Twenty years of *Swift* observations of Short GRBs

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Abstract

Before the *Neil Gehrels Swift Observatory*'s launch, little was known about short Gamma-ray Bursts. While the short duration of the γ-ray emission pointed to an origin linked to compact objects, proof was lacking, and nothing was known about the afterglow.

I will briefly discuss how *Swift*, thanks to the unique abilities of autonomous pointing, early start of observations and sensitivity, enabled the community to find short GRB afterglows and define general properties such as energy, galaxies, offsets, environment. I'll also summarize how Swift/UVOT permitted the study of peculiar and watershed events such as the kilonova in the short GRB170817A, counterpart to the gravitational wave source GW 170817A, and other similar bursts. I'll mostly focus on the contributions of the UV/Optical Telescope (UVOT) onboard Swift.

Introduction.

Short Gamma-ray bursts (sGRB), first identified in 1993 (Kouveliotou et al. 1993) are cosmological GRBs with γ-ray emission lasting $\lesssim 2$ s and spectrum harder than that of longer events.
The *Swift* mission (Gehrels et al. 2004) launched in 2004, to study GRBs by means of its fast and autonomous slewing capability that enables it to start observations with onboard narrow field telescopes ~100s after the trigger.

Swift has greatly contributed to the systematic study or constraining of:

- sGRBs weak afterglow emission from its start;
- sGRBs host galaxies of all types, including passive/ellipticals; and the offsets of the bursts from them;
- sGRBs redshifts;
- absence of associated supernova light in sGRBs.

All hints obtained pointed to progenitors being compact objects, such as Neutron Star - Neutron Star (NS-NS) binary. Finally, such a progenitor could be detected in the case of the Gravitational Wave (GW) source GW170817. Swift studied the associated sGRB counterpart, 170817A. This discovery heralded the era of "Multi-Messenger Astronomy".
GRB170817A showed an early optical colour change, from blue to red. This behaviour could be discovered only thanks to the early observations performed by *Swift* UVOT and its sensitivity to UV light.
UVOT (Roming et al. 2004) has studied many other peculiar sGRBs, including events with associated GeV emission and some that "straddle" the long-short divide, such as 060614, 211211A and 230307A.

Low energetics and low density in *Swift* sGRBs.

Fong et al. (2015) systematically examined Swift sGRB observations in the 2005-2015 interval. Of 107 events with fast ($\lesssim$ 100 s) follow up observations, 91%, 40% and 7% have an X-ray, optical and radio afterglow, respectively. With Swift and ground based observatory data, Fong also constrained their flux F_ν and flux decay and spectral indices, α and β respectively: $F_\nu \propto t^{-\alpha}\nu^{-\beta}$. Then, by using the standard Forward Shock model (Sari et al. 1998), they derived the values of ejecta kinetic energy and environment density needed to explain the fluxes in the observing bands. The results are that the bursts have a **median environment density** $< n > \simeq 3 \times 10^{-3}$ cm^{-3} and **median isotropic kinetic energy** $< E_{k,iso} > \simeq 2 \times 10^{51}$ erg (Fong et al. 2015). The low *n* pointed out to an environment far from the host galaxies.

Host galaxies: normal star formation, large offsets.

For all *Swift* sGRBs from launch to 2022, Fong et al. (2022) examined the X-ray afterglow (optical when available) positions with respect to those of the nearby galaxies, and gauged the most likely hosts using the methodology by Bloom et al. (2002). They obtained 84 associations.

Fong et al. 2022 found that the median redshift of hosts is $< z > \simeq 0.64$, and the **median projected offset of the SGRBs from the host is $7.7^{+20.9}_{-6.05}$ kpc and $\simeq 1.5$ light-radius. These values are 6 and 2.5 times larger than those of long duration GRBs. The median luminosity of the hosts is $< L > \simeq 8 \times 10^9 L_\odot$, several times larger than long GRB hosts.**

Nugent et al. (2022) examined the spectra or the spectral energy distribution of these hosts, and found $\simeq 84\,\%$ are star forming - while only $\simeq$10% are quiescent. The fraction of quiescent galaxies jumps to $\simeq$40% if one considers sGRBs at redshift $z < 0.25$. Interestingly, short GRBs with quiescent host galaxies have larger offsets, by factor of $\simeq 3$ than sGRBs with star-forming galaxies. This suggests a different channels of formation between low-z and moderate-z sGRBs.
sGRBs hosts have the typical star formation expected for their mass, because they populate the star formation main sequence (SFMS).

Relativistic ejecta opening angles

sGRBs, like long GRBs, are supposed to be collimated into jets of opening angle θ_{jet}. The indication of a jet is a break of the light-curve into a $\alpha \simeq 2$ power-law decay (Zhang & MacFadyen 2009).
Being weak sources, sGRBs can rarely be followed up long enough to detect this "jet break"; one usually obtains a lower limit on θ_{jet}. By studying afterglows followed up long enough and attributing the events without visible jet break a lower limit θ_{jet} < $30^{\rm o}$, following Bayesian statistics Fong et al. 2015 found a **median** $< \theta_{jet} > 16 \pm 10$ **degrees**. **This value is comparable to that found for long GRBs: $< \theta_{jet} > 13^{+5}_{-9}$ degrees.** The fraction of illuminated sky is $f_b \simeq \theta_{jet}^2/2 \simeq 0.04^{+0.07}_{-0.03}$. Thus, the real, beaming-corrected energy of short GRBs reduces to $10^{49} - 10^{50}$ erg, including both prompt energy and kinetic energy of the ejecta. The value of f_b found implies that for each sGRB we detect $\simeq 25$ are missed.

sGRB 170817A - GW170817 - AT2017gfo.

The short GRB 170817A/AT2017gfo was the electromagnetic (EM) counterpart to the GW signal 170817, in turn caused by the merger of two NSs (Abbot et al. 2017). ***Swift*/UVOT contributed greatly to the study this first proven association between a GW-emitting merger of compact objects and a sGRB. In particular, in the first hours of observation, UVOT saw a "blue" transient** (Evans et al. 2017)**, whereas theoretical models had predicted that the heavy r-elements ejected in the merger would only have a very high opacity and thus lead to a reddened emission, called "kilonova" (KN).** This discovery was possible because ***Swift* was the only observatory in space (aside HST) able to observe UV emission** and slew fast to the source**.** UVOT contributed to build multi-colour light-curves and spectra that showed a fast reddening of AT2017gfo, which demonstrated that ejecta with heavy r-elements had been produced and had caught up with the first ejecta that produced the blue emission (Evans et al. 2017, Pian et al. 2020, Watson et al. 2019). Moreover, the spectral energy distributions were thermal, and cooling down as expected on theoretical grounds (e.g. Barnes & Kasen 2013). **UVOT helped to constrain the temperature and the total luminosity of the source, and thus the radius and the trans-relativistic expansion speed.** Estimates on the amount of r-element released by this merger were possible as well, with consequences on the study of the metal enrichment of the Universe. **Overall, the observations confirmed the theoretical expectations of sGRBs are product of NS-NS mergers and their being source of GW radiation, although the presence of a short-lived "blue" KN demonstrated that mergers can produce ejecta of complex geometry and diverse composition.**

Subsequent studies demonstrated that sGRB 170817A had been seen off-axis, delaying the afterglow and permitting a fairly clear observation of the KN. **In fact, the observations in X-ray, radio and later in the optical band showed that AT2017gfo, the "afterglow" of GRB 170817A, showed a slow flux rise, followed by a steep decline. This behaviour is expected if the source is made of an energetic, fast and narrow core, and less energetic and slower "wings", and the observer is outside the opening angle of the core.** As the jet decelerates, more and more emission from the core reaches the observer, causing the rise. Troja et al (2019) found that a jet with $\theta_{core} \simeq 4.5^{\rm o}$, observer's angle $\theta_{obs} \simeq 30^0$, half-opening of the jet $\theta_{obs} \simeq 45^0$, beaming-corrected energy of $\simeq 2 \times 10^{50}$ erg, environment density $n \simeq 0.015\ cm^{-3}$ can explain the data. All in all, the characteristics of this event did not look dissimilar to those of the set of Fong et al. (2015). Other configurations of energy across the jet can explain the observations as well, but all require an off-axis observer. **Mooley et al. (2018) and Ghirlanda et al. (2019) confirmed that matter moving at relativistic speed had been present via radio observations.**

The discovery of AT2017gfo prompted research in the light-curves of other short GRBs - including UVOT ones - to find signature of KN emission. According to Rossi et al (2020), out of the events with best light-curves and temporally overlapping with 2017gfo, seven events must have KN emission weaker than that of 2017gfo, ten sGRBs presented a phase of slow afterglow flux decline which can be explained by KN contribution, while **eight have strong indication of a KN present.** Rossi et al. (2020) also could disentangle a red (>900 nm) and blue (< 900 nm) contributions. They found that the ''red KN" was between 0.3 and 3 times as luminous as the red KN of 2017gfo, but the ''blue KN" could vary between 0.2 and 20 times as AT2017gfo blue KN.

Short GRBs masqueraded as long events and peculiar sGRBs

Several short GRBs have shown peculiarities, which UVOT greatly helped investigate. GRB 090510 (De Pasquale et al. 2010) **triggered both *Swift* and *Fermi* observatories, thus enabling us to obtain afterglow light-curves from the GeV band to the eV band.** Interestingly, the UVOT light-curve shows a very broad peak at ~1500 s, while the X-ray and the GeV emissions decline from the beginning. This afterglow has been interpreted as either **1) fully powered by FS emission**, from eV to GeV; the spectral energy distributions taken at five different epochs are well fitted with a FS spectral template. However, the temporal behaviour is not that predicted by the FS model. Alternatively, the **different behaviour of X-ray/GeV emission and optical emission can explained if the latter are FS, while the former are a form of late "prompt emission"**.

GRB 060614 (*z*=0.13; see Rossi et al. 2020) prompt light-curve showed an initial large spike followed by weaker emission lasting several tens of seconds. Initially classified as a long-class GRB, caused by the explosion of a SN, **GRB 0600614's location was examined by very large telescopes but no evidence of a supernova was found down to deep upper limits. It has been thus proposed that 060614 belonged to the class of "short" event followed by weak high energy extended emission (EE), but seen at low redshift. Thus the EE became bright enough to extend the duration of the GRB to the long burst class.** The afterglow showed peculiarities as well. The light-curve in UV/optical bands, all studied in detail by UVOT, showed breaks compatible with the red-ward transit of the synchrotron peak frequency at $\simeq 30$ ks, or KN emission. **Possibly similar cases were GRB 211211A (z=0.08) and GRB 230307A (Rastinejad et al. 2022, Levan et al. 2024).** The events appeared like long GRB, with durations of several tens of seconds. However, the prompt emissions took the form of a bright spike followed by some low-level emission again. **Investigations showed emission temporally, spectrally and in luminosity compatible with that of AT2017gfo, i.e. a KN, at the redshift of the events. Thus, 211211A and 230307A would be events powered by compact object mergers, even thought it looked like long GRBs.**

Conclusions

sGRB have allowed us to enter the Multi-messenger era of Astronomy, in which we'll be studying extreme events in both EM and GW channels. This is an enthusing research field, but one in where there is still a lot to learn: for example, how the jets are structured, whether there are more than one channel that leads to mergers of NSs (or NS and black holes), and the creation and evolution of merger ejecta. With its combination of fast slewing and UV sensitivity, *Swift* and in particular *Swift* UVOT can tell us a lot about the topics just mentioned, especially the presence of diverse outflows.

References

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