



NOT Stockholm Supernovae

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Abstract

This proceeding contribution is a short summary of the invited talk about observational supernova science at Stockholm University that has been conducted at the Nordic Optical Telescope over the past 25 years, and some expectations for the future.

Keywords: Stockholm, Supernovae, Sollerman, Transients, Nordic Optical Telescope

1 Introduction

In the NOT workshop in June 2022, I delivered an invited talk about supernova research conducted at the Nordic Optical Telescope (NOT) from Stockholm University. It was titled *The Nordic Optical Telescope and Stockholm Supernovae 1994-2024 (my personal view)*. This talk was given in a semi-historical context from my own first observing runs in 1994 to future plans for supernova classifications of LSST supernovae. The talk is available on the NOT WWW, and here I simply give a summary of a few of the points given in that presentation. I have been running a supernova program at the NOT as service mode / Target-of-Opportunity for the past 10+ years, most of them as Large Programmes. The talk was not intended to be comprehensive, rather nostalgic.

2 Early days

I have been doing supernova observations for over 30 years and am a keen user of the NOT. It was indeed the first observing runs at this telescope that made me aim for an observational astronomy career, even though all other supernova researchers at Stockholm observatory at that time were doing modeling.

I remember well my first observing runs as amazingly fascinating, although in hindsight maybe not that efficient. Filling the nitrogen dewars yourself while integrating on a supernova, using the offline PC to find coordinates for guide-stars to track on, screwdriver in the pocket to fight with filter wheels. The NOT in the 1990s was a great telescope on a fantastic site, but the instrumentation and automation that enabled efficient observing, including service mode and Target-of-Opportunity, came later. I argued in my talk that this was at least a good way to learn the skills of observing, even if the scattered epochs of supernova observations that emerged from a typical visitor run in the 1990s is a far cry from what modern supernova science requires. The training aspect later motivated me to run two [summer schools](#) at the NOT with Nordic PhD students (2003 and 2006). Other contributions in this conference proceeding focus more on the important educational aspects of the telescope.

In my talk I also briefly reviewed the development of supernova surveys. In the early days, a great number of nearby supernovae were in fact discovered by dedicated amateur astronomers, and professional astronomers were slow to take up the supernova survey strategies developed by Fritz Zwicky in

the middle of the last century. With the High- z Supernova Search team (Tonry et al., 2003) where I participated to search for Type Ia supernovae for cosmology in the late 1990s, the technique was adopted with modern CCDs to image the sky several nights apart and search for transients in the difference image subtractions. With subsequent pre-planned visitor runs on larger telescopes we could then classify the newly discovered SNe. ESSENCE (Miknaitis et al., 2007) followed a similar scheme, whereas the SDSS-II supernova search (Frieman et al., 2008) employed a dedicated telescope with a rolling search. This automatically gave well-covered multi-band, high-cadence supernova light curves. iPTF and its successor ZTF (Graham et al., 2019; Bellm et al., 2019) have added increasingly larger fields, higher cadence and automation and are bringing transient science to the new era that the Vera Rubin Observatory will cement.

This development and evolution in survey capacity has not only hugely increased the number of SNe detected with time, but also the quality of the observations. More SNe means that we find rarer objects, and there is often a lot of physics to deduce from such outliers. Higher cadence means we find the SNe earlier, and the untargeted search strategy gives a less biased view of the underlying populations, which has also revealed new classes of objects.

3 Recent past

I have not done the exercise to count the number of refereed papers that have been published based on the supernova programmes at the NOT led from Stockholm. There must be $\gtrsim 100$ such papers, and deciding which ones have been most important of course depends on who you ask. Some handful of PhD students have based their supernova PhD-theses on NOT data, most of them supervised by myself on the core-collapse side of the supernova spectrum, or by Ariel Goobar for the thermonuclear ones. A handful of publications have made it into high-impact journals like *Nature* and *Science* over the years¹.

The reason NOT is so good for us doing transient astronomy is that it is **flexible**, simple, accessible and often fast. Transient astronomy is about getting the data when needed, and within international collaborations we can complement or even rival larger telescopes by being smart on when and how to get the spectra. This has allowed us to participate in many interesting investigations, but also to take the lead in a number of projects.

Figure 1 illustrates this by showing a person-gallery of Stockholm scientists that have all led papers based on data from the NOT, including work on (this is from left to right, from top to bottom in Fig. 1): Helium-rich Type Ia-CSM supernova with radio detections (Kool et al., 2022), oxygen abundances in Type II supernovae (Jerkstrand et al., 2014), the stripped-envelope supernova iPTF13bvn (Fremming et al., 2016), superluminous supernovae from ZTF (Lunnan et al., 2020) the magnetar-driven iPTF15dtg (Taddia et al., 2019), and the enigmatic zombie-supernova iPTF14hls (Arcavi et al., 2017; Sollerman et al., 2019).

A stripped-envelope SN with a H-shell (Tartaglia et al., 2021), Type Ia supernova distances (Johansson et al., 2021), the candidate pair-instability supernova SN 2018ibb (Schulze and et al., 2022), or hydrogen deficient Type Ibn supernovae (Karamehmetoglu et al., 2021), and a Type Ic SN metamorphing into a Type IIn (Chen et al., 2018), or the bumpy light-curve of Type IIn iPTF13z (Nyholm et al., 2017).

The PhD-thesis papers on the now canonical Type IIB [SN 2011dh](#) (Ergon et al., 2014, 2015), the low-luminosity supernova SN 2020cx (Yang et al., 2021), the almost superluminous SN 2012aa (Roy

¹For the 2 dozens of papers in *Nature/Science* journals that I have co-authored over the past 20 years, about a third include data from the NOT, including the birth of the field of Flash spectroscopy for supernovae (Gal-Yam et al., 2014; Yaron et al., 2017), and the new Type Icn supernova class (Gal-Yam et al., 2022).



Figure 1: To pick a single slide from my presentation I would select this one. These are all astronomers that first-authored a refereed publication including observations from the NOT while they were working at Stockholm University. See text for further information on some of these articles.

et al., 2016), the multiply imaged gravitationally lensed Type Ia supernova iPTF16geu (Goobar et al., 2017), or work on circumstellar interaction supernovae like in the monumental paper on SN 2010jl where NOT data were complemented with spectra from the Hubble Space Telescope (Fransson et al., 2014), or analysis of Type Ia SN spectra (Nordin et al., 2011), the power of supernova siblings (Biswas et al., 2022), or extinction law studies for Type Ia supernovae (Amanullah et al., 2015), and the full sample of stripped-envelope Type Ic SNe from PTF (Barbarino et al., 2021).

Bumpy superluminous supernovae (SLSNe) of Type I (West et al., 2022) and of SLSNe Type II (Kangas et al., 2022), constraints on hydrogen in Type Ia SNe (Lundqvist et al., 2015) and a very detailed study of a normal Type Ia (Stanishev et al., 2007). The NOT spectroscopic follow-up of SDSS-II SNe Ia (Östman et al., 2011) and long-lived interaction powered Type IIn supernovae (Stritzinger et al., 2012), an oxygen-rich stripped envelope supernova (Schweyer et al., 2022) and finally the Crab supernova remnant and its famous pulsar (Sandberg and Sollerman, 2009).

There is a strong legacy not only in the scientific data and these published results, but also in the number of researchers that have benefited from this long-term collaboration. The relative diversity in the topics mentioned above also illustrates that an observing programme for transient sources needs flexibility to allow seizing the opportunities as they arise in the universe. We must both be ready to work on systematic and complete samples and to quickly jump on whatever new explosion that occurs.

That Nordic transient astronomy has flourished with the help of the NOT was also obvious from the many presentations given during this workshop. In the distant past, the proposal I lead was the only one for supernovae at the NOT, while today there is a plethora of projects from for example Århus, Åbo, Copenhagen and also several from outside the Nordic countries (like Spain and Italy). Many of these Nordic supernova nodes are now led by astronomers that once did an observational supernova

postdoc with us in Stockholm. NOT has clearly been a key component for allowing astronomers in the Nordic countries to do competitive transient science on the international scene.

4 Nowadays

The current main focus of my own SN research is the [Zwicky Transient Facility](#) (ZTF). With a refurbished Schmidt telescope (P48) on classical Palomar, a super-sized 47 square-degree detector, and a very low-resolution dedicated follow-up spectrograph (SEDM on P60), I can discover a handful of supernovae every night, immediately get a spectrum and classify them. Since 2018 we have trawled the Northern sky on a nightly basis and within the Bright Transient Survey (BTS) (Fremling et al., 2020; Perley et al., 2020) we have so far classified over 6000 SNe. I have discovered just as many myself, which highlights the new era we are in². The light curves of these supernovae are directly made available to the public via the [Bright Transient Survey explorer](#) and the classification spectra are immediately uploaded to the Transient Name Server (TNS).

In contrast to the early days of supernova science, this rolling, untargeted and systematic system more or less automatically provides three (*gri*) photometric band light curves for supernovae and other transients. The new era thus combines the survey strategies once developed in the supernova cosmology framework with the rapid follow-up capacities inherited from the fast-shooting γ -ray burst community.

An illustrative example of how the scope of the transient astronomy has expanded could be to think of supernova 1987A, which was the main topic of research for the supernova group in Stockholm when I started my PhD. It got the designation ‘A’ since it was the first supernova discovered in that year, on February 24 1987. This means that the first 54 days that year did not have a single supernova. In contrast, this year, 2022, 340 classified SNe had already been reported to the TNS up to February 24 (about 6 per day), so a SN discovered that day got a more complicated name such as SN 2022dek. Of these 340 SNe, ZTF follows some 68% and discovered around 20%. But the classified supernovae are only a small fraction of the reported transients; there were in fact over 3000 transients reported to TNS in the first 55 days of the year 2022, so only 11% were classified supernovae. One third of the classifications were done with the SEDM on the P60, for which I am the main responsible.

The name of the game is now instead to recognize which of all the new objects are interesting enough for a dedicated follow-up campaign. We have seldom used the NOT for pure classifications, most objects are simply not interesting enough to waste valuable NOT time. Today the SEDM on the P60 is the classification work horse, and we trigger NOT mainly for objects that we already know are going to be of interest (for some specific publication). Once I have allocated a target to SEDM, the robotic execution is automatic, the reductions are automatic (Rigault et al., 2019) and if it is a typical SN Ia it will automatically be classified (Fremling et al., 2021) and uploaded to the TNS. Once NOT confirms the interest of a particular object, many other, often larger, telescopes are typically triggered for further investigations. This is a good food-chain for transient astronomy where every telescope kicks in where (and only where) it is best needed.

5 Future

I strongly believe NOT will continue to be competitive due to its size, location and flexibility. At Stockholm University, half a dozen of scientists have joined the Vera Rubin Observatory to conduct

²Fritz Zwicky himself was for a long time the record holder in discovering SNe, with 120 SNe over a period of ~ 50 years. Hard work at a cold telescope, daytime blinking of the plates and endurance that contrasts with my own clicking on the computer over breakfast coffee.

the Large Synoptic Survey Telescope (LSST) survey over the coming 10 years (starting 2024). This will find tens of thousands of transients and will again transform time domain astronomy. We have offered to provide ~ 300 hours of NOT telescope time over three years to the LSST project for classifications of supernovae, and for this we, of course, hope to use the new Nordic Transient Explorer (NTE) with its improved sensitivity and extended wavelength range. There will be no lack of targets for future supernova astronomers, the challenge will be to cope with the flood of data and cleverly select the most interesting targets for follow-up.

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