. The “nurture” part of the model, i.e., the comet cloud, is more essential for the model, which gives an alternative mechanism (other than magnetic fields) to power the SGR bursts.
The “nature” part of the model, i.e., strange stars, may be not definitely necessary (see more in §3), although their existence makes interpretations easier. 2. An important expectation of this model is the quasi-periodicity of the SGR bursting behavior due to the orbital motion of many comets circulating the SGR host. This results in a direct prediction, i.e., SGR 1900+14 will become active again in the year 2004-2005.

2. Confronting models with observations

2.1. Spindown behavior

The prominent properties of SGRs/AXPs are their long periods and high spindown rates comparing with normal radio pulsars. In the conventional $P - \dot{P}$ diagram, they form a separate island in the upper right corner. Periods are clustering within a narrow range, i.e., 5-12 s. No spin-up is ever observed from these objects. The spindown behavior is usually steady, but not always. Increases of the spindown rate have been observed in two SGRs, which are not necessarily related to the bursting behavior. With $P$ and $\dot{P}$, one can define the characteristic age $\tau \sim P/2\dot{P}$, which is typically $10^3 - 10^4$ year, and the dipolar surface magnetic field $B_s = 6.4 \times 10^{19} G(P\dot{P})^{1/2}$, which is typically $10^{14} - 10^{15} G$. But these estimates are not fully reliable due to the variable $\dot{P}$. Glitches might have been observed from some SGRs/AXPs, but with diverse characteristics. More specifically, the glitch accompanied with the August 27 event of SGR 1900+14 has an opposite sign to those observed in normal pulsars.

The magnetar model gives a straightforward interpretation to the long $P$ and high $\dot{P}$ of the SGRs/AXPs. Electromagnetic dipolar spindown with the magnetic fields inferred from the spindown data can naturally interpret the steady spindown, and the inclusion of some other processes, such as an Alfvén-wave driven particle outflow or free precession of the star due to magnetic distortion, can interpret the viable spindown behavior, including the “negative” glitch (e.g. Thompson et al. 2000). A question is how substantial increase of the wind luminosity could be not related to the bursts.

An alternative model is to attribute the peculiar spindown behavior to accretion from a fossil disk formed after the supernova explosion, which is adopted in the model of ZXQ00. In this model, the spindown behavior of the SGRs/AXPs is also well-interpreted (Chatterjee et al. 2000). The irregular spindown observed in some objects could be due to slightly variation of the accretion rate. It has been argued that long-term steady spindown in some AXPs could be an evidence against the accretion scenario. This criticism is not robust since at least one accretion system has been steadily spinning down for 15 years (Baykal et al. 2000). The “negative” glitch accompanied with the August 27 event may be interpreted in the ZXQ00 model by assuming that the torque exerted by the impact happened to be opposite to the angular momentum of the star.

2.2. Counterparts

No counterpart of SGRs/AXPs in other wavebands has been firmly detected until the recent report by Hulleman et al. (2000), who discovered an optical counterpart for the AXP 4U 0142+61. The authors claimed that optical emission is too faint to admit a large accretion disk, but may be consistent with magnetospheric emission from a magnetar,
although no optical emission model for magnetars is known. It is unclear whether this observation is indeed a support to the magnetar model, but it definitely constrains the accretion models. Two caveats ought to be kept in mind: 1. Invoking beaming effect or truncating inner part of the fossil disk may still revive the accretion scenario (Perna & Hernquist 2000); 2. This particular AXP has no supernova association, which may be intrinsically different (e.g. magnetic white dwarfs) from other AXPs and SGRs.

If the fossil-disk accretion scenario has to be abandoned, the impacting model for SGRs (ZXQ00) ought to be modified to interpret the large spindown rate. Besides the magnetar idea, an alternative approach is to appeal to the peculiar properties of a strange star or a hybrid star as the central object. If the star can excite substantial long-term wind throughout its life, the SGRs/AXPs can keep spinning down rapidly with normal field strength below critical. At present, any operative proposal is lacking.

No SGR/AXP is firmly detected to have pulsed radio emission. Within the magnetar model, this very likely requires that photon splitting operate for both polarization modes in the magnetar environment which completely suppresses pair production (see Zhang & Harding, 2001, and references therein). In the accretion scenario, lack of radio emission is straightforward since accretion prohibits any outflow. That a high magnetic field radio pulsar with similar spin parameters to the AXP 1E 2259+586 lacks strong X-ray emission is a bit problematic for the magnetar model. Something special (much stronger multipole field or different magnetic field origin) has to be assumed at least for 1E 2259+586. The accretion scenario can explain these complications naturally.

2.3. Environments

All SGRs and some AXPs have supernova remnant (SNR) associations. If these associations are real, the ages of the SNRs are found to be usually (an order of magnitude) longer than the “characteristic age” $\tau$ measured from the timing parameters. In some cases (e.g. 1E 2259+586), the discrepancy is the other way round. Assuming SNR associations, the inferred proper motion velocities of the SGRs are generally much higher than those of the normal pulsars. AXPs, however, are almost sitting right in the center of their SNRs, inferring much slower proper motions. SGRs/AXPs are further found to be associated with some dense environments (Rothschild et al. 2001). Two SGRs are associated with two compact massive star clusters, respectively.

In the magnetar model, the shorter characteristic ages with respect to the SNR ages (which may be more reliable) are compatible with the existence of the winds, but the dipolar field strengths are lowered and it is unclear whether the reduced field strengths are still enough to power both the quiescent emission and the bursts. The longer characteristic age for 1E 2259+586 is even problematic, which requires the source to have much larger $P$ in the past, while observations show that this AXP is among those with most steady spindown. The existence of winds makes the things worse. In the accretion scenario, all these are no longer a problem, since the characteristic age is no longer meaningful. There is no explanation within the magnetar model about the large discrepancy between the proper motion velocities of the SGRs and the AXPs. In the picture of ZXQ00, AXPs are assumed to be still neutron stars, while SGRs are assumed to be strange stars, which might have received an additional “kick” during the supernova
explosions. It is also not straightforward why a magnetar should be accompanied with a dense environment and a compact cluster, although their existence do not directly expel the magnetar model. On the other hand, the dense environment favors the formation of the fossil accretion disk, and the compact clusters are ideal places where plenty of comet-like objects required by the impacting model (ZXQ00) may be available.

2.4. Quiescent emission

Both SGRs and AXPs have quiescent pulsed emission with luminosities of \( L_x \sim 10^{35} - 10^{36} \text{ ergs s}^{-1} \), well in excess of the spindown luminosity \( L_{sd} = 4\pi^2 I\dot{P}P^{-3} \). AXPs usually have a blackbody + steep power-law spectrum. SGRs usually have a slightly flatter power-law, and a blackbody component is also observable sometimes. Recently, Kulkarni et al. (2001) discovered that SGR 0525-66, an SGR which was active 20 years ago and has been inactive since then, has a similar steep power-law as those of the AXPs.

Quiescent emission is interpreted as magnetic field decay or enhanced neutron star cooling within the magnetar model. The high pulsation amplitudes of AXPs may contrain some subtypes of these models. The magnetic field decaying luminosities should be positively correlated to the field strength in the decaying model, but such a correlation is not seen from the data, e.g., 1E 2259+586 has the weakest dipolar magnetic field, but a much higher quiescent luminosity than some other SGRs/AXPs. In the accretion scenario, no direct correlation between the X-ray luminosity and \( \dot{P} \) is expected due to the unknown field strength of the star, and high pulse amplitudes are natural due to the accretion column in the polar cap region. However, if the optical counterparts from more AXPs rule out the accretion scenario, some other energy sources have to be incorporated if SGRs/AXPs are not magnetars. A possible source is quark deconfinement (i.e. phase conversion) energy from the central star, which could be either a strange star covered by a crust (Cheng & Dai 1998) or a slowly-contracting “hybrid” star (Dar & de Rújula 2000). No reasonable operative mechanism has been fully proposed so far. The steep power-law spectrum of SGR 0525-66 strongly supports the magnetar model, in which AXPs are inactive SGRs so that a SGR should resemble an AXP after it enters the quiescent phase for a while. It is unclear whether this feature could be incorporated in the impacting model. There are two other arguments against the accretion models (Thompson et al. 2000): 1. the increase in persistent \( L_x \) after a burst is inconsistent with a constant spin-down torque; 2. it is impossible to recover the quiescent emission within one day after the August 27 giant flare since the disk may have been evaporized. These criticisms are valid if bursts are also powered by the disk accretion, but may be invalid for the impacting model (ZXQ00) since the comet impacts are an additional energy source and that they usually occur in the off-polar-cap region.

2.5. Burst characteristics

A prominent feature is that SGR bursts are super-Eddington with luminosities \( L_b \sim 10^{38} - 10^{42} \text{ ergs s}^{-1} \). The fluence distribution is a power law and the waiting time distribution is lognormal. Two giant flares share very similar properties and very detailed information has been collected (see more in Kouveliotou 2001).
In superstrong magnetic fields, the Compton cross section for E-mode photons is strongly suppressed, and the enhanced magnetic Eddington limit could be much higher than the conventional Eddington limit. SGR repeating bursts are interpreted as crust crackings, thus a power law fluence distribution is natural since it has been observed in earthquakes. Giant flares are due to large scale field reconnection, and detailed modeling has been done which can well interpret the August 27 event. Successfully interpreting the SGR burst phenomenology is a key strength of the magnetar model. In the impacting model (ZXQ00), the SGR host is a bare strange star, which may not subject to the Eddington limit at all. The power law fluence distribution can be attributed to a power law distribution of the comet mass (Salpeter’s mass function). The bursting spectra and light curve have been studied by some other authors within the neutron star impacting model. More detailed work needs to be done to meet the recent observations.

3. Some theoretical issues

• Conciseness

In terms of conciseness, the magnetar model is more elegant in that only one assumption (strong fields, i.e. nature) is made. The impacting model is more messy which requires three independent assumptions (§1). However, the special environments of SGRs may indeed require at least two assumptions (nature + nurture), unless one can justify the connection between the nature of the star and the special environments.

• Is a strange star necessary?

In ZXQ00, the necessity of invoking the strange star hypothesis is mainly to interpret the super-Eddington luminosities. Katz (1996) claims that super-Eddington luminosity is achievable in neutron stars if the energy transfer is through magnetic fields. In this sense, the strange star may be not definitely necessary, but one needs to confront the baryon contamination and the large proper motion problems which may be solvable in the strange star picture (ZXQ00). However, if the fossil-disk scenario is eventually ruled out, the strange star hypothesis may be also necessary to interpret the large spindown and quiescent emission, although any operative model has yet been proposed.

• Is the strange star necessary to be bare?

The “bare” strange star invoked by ZXQ00 could exist as long as: 1. the fallback materials in the initial phase of the supernova explosion are not accreted onto the surface (but are “propelled” away), and 2. the accretion luminosity in the “tracking phase” is below $\sim 4 \times 10^{36}\text{ergs s}^{-1}$. Although the second condition is satisfied for SGRs/AXPs, the case for the first condition is unclear. One thing should be commented is that even if the strange star have a crust, the merit of super-Eddington luminosity may still pertain in the impact picture, since the impact may punch a hole all the way down to the quark core and the hole will allow super-Eddington emission (Z. G. Dai, personal communication). However, if the bursts are not powered by impacts, but by some internal processes (Cheng & Dai 1998), the Eddington limit may not be avoided.

• Magnetar, strange star, or strange magnetar?

The magnetar hypothesis is not less exotic than the strange star hypothesis. The possibility of sustaining superstrong magnetic fields by a neutron star was not justified
before, recently, Pérez Martinez et al. (2000) pointed out that under the superstrong magnetic fields conjectured in the magnetar model, the neutron gas pressure in the equatorial direction is too small to balance the magnetic pressure, so that the star will endure a transverse collapse to form a strange star or a hybrid star with a normal magnetic field. Thus magnetars can be only formed temporarily, (i.e. those conjectured to power the cosmic Gamma-ray bursts may exist), but there is no stable magnetars to power SGRs/AXPs. This effect, however, provides a natural mechanism (otherwise may be questionable) to form strange stars. If such a criticism is valid, some other mechanisms such as the impact picture conjectured by ZXQ00 may be responsible for the SGR bursts. On the other hand, Xu & Busse (2000) argued that strange stars, during their birth, may also undergo vigorous convection and dynamo actions to achieve superstrong magnetic fields. Since the star is completely composed of charged quarks, it may be free of the transverse collapse discussed by Pérez Martinez et al. Thus, magnetars, if they do exist in nature, may have to be strange magnetars.

To conclude, the magnetar model is successful in interpreting most of the SGR/AXP phenomenology, but some issues (including their existence) are not fully satisfactory. The impacting strange star model (ZXQ00) may also interpret most of the observations, but more work needs to be done to compare with the detailed data, especially if the fossil-disk accretion scenario is ruled out. Whether SGR 1900+14 becomes active in 2004-2005 may be a key criterion to differentiate between the two scenarios.

Acknowledgements

I thank NASA NAG5-9192 and NAG5-9193 for support and R. X. Xu and G. J. Qiao for stimulative collaborations.

References

Baykal, A., et al.: 2000, astro-ph/0011404.

Chatterjee, P., Hernquist, L., Narayan, R.: 2000, Astrophys. J. 534, 373.

Cheng, K. S., Dai, Z. G.: 1998, Phys. Rev. Lett. 80, 18.

Dar, A., de Rújula, A.: 2000, [astro-ph/0002014].

Hulleman, F., van Kerkwijk, M. H., Kulkarni, S. R.: 2000, Nature 408, 689.

Katz, J. I.: 1996, Astrophys. J. 463, 305.

Kulkarni, S. R., et al.: 2001, Nature, submitted.

Kouveliotou, C.: 2001, in these proceedings.

Pérez Martínez, A., Pérez Rojas, H., Mosquera Cuesta, H. J.: 2000, hep-ph/0011399.

Perna, R., Hernquist, L.: 2000, Astrophys. J. 544, L57.

Rothschild, R. E., et al.: 2001, in these proceedings.

Thompson, C.: 2001, in these proceedings.

Thompson, C., Duncan, R. C.: 1995, Mon. Not. R. Astr. Soc. 275, 255.

Thompson, C., et al.: 2000, Astrophys. J. 543, 340.

Xu, R. X., Busse, F. H.: 2000, astro-ph/0101011.

Zhang, B., Harding, A. K.: 2001, in these proceedings.

Zhang, B., Xu, R. X., Qiao, G. J.: 2000, Astrophys. J. 545, L127 (ZXQ00).