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A Christmas comet falling onto a neutron star

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Abstract. The Sun and the planets are the main, but not the only, bodies of the Solar System. There are thousands of asteroids and several tens of comets, many of which are still unknown. They are the remnants of the planetesimals that formed at the origin of our Solar System, and they are rocky objects of different dimensions and irregular shape. Sometimes these minor bodies fall onto the Sun or onto planets, like Jupiter. Less dramatic events occur when the infalling bodies do not directly impact onto the target but are tidally disrupted. The tidal disruption of solar mass stars around supermassive black holes has been extensively studied analytically and numerically. In these events the star, as it approaches the black hole, develops into an elongated banana-shaped structure, the most tightly bound debris being at the closer end to the compact object. After completing an (few) eccentric orbit(s), these bound debris fall onto the black hole, emitting energy. Orbital precession may lead to the crossing of the debris orbits producing an accretion disk. Observationally, these events will give rise to luminous events with different temporal decays in different energy bands. Tidal break-up events occur also in planetary systems around normal stars but these events are too faint to be detected. Things change when the star is a compact object. Indeed planets have been discovered around radio pulsars, making likely the existence also of orbiting minor bodies. The direct impact of minor bodies onto neutron stars has been studied in the past and it has been envisaged as a possible (local) explanation for Gamma-Ray Bursts (GRBs), producing short-duration (∼ seconds) events. To explain the peculiarities of GRB 101225A (Christmas burst) we propose that it resulted from the tidal disruption event of a minor body around a neutron star in our Galaxy.

Key words. Gamma-ray burst: general – Gamma-ray burst: individual: GRB 101225A – Minor planets, asteroids: general

1. Introduction

GRB 101225A image-triggered the Burst Alert Telescope (BAT) onboard the *Swift* space mission on 25.776 December 2010 Universal Time. The event was extremely long, with a $T_{90} > 1.7$ ks, and smooth (Racusin et al. 1998). The total 15–150 keV fluence recorded by the BAT over more than 3 ks is $\gtrsim 3 \times 10^{-6}$ erg cm^{-2}, with no signs of decay. The X-ray Telescope (XRT) and the UltraViolet Optical Telescope (UVOT) onboard *Swift* started observing 1.4 ks after the BAT trigger. XRT and UVOT found a bright long-lasting X–ray and UV counterpart. The 0.3–10 keV unabsorbed fluence (1.4–15 ks) was $\sim 10^{-5}$ erg cm^{-2}. Strong variability is observed in the early X–ray light curve. The optical counterpart was detected in all UVOT filters, lagging the X–

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ray light curve (see Fig. 1). The detection in the bluer of the UV filters ($UVW2$, central wavelength 2030 Å) implies a source redshift $z \lesssim 1.1$. The X–ray and optical light curves remind a shock break-out event as observed in GRB 060218 (Campana et al. 2006), but fainter (~ 3.5 mag) and without an X–ray afterglow at later times or a bright supernova component. An *XMM-Newton* observation failed to detect the 'afterglow' with a $3\,\sigma$ upper limit of $\sim 10^{-14}$ erg cm^{-2} s^{-1} (0.5–10 keV, $\Delta t = 23$ d after the trigger).

The event was also followed by ground-based telescopes, mainly in the R and I bands (see Fig. 1). Surprisingly, optical spectra taken in the first few days after the event failed to detect any spectral feature, revealing a smooth blue continuum (Thöne et al. 2011). At later times the optical light curves revealed a color change from blue to red. The HST imaged the field on Jan. 13, 2011, finding a quite red object with $F_{606W}(AB) = 24.6$ and $F_{435W} - F_{606W} = 1.6$), with no host galaxy detected down to one magnitude fainter (Tanvir et al. 2011). Later observations were carried out at the Telescopio Nazionale Galileo in the I band. GRB 101225A was detected in $I = 23.64 \pm 0.24$ at $\Delta t = 44$ d but not detected at $\Delta t = 55$ d ($I > 24.5$, $3\,\sigma$ confidence level). Observations at the Gran Telescope Canarias ($\Delta t = 180$ d) detected GRB101225A at $g'_{\rm AB} = 27.21 \pm 0.27$ and $r'_{\rm AB} = 26.90 \pm 0.14$ (Thöne et al. 2011).

2. The strange case of GRB 101225A

Given the peculiarities of GRB101225A we suggest that it resulted from the tidal disruption of a minor body around an isolated neutron star (see Campana et al. 2011 for a full account of the story). An alternative model based on a peculiar Supernova has been proposed by Thöne et al. (2011).

A minor body object gets disrupted if it penetrates within a distance of $\sim 10^5 - 10^6$ km from the neutron star, where the internal forces that hold the object together (either the body's self-gravity or its tensile strength) are overwhelmed by the tidal pull of the neutron star. The debris that remain bound are thrown into highly eccentric orbits and then fall back to form an accretion disk around the star (Ulmer 1999; Cannizzo et al. 1990). If the minor body has a low tensile strength it gets fully disrupted and the bolometric light curve is expected to decay on the long term as $t^{-5/3}$ (Rees 1988; Phinney 1989), while its early behavior can be chaotic due to the formation of the disk with flares coincident with the periastron passages (Bloom et al. 2011; Burrows et al. 2011).

2.1. The model

If the fall-back matter accretes at a sub-Eddington rate at all times (as in our case), the disk emission can be described as a spatial superposition of black bodies at increasing temperature and it depends on the parameters of the encounter (Lodato & Rossi 2011). The debris shock at periastron and rapidly circularize to form a thin accretion disk. The viscous timescale in the disk is initially shorter than the fall-back timescale and the disk can thus be approximated by a sequence of steady state models, extending from $R_{\rm in} \sim R_{NS}$ to the circularization radius set as twice the periastron radius. We then redden the optical and UV fluxes, assuming the Cardelli et al. (1989) reddening law, with a visual extinction coefficient A_V, taken as a free parameter.

In total, our model has thus four free parameters: the mass of the minor body M_*, the periastron $r_{\rm p}$, the source distance D and A_V. We fit the X-ray (1 keV), UV ($UVW2$ and $UVW1$ bands, centered at 2030 and 2634 Å, respectively) and optical (R and I bands, centered at 6400 and 7700 Å, respectively) light curves of GRB 101225A. We find that the following set of parameters provides a good match to the X–ray, UV and optical light curves: $M_* = 5 \times 10^{20}$ g (half the Ceres mass, which corresponds to a radius $R_* \approx 50$ km for the selected density), $r_{\rm p} = 9 \times 10^3$ km, $D = 3$ kpc and $A_V = 0.75$. Our model is indicative of the physics involved but it cannot capture the full details of the event. Note that the resulting periastron is well within the expected tidal radius for a minor body, and therefore consistent with the hypothesis that the object is tidally disrupted. The radius of the minor body is somewhat large but if the density

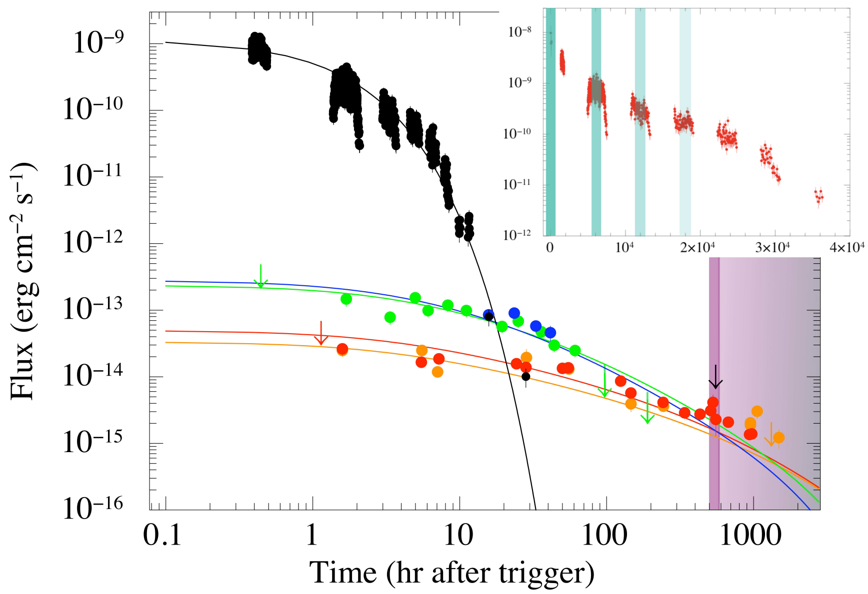

Fig. 1. X–rays at 1 keV (black dots), UV at 2030 Å (green) and 2634 Å (blue), and optical at 6400 Å (*R* band, red) and 7700 Å (*I* band, orange). Error bars are 1 σ. The X–ray light curve only refers to the disk contribution to the total flux ($\sim$ 0.3 of the total, as derived from spectral modeling) and is corrected for the interstellar absorption column density of $N_H = (2.0 \pm 0.1) \times 10^{21}$ cm^{-2} (in excess to the Galactic value of $N_H^{\rm Gal} = 7.9 \times 10^{20}$ cm^{-2}). The continuous lines of different colors (the same as the data) represent the fit with the tidal disruption phenomenological model to the light curves. *Inset:* X–ray light curve as observed by the *Swift* XRT telescope. On top of the light curve we highlighted the periastron passages based on our tidal disruption model, with a timescale of 6,000-10,000 s. It is apparent that outside the colored band the X–ray emission faces a marked decrease, and this effect is stronger for the first passage.

is larger the radius will shrink. For a density of 10 g cm^{-3} the radius will be $\approx$ 24 km.

The peak mass accretion rate with these parameters turns out to be $\dot{M}(t_{\rm min}) \approx 2 \times 10^{16}$ g s^{-1} and the peak luminosity is thus $L(t_{\rm min}) \approx 3 \times 10^{36}$ erg s^{-1}, consistent with our hypothesis of a sub-Eddington accretion. Note that this will imply that no emission lines are expected from super-Eddington wind as expected in tidal disruption models. Comparing this luminosity with the BAT peak flux (including a factor of 2.2 for the bolometric correction based on spectral modeling) we obtain a distance of $\sim$ 3.5 kpc. We assumed a distance of 3 kpc, as motivated also by the matching of the observed fluence with the conversion of the minor body gravitational energy into radiation. The two estimates match with very good approximation. This distance places the neutron star in the Perseus arm. Its height above the Galactic plane is $\sim$ 1 kpc.

The observed radiation is emitted either by an accretion disk (outer radius as large as twice the periastron) around the neutron star and during the impact of matter onto the neutron star surface. The early spectral energy distribution (SED) at five different epochs can be adequately fitted by the emission from an accretion disk ($T_{\rm d} \sim 1.8$ keV in good agreement with the model predictions) plus the emission from a boundary layer where the disk matter slows down to accrete onto the neutron star. In particular, the initial high energy emission observed by the BAT instrument can be modeled as a black body with $T \sim 10$ keV. This cannot come from the disk but can be easily accounted for by mass accretion onto the neutron star surface. The presence of the boundary layer component excludes that the compact object is a black hole. Inhomogeneities in the retuning debris are expected during the first periastron passages and these give rise to variability on a fall-back timescale[21], as observed in the X–ray band (inset in Fig. 1). The X–ray variability timescale is indeed very similar to the fall-back timescale obtained from our modeling.

2.2. Late time modelling

It is well known that accretion disks around compact objects are thermal-viscous unstable at a temperature corresponding to partial ionization of hydrogen. A model based on this instability captures the main properties of dwarf nova and transient low mass X–ray binary outbursts (Lasota 2001). The same physics applies to disk made of helium or of heavier elements leading to a critical mass inflow rate at a given radius, where the instability sets in and then quickly propagates to the entire disk (Lasota et al. 2008). In our case, the accretion rates decreases with time (Eq. 3), the disc cools down and eventually will hit the critical ionization temperature. The outer disc radius is the first radius at which this occurs. In our sub-Eddington regime, the outer disc is always gas pressure dominated, where the main opacity is Kramer. Under these conditions, the temperature at outer disk $R_{\rm out}$ scales with the accretion rate as

$$T(R_{\rm out}) = 9.6 \times 10^3 (\dot{M}_{-13}(t))^{3/10} {\rm K}, \qquad (1)$$

where $\dot{M}_{-13}$ is the mass accretion rate in units of $10^{-13}~M_\odot~{\rm yr}^{-1}$ and we assumed a standard Shakura & Sunyaev disk and a viscosity parameter $\alpha = 0.1$. For low metallicity disc, the critical accretion rate is around $10^{-13}~M_\odot$ ${\rm yr}^{-1}$ (corresponding to transition temperature of $T \sim 10^4$ K, due partial hydrogen ionization (Lasota 2001)). From Eqs. 3 and 6, we thus get that the the transition happens at $t \gtrsim 15$ d. It is well-known that the critical temperature decreases with metallicity (Lasota et al. 2008). Our disc will likely have solar metallicity or higher, so 15 d is just a lower limit. If we take a slightly lower ionization temperature of $\sim 8,000$ K, we obtain a transition at $t \sim 20$ d. We thus conservatively assume a transition time around 20 d. After the transition to the 'cold' phase the disk emission would drop faster in the blue optical filters and slower in the red optical filters.

A second known effect occurs to the disk for decreasing mass inflow rates. For high mass inflow rate the mass inflow can reach the neutron star surface developing a boundary layer where matter is slowed down before accreting onto the neutron star surface. If the neutron star possesses a significant magnetic field ($10^8 - 10^9$ G), for a sufficiently low mass inflow rate this magnetic field will be able to disrupt the disk flow at a magnetospheric boundary. This happens when the magnetic pressure ($P_{\rm mag}(r) \propto B^4\, r^{-6}$, with B the neutron star magnetic field) equates the disk ram pressure ($P_{\rm disk}(r) \propto \dot{M}\, r^{-5/2}$, where $\dot{M}$ is the mass accretion rate) at a radius larger than the neutron star radius. When this occurs the disk inner edge ends at the magnetospheric boundary and for smaller radii the motion of the infalling matter is controlled by the neutron star magnetic field. Since the magnetospheric radius is proportional to $r_{\rm M} \propto B^{4/7}\, \dot{M}^{-2/7}$, larger magnetospheric radii are expected for lower mass inflow rates. Since $\dot{M}$ decrease as $t^{-5/3}$, being a tidal disruption event, we can impose to our model that the inner radius of the disk $r_{\rm in}(t) \propto t^{-10/21}$.

With these well-know ingredients we approached the late time SEDs. At very late times ($\gtrsim 20$ d), the mass accretion rate is very low and we expect a large magnetospheric radius (if the neutron star has a non-negligible magnetic field). Given that the outer disk is $\sim 2\, r_{\rm p} \sim 2{\times}10^9$ cm, we approximate the disk in this time interval as a small ring and treat its emission like a black body. We fit an optical-IR SED at 40 d taken from ref. 11. A black body fit (absorbed at $A_V \sim 0.75$ as derived from the light curve fitting) provides a good description of the data, with a reduced $\chi^2 = 1.7$ for 3 d.o.f. (16% null hypothesis probability). The resulting temperature and radius are $T_{\rm BB} \sim 4500$ K and $R_{\rm BB} \sim 2.2 \times 10^8$ cm (at 3 kpc). The derived temperature and emitting radius nicely fit with the predictions of our late time disk model.

Taking $R_{\rm BB}$ as the radius of the magnetosphere at 40 d, based on the model predictions about the evolution of the mass accretion rate we can estimate the magnetic field of the neutron star, which is $B \sim 10^9$ G. This is in line with the magnetic field of millisecond radio pulsars.

A very late time detection (Δt = 180 d) has been reported (Thöne et al. 2011). These data show a large decrease in the r' band from data taken at Δt = 40 d (factor of 4.6 in flux) but a mild decrease in the bluer g' band (factor of ~ 1.5 in flux). To model this spectrum we need a hot component that we identify with surface emission from the neutron star heated by the accretion episode and a cold component that may come from a dusty ring/disk, where the minor body formed. Assuming a neutron star with a temperature of $\sim 10^6$ K we obtain a disk inner radius of $\sim 10^{13}$ cm and a temperature of ~ 650 K. Clearly with just two points this is just indicative[1].

3. Conclusions

Estimating the rate of such events is challenging. A wandering neutron star can intercept minor bodies as it passes through a planetary system. Shull & Stern (1995) estimated the capture rate of minor bodies by neutron stars based on the hypothesis that all stars have Oort clouds similar to the one of our Sun. This capture rate is linearly proportional to periastron due to the effect of gravitational focussing. Rescaling these estimates to our system ($r_{\rm p} \sim 9,000$ km), we derive a rate within 3 kpc of the order of ~ 0.3 yr^{-1}, in line with *Swift* observations, being it in orbit by 6.5 yr. Indirect arguments suggest however a lower capture rate and, in addition, large minor bodies are rare (Jura 2011). The likelihood of a neutron star retaining its original population of small bodies is rather low, as they are unlikely to survive the supernova event. Still, a planetary-like system can reform around millisecond radio pulsars (Wolszczan & Frail 1992; Sigurdsson et al. 2003). In this case we predict that an IR signature might be detected from the planetary disk.

[1] Assuming the same neutron star component to be present in the Δt = 40 d data, the best fit parameters for the disk change only mildly to $R_{\rm BB} \sim 2.8 \times 10^8$ cm and $T_{\rm BB} \sim 4000$ K

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