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Systematic study of magnetar outbursts

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Abstract. We present the results of a systematic study of all magnetar outbursts observed to date through a reanalysis of data acquired in about 1100 X-ray observations. We track the temporal evolution of the luminosity for all these events, model empirically their decays, and estimate the characteristic decay time-scales and the energy involved. We study the link between different parameters, and reveal several correlations between different quantities. We discuss our results in the framework of the models proposed to explain the triggering mechanism and evolution of magnetar outbursts.

Keywords. stars: magnetic fields, stars: neutron, pulsars: general, X-rays: stars

1. Introduction

Magnetars are strongly magnetized (up to $B \sim 10^{14} - 10^{15}$ G) isolated X-ray pulsars with spin periods $P \sim 2 - 12$ s and secular spin-down rates $\dot{P} \sim 10^{-15}$–10^{-11} s s^{-1}, whose emission is ultimately powered by the decay and the instability of their ultra-strong magnetic field. They unpredictably undergo outbursts, where the persistent X-ray luminosity increases by a factor of $\sim 10 - 1000$ up to $\sim 10^{35} - 10^{36}$ erg s^{-1}, and then declines back to the quiescent level on a time-scale ranging from a few weeks up to years.

Here we present the results of a systematic and homogeneous analysis of the spectral properties for 23 outbursts (from the very first active phases throughout their decays) from 17 magnetars using all the available data acquired by the *Swift*, *Chandra* and *XMM–Newton* X-ray observatories, as well as data collected in a handful of observations by the instruments aboard *Beppo*SAX, *ROSAT* and *RXTE*. This sums up to about 1100 observations, for a total dead-time corrected on source exposure time of more than 12 Ms.

2. Data analysis and correlation searches

We adopted standard procedures to extract source and background spectra and create or assign the response and auxiliary files starting from the raw *Swift*, *XMM–Newton* and *Chandra* data files publicly available. We fitted either a black body, a power-law, a black body plus a power-law, the superposition of two blackbodies or a resonant cyclotron scattering model (NTZ) to the spectral data sets, within XSPEC. In a few cases, the higher statistics quality available from *XMM–Newton* observations allowed us to probe more complicated models, such as the sum of three black-body components. The photo-electric absorption by the interstellar medium along the line of sight was described via the Tuebingen-Boulder model. The fluxes for the additive components and the total one (all in the 0.3–10 keV energy range) were computed for each fitted spectrum. Unabsorbed

Table 1. Results of the search for (anti-)correlations between different parameters. Values for the significance are not reported if below 2σ. Values for the power-law index indicate the shape of the (anti-)correlation, and were estimated via a power-law regression test.

First parameter	Second parameter	Corr/Anticorr, Significance (σ) (c) or (a), Spearman / Kendall τ	PL index
Quiescent X-ray luminosity	Maximum luminosity increase	(a), 5.7 / 4.9	-0.7
Dipolar magnetic field	Quiescent bolometric thermal luminosity	(c), 3.2 / 2.9	2.0
Dipolar magnetic field	Peak luminosity	(c), 2.5 / 2.4	0.5
Dipolar magnetic field	Outburst energy	(c), 3.7 / 3.3	1.0
Characteristic age	Outburst energy	(a), 3.3 / 3.0	-0.4
Peak luminosity	Outburst energy	(c), 4.0 / 3.7	1.4
Outburst energy	Decay time-scale	(c), 3.9 / 3.6	0.5

fluxes were converted to luminosities (as measured by an observer at infinity) assuming isotropic emission and the most reliable value for the distance of the source. We then modelled the decays of the X-ray luminosities of the single spectral components and of the thermal bolometric luminosities using a constant (representing the quiescent level) plus one or more exponential functions, and estimated the outburst energy by integrating the best-fitting model for the bolometric light curves over the whole duration of the event.

Table 2 lists the significance for the correlations between different parameters for all sources of our sample and their outbursts.

3. Results

The anticorrelation between magnetars quiescent luminosities and their luminosity increases during outbursts suggests the existence of a limiting luminosity of $\sim 10^{36}$ erg s^{-1} for magnetar outbursts (regardless of the quiescent level of the source), and is interpreted in the framework of the internal crustal heating model as the result of the self-regulating effect resulting from the strong temperature-dependence of the neutrino emissivity: the surface photon luminosity for injected energies larger than $\sim 10^{43}$ erg reaches a limiting value of $\sim 10^{36}$ erg s^{-1} because the crust is so hot that most of the energy is released in the form of neutrinos before reaching the star surface. The observed anticorrelation is expected also in the scenario of the untwisting magnetospheric bundle, where the maximum theoretically expected luminosity might be a few 10^{36} erg s^{-1} even for the generous case of a twist with $\psi \sim 1$ rad affecting a large part of the magnetospheric volume. The correlation between the magnetic field and the outburst energetics supports the idea that the energy reservoir of the outbursts is mainly provided by the dissipation of the magnetic field. Young magnetars tend to experience more energetic outbursts than older magnetars, a characteristic that can be explained simply in terms of field decay. The outburst energy correlates with the peak luminosity, but not with the quiescent X-ray luminosity. These results suggest that a larger luminosity at the peak of the outburst results in a larger energy released during the outburst event, regardless of the quiescent level of the source, and indicate similar patterns for the decay curves of magnetar outbursts (as supported also by the correlation between the decay time-scale and the energetics).

Reference

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