Mem. S.A.It. Vol. 88, 459

Memorie della

A rummage in the Spitzer Heritage Archive: searching for signs of circumstellar interaction in supernovae

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Abstract. In thermonuclear (Type Ia) and stripped-envelope core-collapse (SE CC, including Type Ib/c and IIb) supernovae (SNe), the primary source of late-time mid-infrared (mid-IR) excess may be some kind of interaction between the SN ejecta and the circumstellar matter (CSM) that originated from the pre-explosion mass-loss of the progenitor and/or its companion star. Up to now, the signs of ejecta-CSM interaction have been detected only in a few of these objects. Nevertheless, based on a wide-spreading concept, many of Type Ia and SE CC SNe may show such detectable signs; in these cases, CSM shells may be much further away from the explosion site than in other, well-known interacting SNe (e.g. Type IIn ones). Here we present some preliminary results of a comprehensive study based on archive, mainly unpublished Spitzer/IRAC data of more than 900 Type Ia or SE CC SNe, which goal is to find signs of ejecta-CSM interaction in the mid-infrared range.

Key words. supernovae: general – infrared: stars – stars: mass-loss

1. Introduction

Observing the interaction of supernova (SN) ejecta with the circumstellar matter (CSM) offers a chance to find answers to some open questions regarding the final stages of stellar evolution. In the cases of stripped-envelope core-collapse (SE CC, including Type Ib/c and IIb) SNe, both the transition to and the duration of the pre-explosional phases can be probed via revealing the mass-loss history of the progenitor. In thermonuclear explosions of C/O white dwarfs, called Type Ia SNe, the key-question is the presence of any CSM, which could serve as an evidence in a long-term debate about which fraction of Ia progenitor systems contain a non-degenerate companion (known as single-degenerate scenario).

Up to now, only a few known SE CCSN – Type IIb SN 1993J (e.g. Patat et al. 1995; Matheson et al. 2000, 2001) and SN 2013df (Maeda et al. 2015; Kamble et al. 2016), Type Ib/c SN 2001em (e.g. Stockdale et al. 2004; Pooley & Levin 2004; Soderberg et al. 2004), Type Ibn SN 2006jc (e.g. Foley et al. 2007; Smith et al. 2008), and Type Ib SN 2014C (Milisavljevic et al. 2015; Margutti et al. 2017) – produced significant signs of ejecta-CSM interaction. Such kind of interaction has not been identified yet in any "normal" SN Ia; however, dense, H-rich shells of CSM have been detected around special objects called SNe Ia-

CSM (e.g. Silverman et al. 2013; Inserra et al. 2016).

Based on a wide-spreading concept (see e.g. Vinkó et al. 2017), many of thermonulear and SE CC SNe may show detectable sign of circumstellar interaction. In these cases, CSM shells may be far away from the explosion site, thus, the interaction and the radiation that are produced by it would occur at later times than was seen in SNe IIn or other strongly interacting SNe (maybe over a decade). While the general way of the direct confirmation of ejecta-CSM interaction is obtaining spectroscopic and/or multi-wavelength (usually X-ray/radio) observations, the previous assumption can be confirmed most effectively via large-sample imaging surveys carried out in specific wavelength ranges.

The mid-infrared (mid-IR) range belongs to this category and, thanks to the NASA's *Spitzer Space Telescope* (hereafter *Spitzer*), there are available datasets for this purpose: targeted surveys and, moreover, archive data from non-SN targeted galaxy surveys allow us to follow the mid-IR evolution of a number of nearby SNe during several years. Here we present some preliminary results of a comprehensive study based on archive, mainly unpublished *Spitzer* data of more than 900 Type Ia or SE CC SNe.

2. Expected signs of SN-CSM interactions in Mid-IR

Within the framework of targeted observations and surveys (see e.g. Fox et al. 2013; Tinyanont et al. 2016), more than 200 SNe has been followed with *Spitzer* to date; however, there are even more SNe that have been captured during non-SN targeted surveys. There are many known H-rich SNe with detected late-time (>1 yr after explosion) mid-IR excess, see e.g. Fox et al. (2013) and Szalai & Vinkó (2013) regarding SNe IIn and II-P, respectively; in these cases, the main source of mid-IR excess is thought to be the emission of pre-existing dust grains heated during the ejecta-CSM interactions (SNe IIn) or dust formation in the expanding ejecta (SNe II-P). At the same time, many fewer (published) results regarding thermonuclear or SE CC SNe are present; however, based on theoretical considerations, ejecta-CSM interaction could lead to either an IR echo or dust formation inducing late-time mid-IR excess even in Type Ia and SE CC SNe (see e.g. Nozawa et al. 2011; Gall et al. 2011).

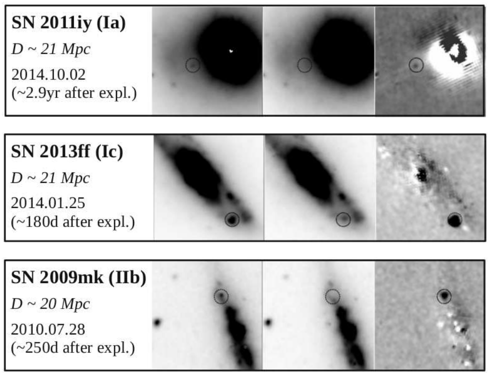

Fig. 1. All blocks consist of three panels show the detection of the SN on a late-time Spitzer/IRAC 4.5 μm image (left), a pre-explosion image of the site (middle), and the difference image created with HOTPANTS (right), respectively.

Up to now, there is no detection of significant late-time mid-IR emission of "normal" SNe Ia, not even in the cases of the closest and most well-studied objects like SN 2011fe or SN 2014J (see Johansson et al. 2017). On the other hand, the detected SNe Ia-CSM are very bright in mid-IR (more precisely, at 3.6 and 4.5 μm), even 2-3 years after explosion; actually, even ~10-100 times fainter events would be possible to detect with *Spitzer* in close SNe Ia than those observed in these strongly interacting, distant (d > 200 Mpc) objects (see e.g. Fox & Filippenko 2013). Note that there is another very interesting object, SN 2014dt, classified as a Type Iax SN, which showed clear and even growing mid-IR excess ~1 yr after explosion (Fox et al. 2016).

In the cases of SE CC SNe, different processes on different time-scales are expected to see in mid-IR. SNe Ib/c, thought to go through intense pre-explosion mass-loss processes, are expected to show mid-IR radiation from pre-existing dust heated by the optical/X-ray flux

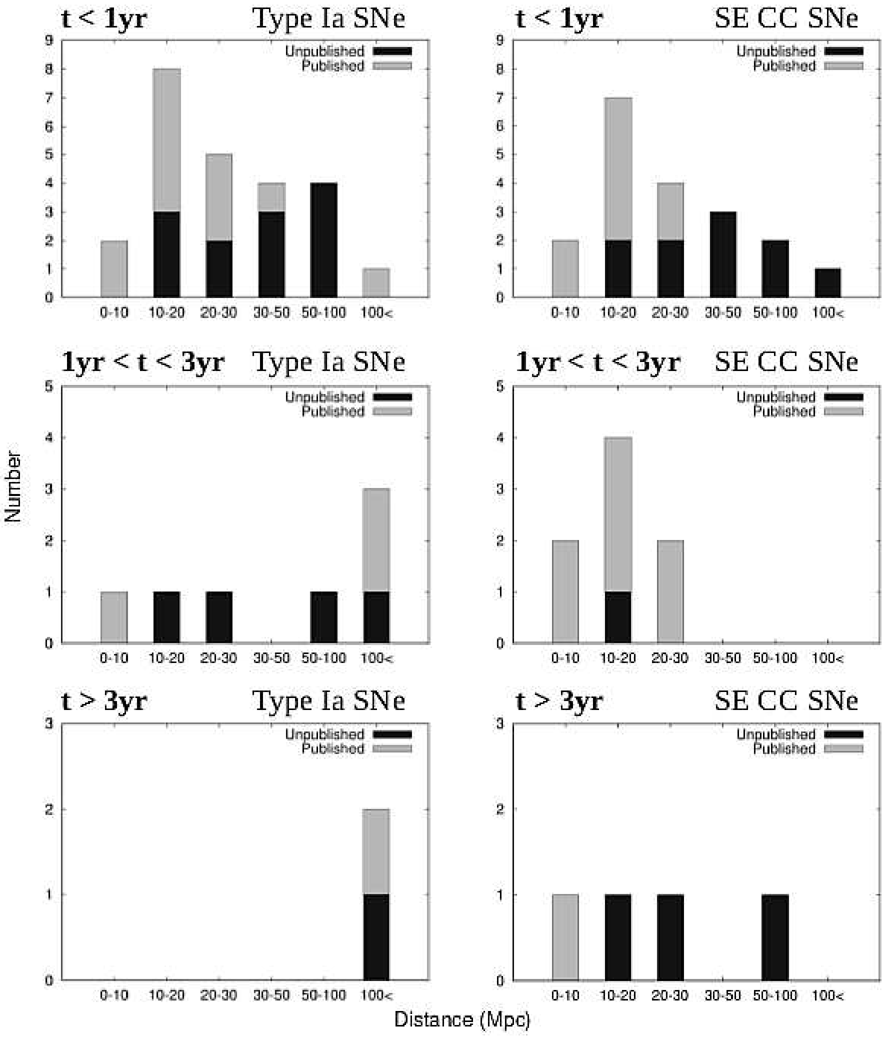

Fig. 2. The panels show the number of detected Type Ia and SE CC SNe on *Spitzer*/IRAC images within different timescales after explosion. The main sources of the published data are the papers of Tinyanont et al. (2016) and Johansson et al. (2017), while detections of certain single objects are from Mattila et al. (2008); Kochanek et al. (2011); Fox et al. (2013); McClelland et al. (2013); Kankare et al. (2014); Ergon et al. (2015), and Fox et al. (2016).

emerge during the ongoing CSM interaction, maybe within a few years after explosion. Even so, there are only a few of these objects with detected late-time mid-IR excess; however, these includes the bright and well-known interacting SN 2001em and SN 2014C (see the latter one in Tinyanont et al. 2016). In SNe IIb, either a small amount of newly-formed ejecta dust or the effects of ejecta-CSM interaction could be the source of mid-IR excess; anyway, such signs has been only detected in SN 2013df to date (Szalai et al. 2016; Tinyanont et al. 2016), while the well-known interacting SN 1993J is still visible in *Spitzer*/IRAC im-

Table 1. Preliminary statistics regarding the Spitzer data of studied Type Ia and stripped-envelope core-collapse supernovae. "Type Ia SNe" include "normal" SNe Ia, Iax, and Ia-CSM, while "SE CC SNe" include SNe Ib/c, Ibn, and IIb.

	All detected SN sites	Positive detections	
		Total	**Unpubl.**
Total	929	53	**29**
Type Ia SNe	761	30	**17**
SE CC SNe	168	23	**12**

ages more than two decades after explosion (Tinyanont et al. 2016). The special SNe Ibn, expected to explode in He-rich CSM, do not show late-time mid-IR excess; however, one of these objects, SN 2006jc, was bright in early-time Spitzer images (Mattila et al. 2008).

3. Analysis of Spitzer data: preliminary results

We have carried out a comprehensive study based on archive, mainly unpublished *Spitzer*/IRAC data of more than 900 Type Ia and SE CC SNe used the Spitzer Heritage Archive[1]. Sometimes it was difficult to decide whether there is a positive detection or not (diffuse background, SN position too close to the center of the host galaxy); in these cases, if pre-explosion images are also available, we applied the image subtraction technique using the HOTPANTS code (A. Becker).

While the detailed analysis is still in progress, some preliminary results can be presented here. In Fig. 1, we show some unpublished detections originating from non-SN targeted surveys; these examples also demonstrates the usefulness of the image subtraction technique. Table 1 and Fig. 2 show statistics regarding the studied Type Ia and SE CC SNe. It can be seen that our current study has almost doubled the number of both Type Ia and SE CC SNe with detected mid-IR excess. Nevertheless, as it can be seen in Fig. 2, most of the new detections are related to early-time detections (<1 yr after explosion); however, there are also some very late-time detections (>3 yr after explosion).

[1] http://sha.ipac.caltech.edu

Acknowledgements. This work is supported by the NKFIH grant PD112325 of the Hungarian National Research, Development and Innovation Office. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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