Mem. S.A.It. Vol. 80, 186

Memorie della

The giant flare of 2004 Dec 27 from SGR1806-20 and fundamental physics from magnetars

L. Stella, S. Dall'Osso, and G. L. Israel

INAF-Osservatorio Astronomico di Roma, Via di Frascati 33, I-00040 Monteporzio Catone (Roma), e-mail: stella@mporzio.astro.it

Abstract. In the last decade strong evidence has been found for the existence of magnetars, neutron stars whose electromagnetic emission is powered by their extremely high magnetic field. Two classes of X-ray/gamma-ray sources, the Soft Gamma Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs) have been identified with isolated, slowly spinning magnetars. A new perspective in this field was brought about by the 2004 December 27 giant flare from SGR 1806-20. The enormous energy liberated in this event (5×10^{46} ergs) points to an internal magnetar field of $> 10^{16}$ Gauss. Some of implications of this extraordinary event are surveyed here. These include: (a) the opening of the new field of neutron star astroseismology; (b) the detection of the highest luminosity derivative ever from a non-expanding source, with implication for radiative transfer effects in very strong magnetic fields; (c) newborn fast spinning magnetars can be very powerful sources of gravitational waves, detectable up to Virgo Cluster distances with Advanced LIGO/Virgo; (d) a sizable fraction of Short Gamma Ray bursts might be due to very powerful giant flares from magnetars in the nearby universe; (e) The effects of a nearby very powerful giant flare on the Earth are of interest for understanding the past and future of life.

Key words. stars: individual (SGR 1806-20) – X-Rays: bursts – stars: magnetic fields – stars: neutron gravitational waves – Stars: Oscillations

1. Introduction

Most of the neutron stars that are currently known are either radio pulsars, whose electromagnetic emission is powered by their rotational spindown, or accreting neutron stars in binary systems, which emit high energy radiation as a result of the gravitational energy liberated by the accreting matter. For both classes of neutron stars, magnetic field strengths over the range $\geq 10^{8} - 10^{13}$ Gauss have been inferred. Predating the discovery of radio pulsars, the idea that neutron stars could radiate energy deriving from the dissipation of their magnetic field (Woltjer 1964) has, since the early 90's, been invoked in the *magnetar* model (Duncan & Thompson 1992; Thompson & Duncan 1993, 1995, 1996, 2001). The scenario assumes the existence of neutron stars in which a strong toroidal field, reaching strengths that may exceed 10^{15} G, is produced by differential rotation of the proto-neutron star (Duncan & Thompson

Send offprint requests to: L. Stella

1992; Thompson & Duncan 1993). A gradual and/or impulsive dissipative release of energy from this powerful magnetic reservoir then powers the electromagnetic (mainly high-energy) emission from such objects.

Two classes of high-energy sources, the Soft Gamma Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs) are believed to host *magnetars* (Mereghetti & Stella 1995; Kouveliotou et al. 1998; Woods & Thompson 2006). About 15 SGRs and AXPs are known at present in our Galaxy and the LMC; they are isolated X-ray/gamma-ray sources, have spin periods of $\sim 2 \div 12$ s and spin-down secularly with $\sim 10^4 \div 10^5$ yr timescale. Rotational energy losses are ~ 100 times too low to explain their $\sim 10^{34} \div 10^{35}$ erg/s persistent luminosity: therefore the main source of power of AXPs and SGRs cannot be rotational power (this is unlike radio pulsars). Both AXPs and SGRs undergo periods of paroxysmal activity during which recurrent bursts with subsecond duration are emitted; in SGRs must bursts have peak luminosities of $\sim 10^{38} \div 10^{41}$ erg/s. SGRs also show, on rare occasions, much more extreme events known as giant flares. These are characterised by an initial spike of duration comparable to that of recurrent bursts, but many orders of magnitude larger luminosity. Only three giant flares have so far been observed in over 30 yr of monitoring. The highly super-Eddington luminosities of recurrent bursts and, especially, giant flares, rule out accretion as the (main) energy source: therefore SGRs and AXPs are unlike accreting neutron stars.

The magnetar model was proposed in order to explain the salient observational features SGRs and AXPs, circumventing the above difficulties of canonical scenarios. In addition to the internal (mainly toroidal) field, magnetars possess an external (mainly poloidal) field that makes up the neutron star magnetosphere; external field strengths of $B_d \sim 10^{14} \div 10^{15}$ G are required to give rise to the observed spin-down via dipole radiation losses (Thompson & Duncan 1993; Thompson & Murray 2001). Other independent arguments indicate values of the external magnetic in the same range. According to the magnetar model energy is fed impulsively to the neutron star magnetosphere when local "crustquakes" let magnetic elicity propagate outwards, giving rise to recurrent bursts with a large range of amplitudes. Giant flares are believed to originate from large-scale rearrangements of the inner field or catastrophic instabilities in the magnetosphere (Thompson & Duncan 2001; Lyutikov 2003). Most of this energy breaks out of the magnetosphere in a fireball of plasma expanding at relativistic speeds which produces the initial spike of giant flares. The decaying, oscillating tail that follows the spike displays many tens of cycles at the neutron star spin. This is interpreted as due to a "trapped fireball" which remains anchored inside the magnetosphere and cools in a few minutes. The total energy released in this tail is $\sim 10^{44}$ erg in all three events detected so far.

An estimate of the internal field strength of magnetars can be obtained through energy arguments: the energy in the field must be high enough to power the emission of SGRs and AXPs over their $10^4 - 10^5$ yr lifetime (as estimated from the spin-down timescale and/or the age of the supernova remnants some magnetars are associated to). Until 2004, the energy budget of SGRs and AXPs was believed to be dominated by their persistent emission at a level of $\sim 10^{35}$ erg s^{-1}. This translated into an internal field of $\sim 10^{15}$ G.

The properties of the 2004 Dec 27 giant flare from SGR1806-20 require that the emission budget of magnetars is dominated by Giant Flares. The argument is summarised as follows. About 5×10^{46} erg were released during the ~ 0.6 s initial spike of this event (Terasawa et al. 2005; Hurley et al. 2005; Stella et al. 2005). This is more than two decades higher than the energy of the other two giant flares observed so far. Since only one such powerful flare has been recorded in over 30 yr of monitoring of the ~ 5 known magnetars in SGRs, this converts to a recurrence time of such events of ~ 150 yr per magnetar. In a timescale of $\sim 10^4$ yr about 70 very powerful giant flares should be emitted which release in total an energy of $\sim 4 \times 10^{48}$ erg. We note that if these giant flares were beamed in a fraction b of the sky (and thus the energy released in individual flares a factor of b lower), their recurrence time would be a factor of b shorter. Therefore the total energy released in giant flares would remain the same. The magnetar internal B-field required to give rise to this energy is $\geq 10^{15.7}$ G. Taking into account the contribution from neutrino emission that accompanies magnetic field dissipation, the lower limit on the magnetar internal field becomes $\geq 10^{15.9}$ G (Stella et al. 2005). Very strong toroidal B fields of $\geq 10^{16}$ G are expected to be generated inside a differentially rotating millisecond spinning neutron star, subject to vigorous neutrino-driven convection instants after its formation.

The 2004 Dec 27 event from SGR1806-20 has had important implications for several subjects at the forefront of research. We summarise in the following some of them.

2. Fast quasi periodic oscillations and neutron star seismology

A power spectrum analysis of the high time resolution data from the 2004 Dec 27 event led to the discovery of fast Quasi Periodic Oscillations in the X-ray flux of the ringing tail of SGR giant flares (Israel et al. 2005). QPOs of different frequencies were detected, some of which were active simultaneously. The ringing tail of giant flare from SGR 1806-20 displayed highly significant QPO signals at about 18, 30, 93, 150, 625 and 1840 Hz (Watts & Strohmayer 2006). A re-analysis of the ringing tail data from the 1998 giant flare of another magnetar, SGR 1900+14, revealed QPOs around frequencies of 28, 54, 84 and 155 Hz (Strohmayer & Watts 2005). Hints for a signal at ~ 43 Hz in the March 1979 event from SGR 0526-66 were reported as early as 1983 (Barat et al. 1983). These QPO signals show large amplitude variations with time and, especially, phase of the star's rotational modulation as seen during the ringing tail of the giant flare.

The similarity of some of the QPO frequencies across different SGRs indicates that the QPO production mechanism is the same in all SGRs. The most natural interpretation involves the excitation of neutron star oscillation modes, that propagate to the neutron star magnetosphere and modulate the radiation emitted by the trapped fireball. In fact, if giant flares originate in massive fracturing of the crust caused by instabilities of the internal magnetic fields, then the excitation of crustal and as well as global neutron star modes is to be expected (Levin 2006). Some of the expected eigenfrequencies match the observed QPO frequencies (Duncan 1998; Israel et al. 2005; Piro 2005). These findings have opened the field of neutron star seismology: they provide an unprecedented probe of the star's crust and interior.

3. The highest luminosity derivative from a non-expanding source

The fastest QPO signals from the giant flare of 2004 Dec 27 from SGR 1806-20 testify to the presence of exceptionally high luminosity time derivative (Watts & Strohmayer 2006). The power spectrum peaks through which these QPOs are revealed, are a few Hz wide and do not have higher harmonics. Therefore their signal must have been nearly sinusoidal and coherent for hundreds of cycles. The 1840 Hz QPOs were detected only during a ~ 50 s long interval of the ringing tail and reached amplitude of $a_{rms} \sim 18\%$ over a ~ 140 deg interval in the star's rotational phase. Such variations translates into a luminosity derivative of $\Delta L/\Delta t \sim 3 \times 10^{44}$ ergs s^{-2}. After correction for the effects of beamed radiation (which can only be moderate) the above value reduces to 6×10^{43} ergs s^{-2} (see Vietri et al. 2007). The very fact that the QPO amplitude is modulated at the rotational phase of the neutron star and that the ringing tail displays pulsations at the star spin that are similar to those seen in quiescence indicates that the emitting region remains anchored to the star's magnetosphere, and thus that relativistic bulk motions are not present at this stage of the flare.

The above value of the luminosity derivative is thus the highest ever detected from a *non-expanding* source. It exceeds by more than an order of magnitude the so-called Cavallo-Fabian-Rees (CFR) luminosity variability limit for a matter-to-radiation conversion efficiency of $\eta = 100\%$. This limit is derived in the basis of simple arguments and is very difficult to overcome. In essence the reasoning is the following: suppose that a fraction η of the rest mass energy of a sphere of matter is instantaneously converted into radiation. The more matter is in the sphere the more radiation is produced. However the time it takes radiation to escape from the sphere, besides the sphere size, is dictated by the time it takes radiation to random-walk out. The latter increases rapidly when the mass, and thus the number of scattering particles, increases. The highest luminosity derivative of CFR ($\Delta L/\Delta t < \eta\, 2 \times 10^{42}$erg s^{-2}) results from a trade-off between the two effects described above, when Thomson cross-section dominates the (scattering) opacity. Vietri et al. (2007) demonstrate that the extreme luminosity derivative associated to the fast QPOs in the ringing tail of the 2004 Dec 27 giant flare can be reconciled with the CFR limit if the emitting region is immersed in a magnetic field $\gtrsim 10^{15}$ G at the star surface, an environment in which the cross-section for electron scattering by photons (in the *extraordinary mode*) is much reduced with respect to the Thomson cross-section. This result provides independent evidence for the superstrong magnetic fields of magnetars, through the effects that such fields have on radiative transfer (Vietri et al. 2007).

4. Newborn fast spinning magnetars and gravitational waves

It has long been known that the anisotropic pressure of the B-field induces an ellipticity in a magnetic star. If the axis of the magnetic distortion is not aligned with the spin axis, the star's rotation causes the emission of gravitational waves, GWs. Several authors, notably Cutler (2002), discussed the likely implications for fields of $\sim 10^{15}$ G: a newborn magnetar spinning at a few millisecond period will radiate a GW signal that interferometers such as Advanced LIGO/Virgo would easily detect in our galaxy. Unfortunately, the expected magnetar birth rate in the Galaxy is disappointingly low (of order $\sim 10^{-3}$ yr^{-1}).

If instead a magnetar's internal B-field is of $\geq 10^{16}$ G, as implied by the 2004 Dec 27 giant flare, then newly born, millisecond spinning magnetars are conspicuous sources of gravitational radiation, detectable for days to weeks up to Virgo cluster distances by the forthcoming generation of GW interferometers. A very relevant point is that a rich cluster containing ~ 2000 galaxies such as Virgo, is expected to give birth to magnetars at a rate of ~ 1 yr^{-1}. A fraction of these are likely to have sufficiently high toroidal fields that their signal can be detected with the Advanced LIGO/Virgo class interferometers. An evolving periodic GW signal at ~ 1 kHz, whose frequency halves over a few days, would unambiguously reveal the early days of a fast spinning magnetar.

This scenario is fully compatible with recent X-ray studies of Supernova Remnants surrounding galactic magnetar candidates (Dall'Osso & Stella 2007). These remnants do not show any signature of a larger than usual energy injection in the first days after their explosion (Vink & Kuiper 2006). This excess energy injection would be expected if the peculiarly large NS initial spin energy were emitted in the electromagnetic channel, e.g. through magnetodipole spin-down. The finding by Vink & Kuiper which may at first rise doubts on the magnetar formation scenario, is in fact consistent with it provided the internal magnetic field at birth was $> 10^{16}$ G range. In this case, a newly formed magnetar spinning at $\sim$ ms period would have lost most of its initial spin energy to GWs rather than electromagnetically.

5. Very powerful giant flares from magnetars and short gamma ray bursts

A sizeable fraction of the short Gamma Ray Bursts might be due to very powerful giant flares form magnetars. Soon after the 2004 Dec 27 event it was realised that powerful giant flares could be observed from distances of tens of Mpc and thus might represent a sizeable fraction of the short Gamma Ray Burst population (see e.g., Hurley et al. 1999). This motivated searches for 2004 Dec 27-like events in the BATSE GRB database. The conclusion of these studies are ambiguous. Based on the paucity of candidate events, upper limits were derived on the incidence of very powerful giant flares in the BATSE sample of short GRBs and on the recurrence time of powerful giant flares (Lazzati et al. 2005; Popov & Stern 2006). The conclusion of these studies was that the 2004 Dec 27 event was "statistically unlikely". On the other hand Tanvir et al. (2005) found that the location of $10 \div 25\%$ of the short GRBs in the BATSE catalogue correlates with the position of galaxies in the local universe (< 110 Mpc), suggesting that a comparable fraction of the short GRBs may indeed originate from a local population of very powerful giant flare-like events. This is an important open issue in magnetar research.

6. Nearby giant flares from magnetars and life on Earth

High energy impulsive events such as GRBs or Magnaters' Giant Flares occurring close to the solar system might have caused some of the mass extinctions in the Earth's geological record (Scalo & Wheeler 2002; Melott et al. 2004). An important impact of a high energy event is on atmospheric chemistry due to ionisation and dissociation of O_2 and N_2, and the resulting formation of nitrogen oxide compounds. The destruction of stratospheric ozone increases the amount of solar UVB radiation reaching the ground and enhances dramatically DNA damage. According to recent studies total burst fluence and average photon energy are the most important parameters driving the impact of a nearby high energy event on the Earth atmosphere (Thomas & Melott 2006; Ejzak et al. 2007). The 2004 Dec 27 giant flare from SGR 1806-20 had highest fluence ($\sim$ 2 erg/cm^2) ever recorded from a high energy impulsive event.

7. Discussion

A new very powerful giant flare like that of 2004 Dec 27 from SGR 1806-20 would provide the best confirmation that SGRs emit tens of such events over their lifetime and therefore must contain a very large internal energy reservoir (such as a 10^{16} G internal magnetic field) in order to power them. Given that giant flares in our Galaxy are rare, they can be studied more effectively by sampling a large number of galaxies in the local universe. Both the recurrence times of such events and their fluence distribution can be reliably estimated in this way.

Concerning the birth rate of magnetars, this has so far been estimated based on the number of AXPs and SGRs in our galaxy and their age (as deduced from their spin down age and/or the age of the Supernova Remnants they are associated to). However, the number of magnetars might have been underestimated by a fairly large factor, as recent results show that besides persistent AXPs and SGRs, there exist transients source of this type. Depending on the recurrence time of the latter (which is presently unknown), galactic magnetars (that have so far remained undetected) can be much more numerous than presently estimated and their birth rate correspondingly higher.

Acknowledgements. We are grateful to all our collaborators in magnetar-related projects. This work was partially supported through ASI and MIUR grants.

References

Abbott, B. et al. 2005, [LIGO Scientific Collaboration] gr-qc/0508065
Alpar, A. & Pines, D., 1985, Nature, 314, 334
Alpar A. & Sauls J. A. 1988, ApJ, 327, 723
Arzoumanian, Z., Cordes, J. M., & Chernoff, D. F. 2002, ApJ, 568, 289
Barat, C., et al. 1983, A&A, 126, 400
Bonazzola, S. & Marck, J. A. 1994, Ann. Rev. Nucl. Part. Sci., 45, 655
Bonazzola, S. & Gourgoulhon, E. 1996, A&A, 312, 675
Brady, P., Greighton, T., Cutler, C. & Schutz, B. F. 1998, Phys. Rev. D, 57, 2101
Brady, P. R. & Creighton, T. 2000, Phys. Rev. D, 61, 082001
Cutler, C., Phys. Rev. D 2002, 66, 084025
Cutler, C., Golami, I. & Krishnan, B. 2005, gr-qc/0505082
Dall'Osso, S. & Re, V. 2007, *submitted*
Dall'Osso, S. & Stella, L. 2007, Ap&SS, 308, 119

Duncan, R. C. 1998, ApJ, 498, L45
Duncan, R. C. & Thompson, C. 1992, ApJ, 392, L9
Ejzak, L. M., Melott, A. L., Medvedev, M. V., & Thomas, B. C. 2007, ApJ, 654, 373
Feroci, M. et al. 1999, ApJ, 515, L9
Gaensler, B. M., Gotthelf, E. V. & Vasisht, G. 1999, ApJ, 526, L37
Hurley, K. et al. 1999, Nature, 397, 41
Hurley, K. et al. 2005, Nature, 434, 1098
Israel, G. L., et al. 2005, ApJ, 628, L53
Jaranowski, P., Krolak, A. & Schutz, B. F. 1998, Phys. Rev. D, 58, 063001
Jones, D. I. 2002, Class. Quantum Grav., **1**9, 1255
Jones, D. I. & Andersson, N. 2002, MNRAS, 331, 203
Konno, K., Obata, T. & Kojima, Y. 2002, A&A, 356, 234
Kouveliotou, C. et al. 1998, Nature, 393, 235
Krishnan, B. et al. 2004, Phys. Rev. D, 70, 082001
Lazzati, D., Ghirlanda, G. & Ghisellini, G. 2005, MNRAS, 362, L8
Levin, Y. 2006, MNRAS, 368, L35
Lyutikov, M. 2003, MNRAS, M.N.R.A.S., 346, 540
Mazets, E. P. et al. 1979, Nature, 282, 587
Melott, A. L., et al. 2004, International Journal of Astrobiology, 3, 55
Mereghetti, S. & Stella, L. 1995, ApJ, 442, L17
Mestel, L. & Takhar, H. S. 1972, MNRAS, 156, 419
Nakar, E. et al. 2006, ApJ, 640, 849
Owen, B. J. & Lindblom, L. 2002, Class. Quantum Grav., 19, 1247
Palomba, C., 2001, A&A, 367, 525
Piro, A. L. 2005, ApJ, 634, L153
Prakash, M. & Lattimer, J. M. ApJ, 500, 426
Popov, S. B. & Stern, B. E. 2006, MNRAS, 365, 885
Scalo, J., & Wheeler, J. C. 2002, ApJ, 566, 723
Stella, L., Dall'Osso, S., Israel, G. L. & Vecchio, A. 2005, ApJ, 634, L165
Strohmayer, T. E., & Watts, A. L. 2005, ApJ, 632, L111
Tanvir, N. R., Chapman, R., Levan, A. J. & Priddey, R. S., 2005, Nature, 438, 991
Terasawa, T. et al. 2005, Nature, 434, 1110
Thomas, B. C., & Melott, A. L. 2006, New Journal of Physics, 8, 120
Thompson, C. & Duncan, R. C., 1993, ApJ, 408, 194
Thompson, C. & Duncan, R. C., 1995, MNRAS, 275, 255
Thompson, C. & Duncan, R. C., 1996, ApJ, 473, 322
Thompson, C. & Duncan, R. C., 2001, ApJ, 561, 980
Thompson, C.& Murray, N. C., 2001, ApJ, 560, 339
Thompson, T. A., Chang, P. & Quataert, E. 2004, ApJ, 611, 380
Thorne, K. S. 2000, LIGO Internal Document G000025-00-M
Ushomirsky, G., Cutler, C. & Bildsten, L. 2000, MNRAS, 319, 902
Vietri, M., Stella, L. & Israel, G. L. 2007, ApJ, 661, 1089
Vink, J. & Kuiper, L. 2006, MNRAS, 370, L14
Watts, A. L., & Strohmayer, T. E. 2006, ApJ, 637, L117
Woltjer, L., 1964, ApJ, 140, 1309
Woods, P. M. & Thompson, C. 2004, `astro-ph/0406133v2`