X-RAY FLASHES POWERED BY THE SPINDOWN OF LONG-LIVED NEUTRON STARS

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ABSTRACT

X-ray flashes (XRFs) are a class of high-energy transients whose nature is still open to question. Similar in many aspects to common gamma-ray bursts (GRBs), their strong X-ray emission is accompanied by very low or absent emission in the gamma-ray band. Despite this key difference, a number of indications have consolidated the idea that XRFs and GRBs share a common origin, including a number of potential XRF/supernova associations and the consistency of some XRFs with the Amati relation for long GRBs. However, the difficulties in explaining XRFs as off-axis or intrinsically weak GRBs still cast doubts on this interpretation. Here we explore the possibility that some XRFs are instead powered by the spindown of a long-lived neutron star (NS) formed in a binary NS (BNS) merger or, possibly, in a core-collapse supernova. Focusing on XRF 020903 and a few other cases observed by HETE-2, we show that their lack of gamma-ray emission, spectral properties, duration and X-ray luminosity find a natural explanation within our hypothesis. Moreover, we point out that the agreement of XRF 020903 with the Amati and Ghirlanda relations for long GRBs is respectively only marginal and problematic. Assuming a BNS merger origin for the long-lived NS, we use XRF observations to estimate a lower limit on the rate of BNS mergers accompanied by a potentially observable XRF signal. Within the reach of the advanced LIGO and Virgo gravitational wave detectors, we find $>0.02$–$0.05\;\text{yr}^{-1}$. Finally, we discuss the implications of a supernova association for the XRF events considered.

Key words: gamma-ray burst: general – gamma-ray burst: individual (XRF 020903) – gravitational waves – stars: magnetars – stars: neutron – X-rays: general

1. INTRODUCTION

Commonly interpreted as a subclass of gamma-ray bursts (GRBs), X-ray flashes (XRFs) are characterized by surprisingly low energy fluences in the gamma-ray band and higher fluences in the X-ray band (i.e., $S_X > S_\gamma$, where “X” refers to 2–30 keV and “$\gamma$” to 30–400 keV). Since their discovery with BeppoSAX (Boella et al. 1997) and the numerous observations by HETE-2 (Ricker et al. 2003; Sakamoto et al. 2005), the interpretation of XRFs has been uncertain. Apart from having a much lower peak photon energy $E_p$, their spectral properties appear compatible with those of typical GRBs. Moreover, a careful analysis of an event with known redshift, XRF 020903, has revealed its consistency with the $E_p \sim E_{\text{iso}}$ relation found for long GRBs (Amati et al. 2002), where $E_{\text{iso}}$ is the isotropic energy emission in the 1–10,000 keV band. This collective evidence led to the conclusion that XRFs are GRBs (Sakamoto et al. 2004). This view is further supported by a number of putative XRF/supernova (SN) associations (e.g., Soderberg et al. 2005; Pian et al. 2006) and the existence of “X-ray-rich” GRBs, partially filling the gap between typical GRBs and XRFs (Sakamoto et al. 2005). Nevertheless, current models of XRFs within the GRB paradigm encounter difficulties in explaining their softer emission, casting doubts on their nature. Possible explanations include GRBs observed off-axis (Yamazaki et al. 2002; Zhang et al. 2004; Utara et al. 2015) or inefficient/subenergetic GRB jets (Huang et al. 2002). The possibility that XRFs are far distant GRBs highly redshifted to lower photon energies has been generically ruled out (e.g., Sakamoto et al. 2004).

In this paper, we propose an alternative explanation for XRFs, independent of GRBs, and based on the emission powered by the spindown of a long-lived neutron star (NS) formed as the end product of either a binary NS (BNS) merger or the death of a massive star. We focus our analysis on XRF 020903 and a few other XRFs observed by HETE-2 with no significant gamma-ray emission ($S_\gamma/S_\text{iso} > 5$) to show that our hypothesis is consistent with the observations and that it offers a natural explanation for the puzzling properties of these events.

2. X-RAY EMISSION FROM A LONG-LIVED NS

Since the observation of NSs with a mass of $\sim2\,M_\odot$ (Demorest et al. 2010; Antoniadis et al. 2013) it has been clear that the maximum mass of uniformly rotating NSs is $\lesssim2.4\,M_\odot$ (Lasota et al. 1996). Moreover, the distribution of masses in merging BNSs favors the combination $\sim1.3–1.4\,M_\odot$ (Belczynski et al. 2008), suggesting a typical mass of the merger product of $\sim2.3–2.4\,M_\odot$. This leads to the conclusion that a significant fraction of BNS mergers should result in long-lived NSs, namely NSs that can either survive for about a spindown timescale before eventually collapsing to a black hole (BH) or NSs that will never collapse. The spindown of a long-lived NS can power strong and sustained electromagnetic emission (Yu et al. 2013; Metzger & Piro 2014), which has been invoked to explain the long-lasting ($\sim100–10^5\text{ s}$) X-ray afterglows observed by Swift (Gehrels et al. 2004) in association with many short GRBs (Zhang & Mészáros 2001; Metzger et al. 2008; Gompertz et al. 2013, 2014; Rowlinson et al. 2013; Lü et al. 2015).

Recently, Siegel & Ciolfi (2016a, 2016b) proposed a detailed model to describe the evolution of a long-lived NS and its electromagnetic emission up to $\sim10^7\text{ s}$, taking into account the crucial role of the matter ejected via post-merger baryon-loaded winds. Exploring a wide range of physical parameters, they found that the spindown-powered signal has a delayed onset ($\sim10–100\text{ s}$) and peaks $\sim100–10^4\text{ s}$ after merger. Furthermore,
when higher mass and weaker magnetic fields are considered, the emission shifts to lower energy bands and the model predicts a signal that falls out of the X-ray band, as in Yu et al. (2013).

### Table 1

| XRF       | Duration (s) | $E_p$ (keV) | $S_X/S_\gamma$ | $F_B^0$ (2–30 keV) (cm$^{-2}$ s$^{-1}$) | $z$ | $T_{BB}$ (keV) | $S_X/S_\gamma$ (BB) |
|-----------|--------------|-------------|----------------|----------------------------------------|-----|----------------|---------------------|
| 020903    | 13.00        | 2.6$^{+0.4}_{-0.4}$ | 7.31           | 2.75$^{+0.66}_{-0.42}$              | 0.25$^{+0.01}_{-0.00}$ | 0.68–1.3          | $\geq 4.4 \times 10^6$ |
| 010213    | 34.41        | 3.41$^{+0.35}_{-0.40}$ | 11.38          | 6.33$^{+0.77}_{-0.53}$               | ... | 1.2            | 2.1$ \times 10^6$ |
| 011130    | 50.00        | <3.9        | 5.96           | 5.27$^{+1.27}_{-1.76}$              | ... | <1.4           | >1.3$ \times 10^6$ |
| 020625    | 41.94        | 8.52$^{+0.44}_{-0.41}$ | 20.49          | 2.86$^{+0.97}_{-0.53}$              | ... | 3.0            | 97                  |
| 030723    | 31.25        | <8.9        | 7.47           | 1.98$^{+0.38}_{-0.25}$              | ... | <3.2           | >72                 |

### Notes.

* From Sakamoto et al. (2005). Obtained assuming Band function, power law, or power law plus exponential cutoff spectrum.

* From Soderberg et al. (2004).

* For XRF 020903 we employ BB temperature estimates by Sakamoto et al. (2004) (error $\leq 40\%$) and apply redshift corrections. For the other cases we take $E_p$ as the peak photon energy of the BB spectrum and compute the corresponding BB temperature (no redshift correction).

In order to link XRFs to the spindown-powered X-ray emission from long-lived NSs, we consider cases with $S_X/S_\gamma > 5$ and no significant gamma-ray emission. This choice is more conservative than the common definition of XRFs ($S_X/S_\gamma > 1$) and allows us to avoid contamination from “X-ray-rich” GRBs. Here we focus on the best studied event with known redshift, XRF 020903, while in the next section we extend the discussion to a few more cases.

The main properties of XRF 020903 are summarized in Table 1. With no significant detection of photons above 10 keV, this event represents an ideal candidate for our analysis. In addition to the lack of gamma-ray emission, another strikingly different property of this event compared to typical GRBs is that data can be fit with a mostly thermal spectrum, with an initial BB temperature of $\sim$1 keV, decreasing to $\sim$0.5 keV within $\sim$10 s (Sakamoto et al. 2004). These properties meet the expectations of our model. Note that without fluence observed above 30 keV, $S_\gamma$ depends entirely on the assumed spectral behavior at high energies. The fluence ratio estimated with a power-law spectral fit is $S_X/S_\gamma \geq 7$ (Sakamoto et al. 2005), while adopting a pure thermal spectrum would give $S_X/S_\gamma \geq 7 \times 10^8$.

The X-ray signal emerges above the detector noise for $\sim$13 s (Sakamoto et al. 2004) and from a rough estimate based on photon counts the noise level is at $\sim$80% of the maximum luminosity. From the parameter study by Siegel & Ciolfi (2016b) the corresponding signal duration, which is mostly controlled by the mass ejected via NS winds $M_{wind}$, is $\sim 10^4–10^5 M_\odot$. A shorter duration of $\sim$10 s is still compatible with the model, but suggests $M_{wind} \leq 10^{-3} M_\odot$. Observations of XRF 020903 days/weeks after the trigger revealed an optical signal, from which it was possible to place the event at redshift $z = 0.25 \pm 0.01$ (Soderberg et al. 2004). This excludes that XRF 020903 is an ordinary GRB at large distance (i.e., $z \sim 100$, Sakamoto et al. 2004). Applying the redshift correction to the BB temperature, the...
X-to-gamma fluence ratio for pure thermal spectrum would become $S_X / S_\gamma \gtrsim 4 \times 10^6$. The BNS merger scenario holds as long as the optical signal can be explained in terms of late-time spindown-powered emission. Conversely, a SN (Soderberg et al. 2005; Bersier et al. 2006) would imply a long-lived NS formed from the death of a massive star (see Section 6).

Assuming a standard ΛCDM cosmology with the parameters reported in Planck Collaboration et al. (2015), we estimate a luminosity distance of $d_L \sim 1.3$ Gpc. From the peak flux of $\approx 14.7 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ ($\approx 35\%$ error) in the 2–10 keV band (Sakamoto et al. 2004), the resulting intrinsic luminosity in the 2.5–12.5 keV band is $\approx 3 \times 10^{48}$ erg s$^{-1}$. This value is consistent with the expected range of X-ray luminosities for a long-lived NS (Siegel & Ciolfi 2016b).

We conclude that the observed properties of XRF 020903 are consistent with the spindown-powered emission from a long-lived NS formed in a BNS merger or, possibly, in connection to a SN. In particular, the lack of gamma-ray emission and the compatibility with a predominantly thermal spectrum with BB temperatures of $\approx 1$ keV are naturally explained. These properties, at the same time, represent a challenge for any attempt to model XRF 020903 as a GRB.

4. A SAMPLE OF CANDIDATE XRF EVENTS

Here we extend our discussion to all XRFs with $S_X / S_\gamma > 5$ in the sample of Sakamoto et al. (2005), where the X-to-gamma fluence ratios were obtained under the assumption of power-law (with/without exponential cutoff) or Band function spectrum. The properties of these events (five including XRF 020903) are given in Table 1. Figure 1 (upper panel) shows the peak photon energy $E_p$ versus $S_X / S_\gamma$, for the entire sample of Sakamoto et al. (2005). Above $E_p \approx 10$ keV, there is a tight correlation given by $E_p [\text{keV}] = b (S_X / S_\gamma)^a$, where $a \approx -0.74$ and $b \approx 41$. Our selected cases all have $E_p < 10$ keV and appear broadly consistent with the above correlation, although with a larger scatter. Two more events have $E_p < 10$ keV, but $1 < S_X / S_\gamma < 5$. Although they are potential candidates, we exclude them from our analysis.

As for XRF 020903, all the events in our sample lack a significant gamma-ray emission. Since we cannot rely on a detailed spectral analysis like the one presented for XRF 020903 in Sakamoto et al. (2004), we proceed under the assumption that they can be described by a dominant BB spectrum with peak photon energy approximately given by the value of $E_p$, estimated by Sakamoto et al. (2005), and compute the corresponding BB temperature. We cannot apply redshift corrections for these events. Nevertheless, if their distance is comparable to XRF 020903, corrections are small. Recomputing the X-to-gamma fluence ratio for a purely thermal spectrum, we find that our sample would have $S_X / S_\gamma > 72$ (see Table 1). In the absence of a significant detection of photons above 30 keV, the consistency with the correlation satisfied by all other events with $E_p > 10$ keV depends entirely on the assumption of the Band function or power-law spectrum. Assuming a thermal spectrum gives a completely different result (see the lower panel of Figure 1).

The event durations in our sample are quite homogeneous with a range 13–50 s (average $\approx 34$ s) and compatible with the hypothesis of spindown-powered emission from a long-lived NS. Since the redshift is known only for XRF 020903, we cannot infer the intrinsic luminosity of the other cases. The peak photon number flux in the 2–30 keV band is also very homogeneous, differing only by a factor of $\approx 0.7–2.3$ from the one measured for XRF 020903 (see Table 1). By rescaling the X-ray fluence with this factor to obtain a rough estimate...
conclude that: (i) if all five events were at the same distance (\( \sim 1.3 \) Gpc), the range of intrinsic X-ray luminosities (in the 2.5–12.5 keV band) would be \(~(2–7) \times 10^{58}\) erg s\(^{-1}\); (ii) if all five events had the same X-ray luminosity, the range of distances would be \(~0.9–1.5\) Gpc.

From the properties discussed above, we conclude that a tentative extension of our interpretation of XRF 020903 to the other four cases considered is compatible with the observations.

5. AMATI AND GHIRLANDA RELATIONS

Assuming a cutoff power-law spectrum, Sakamoto et al. (2004) estimated for XRF 020903 an isotropic energy emission in the source rest frame of \( E_{\text{iso}} \approx 2.3 \times 10^{59}\) erg in the canonical band (1–10,000) keV. This value, combined with the estimated peak photon energy in the source rest frame \( E_{p,z} \approx 2.6 (1 + z) \approx 3.3\) keV, is roughly consistent with the \( E_{p,z} - E_{\text{iso}}\) relation found by Amati et al. (2002) for long GRBs. This result was taken as a strong indication in favor of the interpretation of XRFs as GRBs (Sakamoto et al. 2004).

A more recent version of the Amati relation, including XRF 020903, gives \( E_{p,z} [\text{keV}] \approx 94 \times (E_{\text{iso}}/10^{52}\) erg\(^{0.57}\) (Amati et al. 2008) (see Figure 2). As noted by Ghirlanda et al. (2004), however, the slope of the Amati relation depends on whether XRFs are included or not in the fit. Excluding XRFs, Ghirlanda et al. (2004) found a different relation where \( E_{p,z} \propto E_{\text{iso}}^{0.4}\) (see Figure 2), which is only marginally consistent with XRF 020903 (factor \(~20\) discrepancy in \( E_{\text{iso}}\)). This shows that the Amati relation cannot be taken as compelling evidence that XRFs and GRBs are the same phenomenon.

Taking into account the opening angle of a sample of GRBs (as inferred from the jet break in the lightcurve), Ghirlanda et al. (2004) found the relation \( E_{p,z} [\text{keV}] \approx 480 \times (E_{\text{iso}}/10^{51}\) erg\(^{0.7}\), where \( E_{\text{iso}} = (1 - \cos \theta) E_{\text{iso}}\) is the collimation-corrected energy emission and \( \theta \) the half opening angle. In order to be reconciled with the Ghirlanda relation, XRF 020903 should have \( \theta \sim 25^\circ\) (Ghirlanda et al. 2004; see also Figure 2), which is much larger than the typical range for long GRBs, \(~(2–10)^\circ\). Moreover, this opening angle would correspond to a jet break at \(~3\) days that, according to Soderberg et al. (2004), was not observed. This would suggest that XRF 020903 is an outlier of the Ghirlanda relation and therefore its interpretation as a GRB is problematic (Ghirlanda et al. 2004).

If we interpret XRF 020903 as predominantly thermal radiation described by a BB spectrum with \( E_{p,z} \approx 3.3\) keV and scale the total energy fluence in the (1–10,000) keV band so that the observed fluence in the 2–10 keV band (\(~5.9 \times 10^{-8}\) erg cm\(^{-2}\), Sakamoto et al. 2004) is reproduced, we find \( E_{\text{iso}} \approx 1.2 \times 10^{49}\) erg. Unlike the collimated emission observed in many GRBs, the emission mechanism we propose for XRF 020903 is isotropic, i.e., \( \theta = \pi/2\) and \( E_{\text{iso}} = E_0\). This allows for a direct comparison with both the Amati and the Ghirlanda relations (see Figure 2). According to our interpretation, however, the event is not a GRB and we do not have to expect an agreement with these relations.

6. CONCLUDING REMARKS

In this paper, we have shown that the high-energy emission properties of XRF 020903 can be explained in terms of spindown-powered emission from a long-lived NS formed in a BNS merger or, possibly, in connection to a SN. These include spectral properties (lack of gamma-ray emission, mainly thermal spectrum, BB temperature and its evolution) and lightcurve properties (duration, luminosity). At the same time, these properties challenge the common interpretation of XRF 020903 as a GRB. Moreover, we have argued that the concordance with the Amati relation is not as compelling as commonly assumed and we have pointed out difficulties in reconciling the event with the Ghirlanda relation. In addition to XRF 020903, we have selected a few other cases in the sample of Sakamoto et al. (2005), and we have shown that our interpretation can be extended to these events with no contradiction with the observations. If our scenario is correct, it still does not apply to “XRFs” with a significant gamma-ray emission. We propose a redefinition of those events as “X-ray-rich” GRBs, keeping “XRF” only for non-GRB events.

In our discussion we have only considered events observed by HETE-2 during \(~3\) years of operation (2001–2003). In this time period, any event like XRF 020903 would have been possibly detected with the wide field X-ray monitor (WXM) on board HETE-2. If XRF 020903 was powered by a long-lived NS formed in a BNS merger and accounting for the time of operation and field of view of WXM (e.g., P{é}legr{é}on et al. 2008), the detection of this event would imply a lower limit on the rate of BNS mergers leading to a long-lived NS of \(\geq 2.8\) Gpc\(^{-3}\) yr\(^{-1}\). Rescaling with the reach of the advanced ground-based GW detectors LIGO and Virgo (Harry et al. 2010; Accadia et al. 2011), \(d_L \approx 445/2.26 \approx 197\) Mpc (Abadie et al. 2010), we obtain a rate of such merger events detectable in GWs of \(\geq 0.02\) yr\(^{-1}\). As a reference, the lower limit estimated in Abadie et al. (2010) gives \(f > 0.4\) yr\(^{-1}\), where \(f\) is the fraction of BNS mergers forming a long-lived NS. Extending to a total of four events in our selected sample (excluding XRF 020625, which was not first triggered by WXM) and assuming that they all occurred within a luminosity distance of 1.5 Gpc (obtained by imposing that the faintest event had the same intrinsic luminosity of XRF 020903), we obtain an event rate detectable in GWs of \(\geq 0.05\) yr\(^{-1}\).
forming a long-lived NS is rare \((f \ll 10\%)\), the above limit is more stringent than the one provided in Abadie et al. (2010).

If short GRBs are produced by BNS mergers with a long-lived remnant (as, e.g., in the “time-reversal” scenario, Ciolfi & Siegel 2015), they should be accompanied by the isotropic X-ray signal that we propose here as an explanation for events like XRF 020903. In this case, we predict a rate of detectable short GRBs within the reach of LIGO/Virgo for face-on mergers, \(d_L \approx 197 \times 1.5 \approx 296\) Mpc, of \(> f_s f_\theta \times 0.17\) yr\(^{-1}\), where \(f_s\) is the fraction of mergers producing short GRBs and \(f_\theta = 1 - \cos \theta_j\), with \(\theta_j\) the typical half opening angle. From observed short GRBs with known redshift, Metzger & Berger (2012) estimate a rate of \(\sim 0.03\) yr\(^{-1}\). Our lower limit is smaller by a factor \(\sim 6 \times f_s f_\theta < 1\), which would suggest that our rates are pessimistic.

If all/some of the XRF events considered are instead associated with long-lived NSs born in SN explosions, the agreement with the predictions of Siegel & Ciolfi (2016a, 2016b) for the BNS merger case is remarkable. This similarity might be explained in a scenario in which the outer envelope of the progenitor star has been removed from the line of sight of the (on-axis) observer by an early magnetized wind from the proto-NS (Bucciantini et al. 2008, 2009) that was not powerful enough to produce a GRB. However, further investigation is necessary to assess the viability of this scenario.

Finally, if XRF 020903 is associated with a SN and not powered by the spindown of a long-lived NS, its compatibility in the high-energy emission remains to be explained and might provide important hints on the nature of this type of event. Moreover, our interpretation might still apply to any analogous event without confirmed SN association.

To clarify the nature of XRFs and exploit their potential, new X-ray missions monitoring the sky with large field of view and increased sensitivity are urgently needed.

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