Mem. S.A.It. Vol. 81, 432

Memorie della

Soft gamma repeaters

Kevin Hurley

University of California, Berkeley, Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94720-7450, USA, e-mail: khurley@ssl.berkeley.edu

Abstract. The observational properties of the soft gamma repeaters are reviewed briefly, starting with the time histories and energy spectra of their bursts. The short bursts and giant flares are compared. Their quiescent emission is presented, and the context of the magnetar model is discussed.

1. Introduction

A surprising discovery which unfolded during the 1970s, 80s, and 90s, was that numerous experiments which were built to study cosmic gamma-ray bursts found several sources of short duration, soft-spectrum repeating bursts which appeared to be located in our galaxy and in the LMC (Mazets et al. 1979a,b, Cline et al. 1982, Evans et al. 1980, Atteia et al. 1987, Woods et al. 1999). They were named soft gamma repeaters (SGRs), and for many years, the distinction between them and the cosmic gamma-ray bursts was unclear. A related development occurred in 1995, when two groups (Mereghetti & Stella and van Paradijs et al.) noticed that some slowly rotating galactic X-ray pulsars emitted more energy in quiescent X-rays than their rotation and spin-down could account for. Their periods P were in the 5 - 9 s range, and their period derivatives $\dot{P}$ were $\sim 10^{-11}\,\mathrm{s\,s^{-1}}$. A simple calculation gives the available spin-down energy as $IP\dot{P} \sim 10^{34}\,\mathrm{erg\,s^{-1}}$, where I is the moment of inertia, whereas their X-ray luminosities were $\sim 10^{35}\,\mathrm{erg\,s^{-1}}$. These sources showed no evidence for a binary companion, so the question of what powers them had no obvious answer. They were named Anomalous X-ray Pulsars (AXPs). More recently, some AXP's have been observed to emit short, soft spectrum bursts (e.g. Gavriil et al. 2002).

Today, we believe that both the SGRs and the AXPs are manifestations of a peculiar type of neutron star called a magnetar. A magnetar has a surface field of 10^{15} G or more, and its magnetic energy dominates all other sources of available energy. This energy reservoir is sufficient to power the bursting behavior and the quiescent emission. The basic distinctions between these sources and sources of cosmic gamma-ray bursts are now clear, although it is possible that some events which are classified as short GRBs could in fact be galactic or extragalactic SGR bursts.

The last year has seen the discovery of several new SGRs, thanks to more sensitive instruments and better monitoring. Thus the known population is increasing, and this brings both new knowledge about these sources, and, inevitably, it also raises new questions about them. In this short review, we will concentrate on the observational properties of the SGRs. More complete reviews can be found in Woods and Thompson (2006) and Mereghetti (2008).

The soft gamma repeaters are known primarily as sporadic sources of bursts of X- and gamma-rays. SGRs can remain apparently

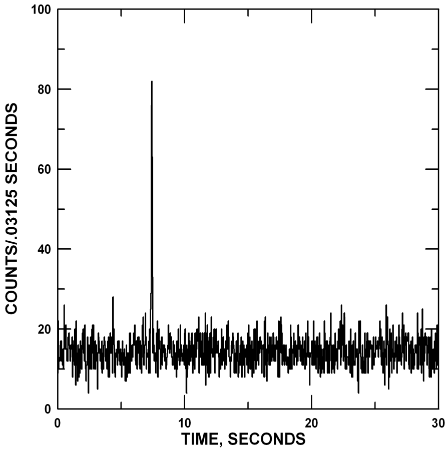

Fig. 1. A typical short burst time history. The time resolution is 32 ms, and the energy range is 25-150 keV. This was recorded with the 20 cm^2 GRB detector aboard Ulysses on 1998 May 30. Bursts such as these are bright enough to be detected from anywhere in the Galaxy by the Interplanetary Network.

burst-inactive for many years; during these periods, although no bursting behavior is observed, the possibility remains that they are indeed emitting very weak bursts which are below the thresholds of most instruments. When they become burst-active however, they emit relatively strong bursts at apparently random times, and it is during these periods that they are discovered. The most common type of burst has a short duration (roughly 100 ms), and a soft spectrum (kT_{BB} $\sim$10 keV). The isotropic energy in this type of event is about 10^{40} erg or more, and the average luminosity is $\sim 10^{41}$ erg s^{-1}. Far rarer, but more interesting, are the giant flares. These last several hundred seconds, have hard spectra extending into the MeV range at least, and display periodic emission. Their total energies exceed 10^{46} erg (Hurley et al. 2005, Palmer et al. 2005, Terasawa et al. 2005). Figure 1 shows the time history of a typical short burst, and figure 2 illustrates the bursting activity of 3 SGRs over a 17 year period.

In figure 3, the broadband energy spectrum of a short burst is shown. The best fit is a two blackbody model, with kT=3.4 keV from 1 to 10 keV, and kT=9.3 keV from 15 to 150 keV. If

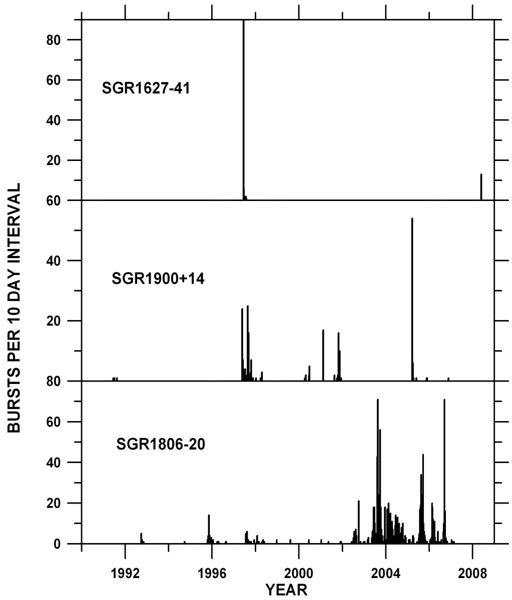

Fig. 2. The bursting activity of 3 SGRs, from the least active at the top, to the most active at the bottom. The number of short ($\sim$100 ms duration) bursts per 10 day interval is shown.

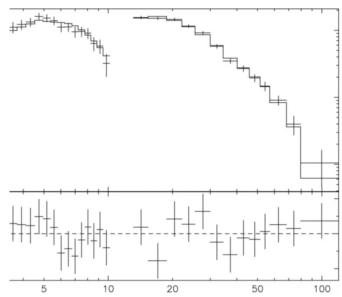

Fig. 3. From Feroci et al. 2004. BeppoSAX MECS and PDS fits to a short burst from SGR1900+14 with a two blackbody function. Reproduced by permission of the AAS.

these fits and temperatures are interpreted literally, they imply emitting areas with radii of 14 and 2 km at 10 kpc, respectively, that is, slightly larger than the surface area of a neutron star, and about equal to its polar cap area.

The most spectacular manifestations of SGRs are the giant flares. Three have been observed to date; no SGR has been observed to emit more than one, but statistical arguments

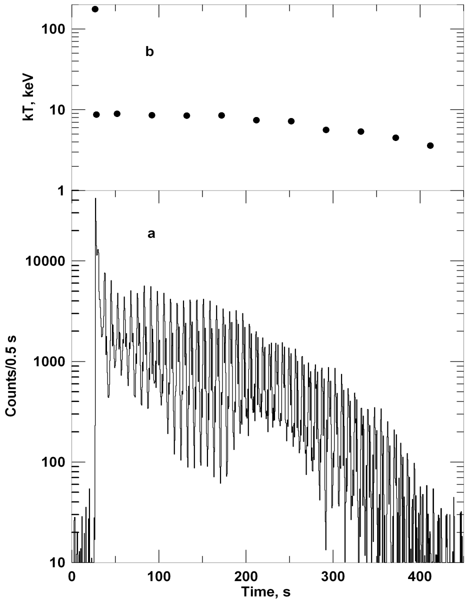

Fig. 4. From Hurley et al. 2005. Bottom panel: the time history of the giant flare from SGR1806-20, as observed by the RHESSI spacecraft in the 20 to 100 keV energy range. Giant flare time histories all display a fast rise, a very intense peak, and a periodic decay with the rotation period of the neutron star. Top panel: the blackbody spectral temperature as a function of time.

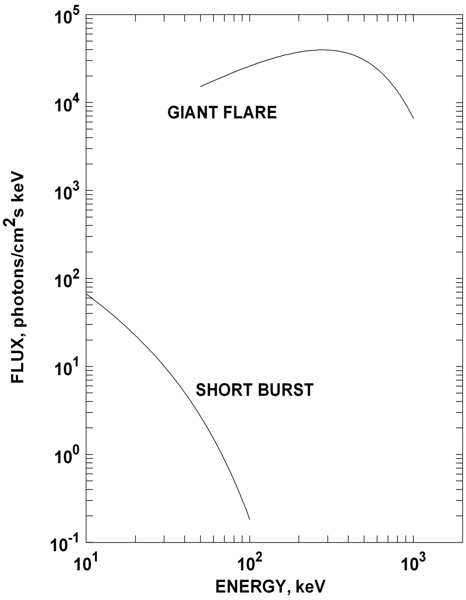

Fig. 5. The energy spectra of short bursts and giant flares compared.

suggest that they could occur perhaps every 30 years on a given SGR. They are extremely intense: the isotropic gamma ray energies reach over 10^{46} erg, and the flux at Earth is 1 erg cm^{-2}. This makes them second only to supernovae in their intensities, albeit a distant second, since SNe release 10^{51} erg. They have very hard energy spectra, which have been observed up to 10 MeV. They create transient radio nebulae and produce dramatic ionospheric disturbances at Earth. Their energetics suggest that they should be detectable in nearby galaxies. Indeed, the March 5 1979 burst from SGR0525-66 originated in the LMC, and there is evidence that they have been detected from M81 and M33 (Ofek et al. 2006, Frederiks et al. 2007, Hurley et al. 2009, Rowlinson et al. 2009, Mazets et al. 2008). Figure 4 shows the time history of a giant flare, and figure 5 compares giant flare and short burst energy spectra.

2. Quiescent emission

The SGRs are quiescent, periodic X- and gamma-ray sources (e.g. Kouveliotou et al. 1998, Hurley et al. 1999, Götz et al. 2006). Even in the absence of detectable bursting activity, this quiescent emission is always present, although it varies in intensity. It has now been measured for most SGRs from around 1 keV to over 100 keV. Figure 6 shows the broadband spectra of two SGRs and 3 anomalous X-ray pulsars. In general, these spectra can be described by a blackbody below 10 keV, and a power law above 15–20 keV. In some cases (e.g. SGR1806-20), the power law photon spectral index would imply a divergent energy output if there were no spectral cutoff. However, the cutoff energies have not been measured yet. Their low energy X-ray luminosities are in the 10^{34} – 10^{36} erg s^{-1} range. The SGRs display period derivatives in the range 10^{-10} to 10^{-11} s s^{-1}, which means that, like the anomalous X-ray pulsars, their X-ray luminosities are greater than can be attributed to spin-down alone. This is one reason why their behavior is often interpreted in the

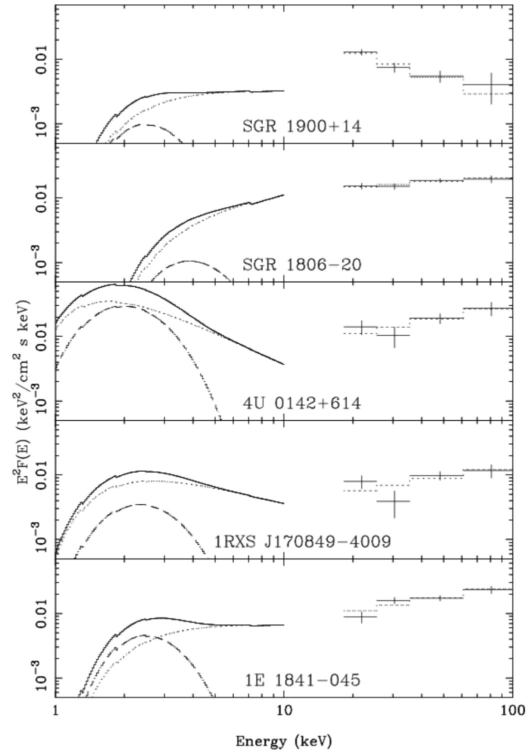

Fig. 6. From Goïz et al. 2006. Broadband ν-Fν spectrum of two SGRs and 3 AXPs. A blackbody fit describes the spectrum below 10 keV, and a power law describes the spectrum above 20 keV. All the high energy spectra have been measured by INTEGRAL-IBIS. Reprinted by permission of Astronomy and Astrophysics.

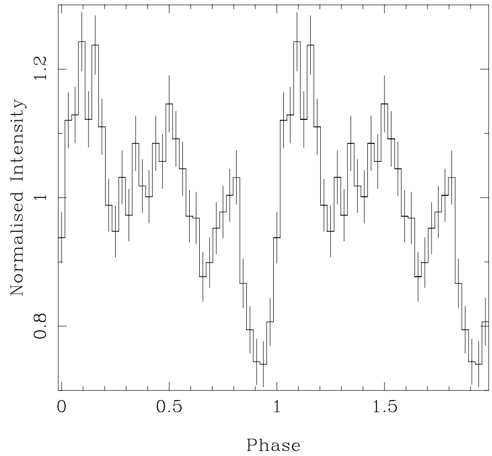

Fig. 7. The folded light curve of SGR1900+14 (Hurley et al. 1999). In the magnetar model, the complexity of the curve is explained by multipolar moments on the neutron star surface and their associated heating. The light curve is time-variable. Reproduced by permission of the AAS.

context of the magnetar model (Thompson and Duncan 1995, 1996).

Folding the X-ray emission modulo the neutron star period gives the light curve shown in figure 7, for SGR1900+14. The light curve is far from a simple sinusoid. It has numerous interpulses, and its shape is time-variable. In the magnetar model, the interpretation is that we are observing hot spots on the neutron star surface which are the result of a multipolar field. The poles evolve and move with time as the magnetic field stresses the surface, causing the light curve to change.

Table 1 gives some of the SGR physical properties. In this table, the surface magnetic field strength is calculated from the measured period and its derivative, and the estimated radius and moment of inertia of the neutron star. Because the period and period derivative are time-variable (the spindown is irregular, and is loosely related to the bursting activity - see Woods et al. 2002, 2006), B can only be calculated approximately.

3. The strange case of 1E1547-5408

One of the newest members of the SGR club was initially thought to be an anomalous X-ray pulsar. 1E1547 was proposed as a magnetar candidate by Gelfand and Gaensler in 2007, and eventually classified as an AXP. In January 2009, however, it was observed to burst by the *Fermi* GBM (Connaughton and Briggs 2009) and the Swift BAT (Krimm et al. 2008). Although this is not unheard of for an AXP, the bursts that it emitted were far more SGR-like than AXP-like. Thus it is tempting to simply say that this source was initially misidentified. However, it would be the only SGR to have a persistent radio counterpart, and one of only two that can be convincingly argued to be associated with a supernova remnant. This object, more than any other, raises

Table 1. Some SGR physical properties. The period, period derivative, and luminosity are time-variable, and approximate.

Name	Giant flare?	Period, s	Period derivative, s s^{-1}	1-10 keV luminosity, erg s^{-1}	B, Gauss
SGR1806-20	Dec 27 2004	7.46	10^{-10}	$2x10^{35}$	$8x10^{14}$
SGR1900+14	Aug 27 1998	5.16	10^{-10}	$3x10^{34}$	$2\text{-}8x10^{14}$
SGR0525-66	Mar 5 1979	8	$7x10^{-11}$	10^{36}	$7x10^{14}$
SGR1627-41	No	2.6	$1.2x10^{-11}$	10^{35}	$2x10^{14}$
SGR0501+45	No	5.8	$5x10^{-12}$	10^{34}	10^{14}
1E1547-5408	No	2.1	$2.3x10^{-11}$	10^{33}	$2.2x10^{14}$

the question of the true differences between AXPs and SGRs, and their significance. The biggest difference seems to be the method of their discovery: AXPs via their quiescent emission, and SGRs via their bursts. Yet AXPs are observed to burst, and SGRs have quiescent X-ray emission whose properties are similar to those of AXPs. It is tempting to downplay the differences between the two, and simply to place them both in the "magnetar" family, with similar DNA, but different appearances.

4. Hosts and progenitors

The host of SGR0525-66 is almost certainly the N49 optical supernova remnant in the LMC (Evans et al. 1980, Cline et al. 1982). 1E1547-5408 lies close to the center of the galactic radio supernova remnant G327.24-0.13 (Gelfand and Gaensler 2007). Other SGR-SNR associations are less certain. SGR0501-4516 lies outside the supernova remnant HB9 (Gaensler and Chatterjee 2008), and may have been ejected from it after acquiring a magnetically driven kick velocity. This idea is testable, because the proper motion of the X-ray counterpart can be measured within a few years.

Two SGRs are probably in massive star clusters. SGR 1900+14 lies along the line of sight to a cluster of about 13 massive stars with ages 1-10 Myr (Vrba et al. 2000, De Luca et al. 2009), and SGR1806-20 lies along the line of sight to a cluster of about 12 stars with ages 3-5 Myr (Fuchs et al. 1999). Bibby et al. (2008) have estimated that the progenitor of the latter SGR must have had a mass of about 48 solar masses. Large progenitor masses are not a requirement of the magnetar model. In the cases of the SGR-SNR associations, the progenitor masses could be considerably less; any star that can produce a core-collapse supernova is probably adequate. Table 2 outlines what is known about hosts and progenitors.

5. Counterparts

All the SGRs have persistent X-ray counterparts. At other wavelengths, the situation is less clear. Most SGRs lie in the galactic disk and are heavily obscured, so no detectable optical counterparts to them are expected. However, at least one SGR has a near-infrared counterpart. Kosugi et al. (2005) and Israel et al. (2005) have identified a faint, variable NIR counterpart to SGR1806-20. Although the IR magnitude varies roughly with bursting activity and with the persistent X-ray flux (the measurements were not exactly simultaneous), the IR flux is not an extrapolation of the X-ray flux. In the case of SGR0501+45, an IR source was found within the X-ray error circle (Tanvir et al. 2008), but its variability has not been definitively established, so it may or may not be the counterpart. In the radio range, only 1E1547 has a persistent counterpart, identified in surveys such as Green et al. (1999); transient radio counterparts to SGR1806-20 and 1900+14 have been observed following their giant flares (Taylor et al. 2005, Frail et al. 1999), but not at other times. These transient radio nebulae presumably consist of clouds of relativistic particles accelerated in the magnetar magnetosphere and expelled from it.

Table 2. SGR hosts and counterparts.

Name	Radio Counterpart?	NIR Counterpart?	X-ray Counterpart?	Host	Progenitor
SGR1806-20	After giant flare (transient)	Yes	Yes	Massive star cluster?	$48M_{sol}$
SGR1900+14	After giant flare (transient)	No	Yes	Massive star cluster?	Massive Star?
SGR0525-66	No	No	Yes	SNR	Normal Star?
SGR1627-41	No	No	Yes	?	?
SGR0501+45	No	Maybe	Yes	SNR?	?
1E1547-5408	Yes	No	Yes	SNR	Normal Star?

6. How many are there?

There are 5 or 6 confirmed SGRs (depending on how one categorizes 1E1547), mostly discovered through their bursting activity. "Confirmed" means that the sources have emitted numerous bursts, their quiescent X-ray counerparts have been identified, and their periods and period derivatives have been measured. There could in principle be many more which are undiscovered because they are not burst-active. In fact, there are several unconfirmed SGRs which have burst once or twice, but went quiescent after that: examples are SGR1801-23 (Cline et al. 2000), 1808-20 (Lamb et al. 2003), and 0418+5729 (van der Horst 2009). Occasionally, GRBs are proposed as possible SGRs due to their time histories, energy spectra, and/or galactic latitude; examples are GRB050906 (Levan et al. 2008), 081011 (Stamatikos et al. 2008), 081024 (Stratta et al. 2008), and 050925 (Markwardt et al. 2005, Holland et al. 2005). It is difficult to confirm any of these sources until and unless they are observed to repeat, and/or their quiescent emission is detected and their periods measured. However, Muno et al. (2008) have done a comprehensive study of Chandra and XMM point sources, in which they searched for periodicities and spin-down. Their study did not reveal any new candidates, and they set a limit of <540 in the Galaxy. This still leaves open the question of extragalactic magnetars. One, SGR0525-66, has definitely been observed. If magnetar giant flares reach intensities of over 10^{46} erg, they should be detectable out to distances of at least 10 Mpc, and possibly ten times farther with sufficiently sensitive detectors, where they would look like short duration, hard spectrum gamma-ray bursts. Their positions would be consistent with those of relatively bright galaxies. Two candidates have been observed recently, one of which is possibly from M81, and the other possibly from M31 (Frederiks et al. 2007; Mazets et al. 2008; Hurley et al. 2009; Rowlinson et al. 2009).

Finally, there could be manifestations of magnetars that we have not yet imagined.

7. Conclusions

Table 3 compares some properties of SGRs and AXPs. As we monitor the existing sources more, and as we discover new ones, their properties are likely to converge even more.

All of the properties of the known and candidate SGRs and AXPs are consistent with the magnetar model. However, independent evidence for this model, such as the repeatable observation of cyclotron resonance features, remains elusive (Strohmayer and Ibrahim 2000; Ibrahim et al. 2002; Ibrahim et al. 2003). Such an observation would provide an independent estimate of the magnetic field strength. Alternative models, such as fall-back accretion disks (Ertan and Caliskan 2006), or transitions in strange stars (Cheng and Dai 2002), have been proposed, but relatively little has been written about them to date. Regardless of the model used to explain them, there is growing evidence that the distinction between AXPs and SGRs is not as meaningful as it was once thought to be, since their physical properties

Table 3. Some SGR and AXP properties compared.

Phenomenon	SGRs	AXPs
Small Bursts	Relatively Frequent	Relatively Rare
Giant Flares	Yes	No
Quiescent X-rays	Yes, to >100 keV	Yes, to >100 keV
Radio emission (1E1547 excluded)	Following giant flares only	1–2 cases known, transient
Periods	2.6-8 s	2-11 s
Spindown	.5-20 × 10^{-11} s s^{-1}	0.05-20 × 10^{-11} s s^{-1}
Hosts	Massive star clusters, SNRs?	SNRs?

are so similar. Only a deeper understanding of their hosts, progenitors, and multiwavelength counterparts will resolve this issue.

8. DISCUSSION

WOLFGANG KUNDT's comment: In your most informative talk, you did not mention the various constraints from fundamental physics which are at variance with large distances (> 30 pc) of the SGRs, such as: photon crowding at the source, early afterglow onsets, largely super-Eddington powers, growth rates of radio lobe, and neutron star energetics.

KEVIN HURLEY: Since this was intended to be an observational review, and since I'm not a theoretician, I did not delve deeply into the theoretical aspects. However I believe that you will find answers in the Duncan and Thompson references to the issues of photon crowding and super-Eddington luminosities, as well as neutron star energetics. For the radio lobe growth following giant flares, see the Taylor et al. reference.

BIDZINA KAPANADZE: None of the SGRs have an optical counterpart. Is it possible that these objects undergo optical flares and what stellar magnitudes could they achieve in such a case?

KEVIN HURLEY: Most of the SGRs have no observable optical counterparts because they are in the Galactic plane and heavily obscured. However, SGR0525-66, which is in the LMC, has very low extinction, and a search for optical flares was done a long time ago (Pedersen, H., et al., Nature 312, 46, 1984). What we found was evidence for 3 optical flashes, the brightest of which reached m_V=8.7. This was in the absence of any bursting activity. I would imagine that there could be very bright optical flares associated with bursts, and particularly with giant flares.

GUSTAVO E. ROMERO: Not long ago it was suggested that the compact object LS I +61 303 was a magnetar. Do you think that such a claim is reasonable?

KEVIN HURLEY: LS I +61 303 is a binary which emits up to TeV energies. It was observed to burst once during a *Swift* observation, although it is not absolutely certain that the observed burst came from this source. Dubus and Giebels (Astron. Tel. 1715, 2009) suggested that the source was a magnetar based on the duration and energy spectrum of the burst. So from this point of view, the suggestion is reasonable. But this would be the first case of a magnetar in a binary system, and the first case of one that emits to TeV energies, so it would be quite unusual. Also, we know that everything that bursts is not a magnetar, so there could be other explanations for this behavior.

ANTONINO DEL POPOLO: In 1992, 3 extra-solar planets (Wolszczan and Frail) were discovered around a pulsar. A couple of years ago a fall-back disk was observed. This leads to think that disks around pulsars behave like the ones in usual pulsar systems. Planetesimals contained in the disk can migrate due to the migration I mechanism. The collision with the pulsar (or better with a strange star) will produce a burst like the ones observed in SGRs. Could you comment on this?

KEVIN HURLEY: Actually, Ali Alpar has revisited this subject very recently and concluded that fall-back disks can co-exist with the magnetar model, although he believes that the fall-back disks are not related to the bursts. I refer you to his Aspen 2009 presentation: `http://www.pd.infn.it/astro/pers/aspen2009/presentations/alpar.pdf`

Acknowledgements. I am grateful to the conference organizers for support, and to NASA for support under the INTEGRAL U.S. Guest Investigator Program, Grant NNX08AC89G.

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