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The first time domain experiment with Swift: monitoring of seven nearby galaxies

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Abstract. We aimed to detect a supernova (SN) shock breakout (SBO) with observations in time domain. The SBO marks the first escape of radiation from the blast wave that breaks through the photosphere of the star and launches the SN ejecta, and peaks in the ultraviolet and soft X–ray bands. The detection of a SBO allows to determine the onset of the explosion with an accuracy from a few hours to a few seconds. Using the XRT and UVOT instruments onboard the *Swift* satellite we carried out a weekly cadenced, six months lasting monitoring of seven nearby (distance ≤ 50 Mpc) galaxies, namely NGC 1084, NGC 2207/IC 2163, NGC 2770, NGC 4303/M 61, NGC 3147, NGC 3690, NGC 6754. We searched for variable/transient sources in the collected data. We found no evidence for a SN SBO event, but we discovered five objects located within the light of the sample galaxies that are variable in the X–ray and/or in the UV. Our sample galaxies are within the Universe volume that will be reached by the forthcoming advanced gravitational waves (GW) detectors (a-LIGO/a-Virgo), thus this work provides an example on how to carry out *Swift* surveys useful to detect the GW signal from SNe, and to detect counterparts to GW triggers.

1. Introduction

Time domain astronomy is one of the most active and growing areas of research in astronomy, being able to touch basically every aspect of this science with a different perspective.

Time domain astronomy focuses on transient sources. These might be extragalactic, usually involving catastrophic events (supernovae are the most common examples) or Galactic, usually involving cataclysmic events (novae). A few thousands of supernovae (SNe) have been discovered so far. These enhanced our understanding of the last stages of massive stellar lives and deaths, and led us to discover that we live in an accelerating Universe that may be dominated by dark energy. In the last few years the decades-ago predicted pulses marking the precise moment that a supernova shock wave breaks out of the progenitor star were discovered [1, 2]. Longer duration (days) shock breakouts (SBOs) were observed with *GALEX* by type II SNe related to larger (red giant) progenitors [3, 4]. This is an important tool, since the direct detection of SN progenitors is incredibly difficult, and has only been possible for a small number of nearby core-collapse SNe with pre-explosion high resolution imaging. The *Swift* UltraViolet/Optical Telescope (UVOT) is particularly sensitive to the cooling envelope emission, which is bright in the UV for up to several days after the SBO, and can provide estimates of the radius of the progenitor star.

Another ingredient in transient astronomy is the prospect to observe gravitational waves (GWs) in the upcoming years. The second generation ground-based GW detectors are expected to reach sensitivity that will make possible to detect transient GW signals from coalescences of neutron star (NS) and/or stellar-mass black hole binary systems and from core-collapse of massive stars. The advanced LIGO [5] and Virgo [6] detectors in full sensitivity will observe coalescences of NSs up to distance (averaged for sky location and system-orientation) of 200 Mpc. The core-collapse events are expected to be detectable within a few Mpc [7] and up to tens of Mpc for more optimistic models [8].

The present work focuses on SNe, that dominate among transient optical events in nearby galaxies and aims at detecting the UV/X–ray SBO by monitoring nearby galaxies using *Swift*, that has already proven its ability to redefine time domain astronomy with its instruments [9]. While the UV/X–ray bright SBOs are directly possible electromagnetic (EM) counterparts of the GW signals from core-collapse events, nearby galaxies are in general the host of all the GW transient sources detectable by the GW detectors. This time domain experiment by *Swift* represents an example for a possible monitoring program to detect potential sources of GWs, and at the same time to shed light on UV/X–ray "transient contaminants" in galaxy fields. Characterising transient events not directly associated with a GW event will be useful when the EM counterparts of compact object coalescences will be searched in the future.

2. Target galaxies and monitoring details

Our project aims is to monitor nearby galaxies that are site of an intense production of SNe. In the selection of the targets one possible problem is dust obscuration in the optical, thus we cannot base the selection of the sample only on the star formation rate. We adopted a different approach, based on the number of observed SNe in nearby galaxies. Using the Asiago database [10], we selected galaxies in which several SNe were already discovered. Requiring at least 3 observed SNe in the last 20 years, we selected 11 galaxies (observed rate ≥ 0.15 SN yr^{-1}). From these we excluded galaxies in the M 81/ M 82 group because their separation is larger than the UVOT field of view. Our final selection criteria are: a) they are close (distance < 50 Mpc, thus within the a-LIGO and a-Virgo horizon) which allows our instruments to resolve their internal structure; b) their angular size is small enough to fit within the field of view of the *Swift* telescopes (the field of view of the XRT is $23'$ in diameter, or $0.12\,\text{deg}^2$, while the field of view of the UVOT is $17' \times 17'$, or $0.08\,\text{deg}^2$).

With our selection criteria the final sample consists of 10 galaxies. *Swift* observed 7 of them (NGC 5468, NGC 6946, and NGC 4038 were left out). The sample is clearly not complete but provides a fair representation of nearby star-forming galaxies. We selected as target galaxies: NGC 1084, the system NGC 2207/IC 2163, NGC 2770, NGC 4303/M 61, NGC 3147, NGC 3690, and NGC 6754. The monitoring has been carried out with a weekly cadence for about six months over the period 2013-2014.

3. Results

In summary, during our monitoring of seven nearby galaxies with the *Swift* XRT and UVOT telescopes we detected:

- one variable X–ray source inside the galaxy NGC 1084 (NGC1084-I1), likely generated by one to three AGNs at higher redshift;

- one low-luminosity AGN at the centre of the galaxy NGC 4303 (NGC4303-I1) and one at the centre of NGC 3147 (NGC3147-I1), both variable in the X–rays but not in the UV band;
- one variable X–ray source inside the galaxy NGC 3690 (possibly due to the unresolved emission of a number of point-like sources detected by *Chandra* and positionally coincident with the NGC3690-I1);
- one Seyfert 1 galaxy located in a region of the sky outside NGC 4303 (NGC4303-O1) variable in the X–rays as well as in the UV band;
- one possible quasar in a region of the sky outside the target galaxy NGC 3147 (NGC3147-O2), variable in the X–rays but outside the field of view of the UVOT;
- a Galactic uncatalogued eclipsing binary, located in a region of the sky outside the target galaxy NGC 2770 (NGC2770-O1);
- a Galactic known nova (CP Draconis) outside the target galaxy NGC 3147 (NGC3147-O1, see Figure 1).

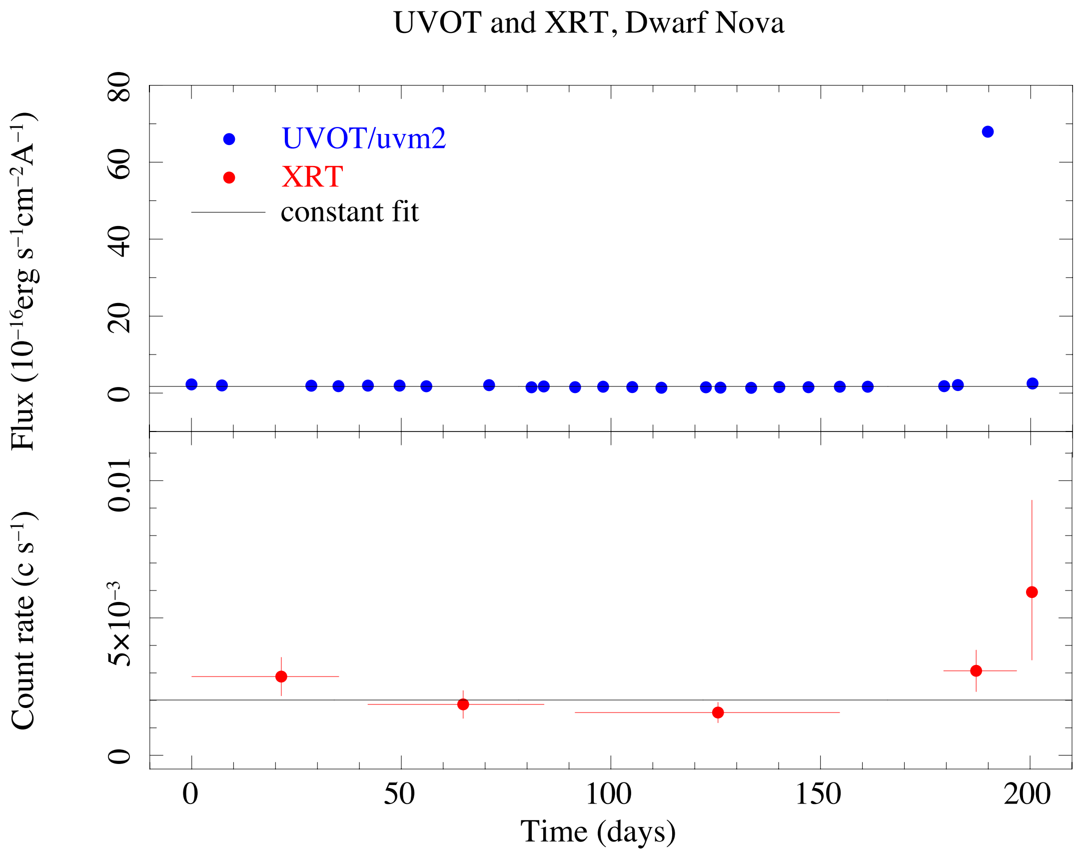

Figure 1. UVOT/*uvm2* light curve (upper panel) extracted with an aperture (radius = 6 arcsec) centred on the dwarf nova CP Draconis (NGC3147-O1). The time zero is set to MET = 409627840 s (2013-12-25). The fit with a constant function provides a $\chi^2 = 3685$ (25 d.o.f.), and a null probability. The X–ray counterpart to this source (lower panel) does not show any significant variability, as the fit with a constant function returns a $\chi^2 = 6.426$ (4 d.o.f.) and a probability $p = 0.1695$.

4. Discussion

During our monitoring of nearby galaxies we aimed at detecting a supernova shock breakout (SBO), that is the soft X–ray and UV outburst expected at the birth of SNe [11]. The SBO marks the first escape of radiation when the blast wave breaks through the surface of the star and launches the SN ejecta. Its detection can enable an early follow-up of the SN, with a detailed study of the luminosity and temperature evolution of the early thermal expansion phase.

We detected several variable sources in both UVOT and XRT data, but we relate none of them to a SN SBO event. The short duration (seconds to hours) of SBOs and the lack of sensitive wide-field searches at high energies make their discovery very hard, but the *Swift*/XRT and UVOT provided evidences of their existence by detecting the early X–ray/UV emission a few days before the SNe 2006aj associated with the GRB 060218 [1] and before the SNe 2008D [2]. Also the *GALEX* satellite detected serendipitous early UV events associated to the SNe SNLS-04D2dc [4, 3], SNLS-06D1jd [3] and 2010aq [12]. These observations constrained the onset time of SBOs, which marks the moment of the star explosion, with a precision better than 1 day.

We estimated the effectiveness of our survey to detect an SBO to be $15.9^{+11,1}_{-6.6}$% from Type II-P SNe, of 0.03% (± 0.02%) from Type Ibc SNe. To calculate these probabilities we assumed a (conservative) detection rate of 3 SNe in the last 20 y (0.15 SNe yr^{-1}) for each galaxy of our sample [10], with a 90% interval corresponding to a Poissonian mean rate of (0.08-0.27) SNe yr^{-1}. We considered the UV emission lasting 3.5 days and 1000 s for Type II-P and Tipe Ibc SNe, respectively. We also accounted for the 65% of SNe exploding as Type II-P, the 25% exploding as Type Ibc [13, 14, 15].

The multi-frequency periodic monitoring of nearby galaxies presented in this work represents a useful explorative study to test the capabilities of the *Swift* satellite for joint surveys with the GW detectors. Our target, the SBO, is an expected EM counterpart to GW signals from core-collapse SNe, and our sample galaxies are within the Universe volume ($<$ 200 Mpc) that will be reached by the forthcoming advanced GW detectors (a-LIGO and a-Virgo) for binary coalescing NS systems. The *Swift* detection of a transient phenomenon that is expected to be a GW emitter, like local (within few tens of Mpc) SNe or "orphan" gamma-ray bursts [16], provides timing and sky position that can be used in the search for the GW signal. The use of external triggers improves significantly the GW search sensitivity [17] with respect to all-sky searches. The narrow field of the *Swift*/XRT and UVOT represents a limitation in the search for the EM counterpart to a GW source given that, even in the era of the advanced detectors, the sky localization uncertainty of GW signals is expected to be large (hundreds of square degrees [18]). For this reason, the effective strategy for the *Swift* satellite is to observe a limited number of fields inside the error region, namely those containing known, nearby galaxies [19, 20, 21, 9].

5. Conclusions

This work demonstrates that the *Swift* satellite is suitable to carry on targeted, multi-wavelength observations in time domain. We stress that a survey like the one we carried out with *Swift* is and will be useful in the framework of multi-messenger astronomy. It can significantly contribute to the detection of EM signature of the GW sources. Indeed, SNe are putative GW emitters, and the detection of their SBO would increase our ability to constrain the time window in which the explosion takes place, which is crucial to search for GW signals. All galaxies included in our sample are close enough ($<$50 Mpc) to lay within the a-LIGO and a-Virgo horizon for NS-NS and black hole-NS merger events. Despite the limited field of view of *Swift*/XRT and UVOT, choosing nearby galaxies as target of a regular, periodic observation is a winning strategy to trigger the GW signal search, to find possible EM counterparts during follow-up of GW detections [21] and to rule out contaminants by the study of their light curves.

Details of this work can be found in Andreoni et al. (2016) [22].

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