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Nuclear Transients

Workshop 11

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Abstract. Workshop 11 covered the substantial recent progress in studies of supernovæ (SNe), tidal disruption events (TDEs), and other types of luminous transients occurring within the nuclear regions of galaxies. In the past, such transients have largely been missed owing to the substantial extinction of those regions, and to the problems of contrast against the bright (and often complex) nuclear background – or mistaken for normal active galactic nucleus (AGN) variability.

Keywords. Supernovæ: general, accretion disks, black hole physics, galaxies: active, surveys

1. Introduction

Nuclear transients have become highly topical owing to the recent progress in the study of supernovæ (SNe), tidal disruption events (TDEs), and other types of luminous transients that occur within the nuclear regions of galaxies. While thousands of SNe are discovered each year, the transients occurring within the nuclei of galaxies have largely been missed by the surveys, or overlooked as the variability of ordinary active galactic nuclei (AGN). In effect, they have been a 'blind spot' of the research community. In the past nuclear transients have been challenging to detect and characterise against a galactic nuclear background that was often bright and complex, but improvements in difference imaging and in machine-learning techniques are now starting to enable us to recover them in significant numbers, and in seeing-limited searches at optical wavelengths as well.

In addition, observations at high spatial resolution in the IR and at radio frequencies have also made possible the detection and study of transients within the highly obscured nuclear regions of luminous infrared galaxies (LIRGs). Nevertheless, it can sometimes be very challenging to distinguish between a SN and an AGN even when spectroscopic observations are available – as demonstrated in Fig. 1. Recent discoveries of particularly interesting cases include (1) a new class of extremely energetic transients in the nuclei of Seyfert galaxies (Drake *et al.* 2011; Kankare *et al.* 2017; Blanchard *et al.* 2017; Graham *et al.* 2017), (2) a dust-enshrouded, extremely energetic TDE in an LIRG (Mattila *et al.* 2018), and (3) evidence for an enhanced rate of TDEs (Tadhunter *et al.* 2017) in such galaxies.

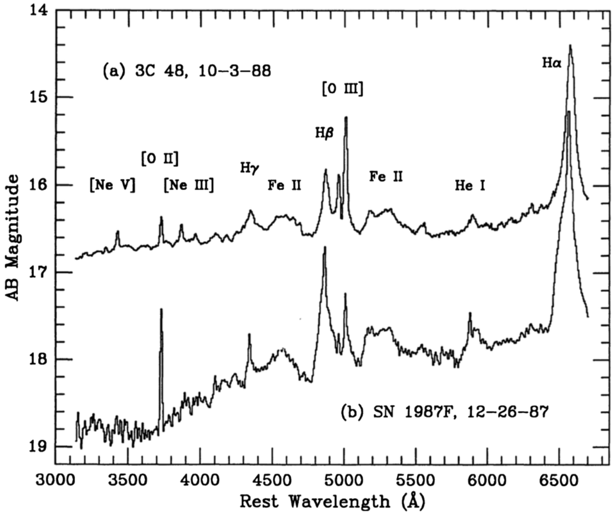

Figure 1. Comparison between optical spectra of the QSO 3C48 and SN 1987F (from Filippenko 1989. *Reproduced with kind permission.*)

The format of the Workshop consisted of presentations that provided a multi-wavelength view of nuclear transients, highlighting some intriguing individual cases and offering possible explanations for these extremely energetic events.

2. Optical AGN Variability

There is a large degree of variety in the optical variability of quasars, and it is unclear whether it can all be attributed to a single (set of) physical mechanism(s). Graham *et al.* (2017) presented the results of a systematic search for major flares in AGNs in the Catalina Real-Time Transient Survey, as part of a broader study into extreme quasar variability. Such flares are defined in a quantitative manner as exhibiting greater than the normal stochastic variability of quasars; a typical event lasts 900 days, and has a median peak amplitude of 1.25 mag. Graham *et al.* identified 51 events from over 900,000 known quasars and high-probability quasar candidates. By characterising the flare profile with a Weibull distribution, they found that 9 of the sources could be described well by a single-point, single-lens model, and supporting the proposal by Lawrence *et al.* (2016) that microlensing is a plausible mechanism for extreme variability. However, Graham *et al.* attributed the majority of their events to explosive stellar-related activity in the accretion disk, such as superluminous SNe, TDEs, or mergers of stellar-mass black holes.

3. Optical Observations of TDEs

The OGLE-IV Real-time Transient Search (Wyrzykowski *et al.* 2014) relies on many years of historic observations of a 700 sq.deg. area of the southern sky. It uses an optimised difference imaging method and is therefore able to subtract a host galaxy successfully and to discover nuclear transients early in their evolution. A particular example is the candidate TDE, OGLE16aaa, which was found in a weakly active galaxy (Wyrzykowski *et al.* 2017). The Gaia Science Alerts programme (Hodgkin *et al.* 2013) is utilising Gaia's superb astrometric capabilities, and a low-dispersion on-board spectrograph, to detect candidates for nuclear transients. Most of the transients confirmed to date are Type Ia or Type II SNe, plus a couple of examples of extreme flares of possible AGN origins. The follow-up spectra are provided by the Nordic Optical Telescope, the Southern African Large Telescope, ESO's NTT and the VLT.

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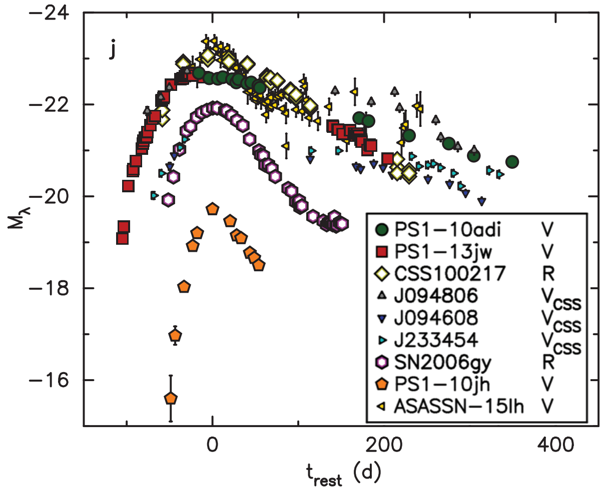

Figure 2. Absolute optical light-curves of the extremely luminous nuclear transient PS1-10adi and the similar objects (PS1-13jw, J094806, J094608 and J233454), compared with CSS100217, SN 2006gy (super luminous SN IIn), PS1-10jh (TDE) and ASASSN-15lh, from Kankare *et al.* (2017). *Reproduced with kind permission.*

4. Observations of Extremely Luminous Nuclear Transients

Recent studies have reported multiple new types of luminous transients that radiate $\sim 10^{52}$ erg of energy but show major diversity in their spectrophotometric evolution. Those events are found in the nuclear regions of their host galaxies, but the hosts themselves are very diverse. However, none of these events appears to be normal AGN variability. There is a population of smoothly evolving nuclear transients (see Fig. 2) which radiate $\sim 10^{52}$ erg, show strong $\lesssim 1000$ km s^{-1} Balmer lines, and have Seyfert galaxy hosts. Such events include CSS100217:102913+404220 (Drake *et al.* 2011), PS16dtm (Blanchard *et al.* 2017), and PS1-10adi (Kankare *et al.* 2017). Furthermore, Kankare *et al.* (2017) presented 4 additional PS1-10adi-like candidates from archived data with similar photometric evolution and Seyfert hosts, of which two have also been independently discovered and reported by Graham *et al.* (2017) in a compillation of several tens of flares in AGNs. Drake *et al.* (2011) proposed that CSS100217:102913+404220 is a SN in the accretion disk of the supermassive black hole of the host galaxy. Blanchard *et al.* (2017) suggested that PS16dtm is a TDE. The conclusion of Kankare *et al.* (2017) was that PS1-10adi-like events are either energetic SNe within the host's narrow-line region, or TDEs with expanding material colliding and sweeping up dense material from the broad-line region.

ASASSN-15lh is a well-known recent transient which radiates $\sim 10^{52}$ erg of energy; its origin has been associated with both a superluminous SN (e.g. Dong *et al.* 2016) and a TDE (e.g. Leloudas *et al.* 2016). As with other PS1-10adi-like events, no historical variability is evident in the host from archived data. While ASASSN-15lh is located at $z = 0.233$, its high intrinsic luminosity and a passive host galaxy with a low line-of-sight extinction in the host galaxy are favourable characteristics for large-scale all-sky optical transient surveys. Nonetheless, no other similar transient has been reported in the literature.

5. Superluminous Transients at AGN Centres

Recent transient surveys are discovering many superluminous events that appear at AGN centres (see Sects. 2 and 4). Their typical peak magnitudes are around –23, and they are bright for a few hundred days (see Fig. 2). The total radiated energy reaches

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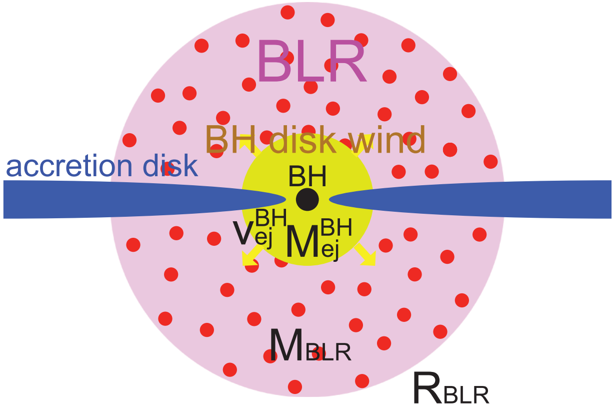

Figure 3. Schematic picture of the black-hole disk wind interaction model to make superluminous transients from AGN centres. From Moriya *et al.* (2017). *Reproduced with kind permission.*

$\sim 10^{52}$ erg. They are also characterised by Type IIn supernova-like spectra, indicating the existence of interaction. They often appear in Narrow-line Seyfert 1 (NLS1) galaxies that reach near- or super-Eddington luminosities of the central black holes. That kind of variability cannot be explained by standard AGN activity.

Moriya *et al.* (2017) suggested that such superluminous nuclear transients are powered by the interaction between accretion disk winds and clouds in broad-line regions surrounding them, as shown schematically in Fig. 3. If the disk luminosity temporary increases by, say, limit-cycle oscillations leading to a powerful radiatively driven wind, strong shock waves will propagate in the broad-line region. Because the dense clouds in the broad-line region typically have densities similar to those found in Type IIn supernovæ, strong radiative shocks emerge and convert the kinetic energy of the ejecta efficiently into radiation. Transients similar to Type IIn supernovæ are therefore likely to be observed in AGN central regions when a strong disk wind is blowing. Since the velocity of a typical black-hole disk wind is $\simeq 0.1c$ where c is the speed of light, the kinetic energy of the ejecta is expected to be $\simeq 10^{52}$ erg when $\simeq 1\ M_{\odot}$ is ejected. That kinetic energy is transformed into radiation over a time-scale for the wind to sweep up a mass similar to its own in the broad-line region, i.e., a few hundred days. Therefore, both the luminosities ($\sim 10^{44}$ erg s^{-1}) and the time-scales (~ 100 days) of the superluminous transients from AGN centres match those expected in this interaction model. If superluminous transients from AGN centres are related to the AGN disk wind triggered by limit-cycle oscillations, they would become bright intermittently with intervals of years or decades.

6. Near-IR Detection and Study of Nuclear SNe

Kool *et al.* (2018) described project SUNBIRD (Supernovæ UNmasked By Infra-Red Detection), which is monitoring over 30 LIRGs for core-collapse SNe in order to characterise the population of SNe in the nuclear regions of LIRGs, so as to improve the constraints on the fraction of SNe that are missed by conventional SN surveys through dust obscuration and poor spatial resolution. Observations are carried out in the near-IR, which is much less affected by dust extinction compared to the optical. Laser guide-star AO imagers are used on the Gemini South and Keck telescopes, achieving a spatial resolution of $\sim 0''.1$. During its first year 3 SNe and one candidate were discovered, with nuclear offsets as small as 200 pc and extinctions of up to 5 magnitudes in V.

Adding the new discoveries to the 8 core-collapse SNe previously discovered in LIRGs by surveys employing AO, Kool *et al.* investigated how effective their method was in

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uncovering CCSNe in the nuclear regions of LIRGs, compared with seeing-limited optical and near-IR surveys. First, the expected core-collapse SN rate of all nearby LIRGs was $\sim$250 yr^{-1}, but in total there were only $\sim$60 documented core-collapse SNe in those galaxies, making it clear that the majority of SNe in LIRGs were not being observed. Secondly, while the coverage of LIRGs in the optical extended over a longer time-base at higher cadence compared to the near-IR by at least an order of magnitude, there have been almost as many core-collapse SN discoveries since 2000 in LIRGs in the near-IR (21) as in the optical (29). That implies that it is substantially more efficient to detect SNe in the near-IR in those galaxies. Finally, almost half of the near-IR core-collapse SN discoveries were from AO-assisted programmes, while the coverage of LIRGs by seeing-limited, near-IR surveys was at least an order of magnitude higher. Furthermore, the majority of AO-detected SNe have nuclear offsets of $<$1 kpc. The effects of reduced dust extinction in the near-IR and improved spatial resolution with AO imaging do therefore enhance the sensitivity to SN detection within the nuclear regions of LIRGs.

7. Radio Observations of Nuclear Transients

The properties and rates of nuclear transients in galaxies have remained largely unexplored because the surveys are almost exclusively ground-based, seeing-limited, and work at optical wavelengths. Starburst galaxies and LIRGs do have large amounts of dust at their centres, and radio offers a natural approach to study their populations of nuclear transients as it is not hampered by dust extinction. Besides, because of the intrinsic vicinity of those transients to the host galaxy's active nucleus – often within just a few pc, or less than one pc – VLBI observations become the unique tool to shed light on the nature of nuclear transients by virtue of the milliarcsecond angular resolution which the observations provide (Perez-Torres *et al.* 2009). For example, both core-collapse SNe and TDEs are expected to yield significant radio emission for a relatively long period, initially with a rapid rise towards the emission peak and followed by a slower decline. High-angular radio observations enable confirmation of the nature of newly exploded SN events, since a radio detection implies that the SN is certainly of core-collapse origin. High-angular resolution radio observations are also telltale signatures of nuclear events, e.g., the discovery of a radio jet in a nuclear transients would rule out a SN, or a GRB cause, and suggest the existence of an AGN/TDE instead.

Nuclear transients are at the dawn of a renaissance, and the new radio facilities (MeerKAT, ASKAP and eventually SKA), thanks to their large fields of view, will help us disentangle the nature of many of those transients, and to characterise their properties in a statistical way.

8. Discussion

The presentations were followed by lively discussions, moderated by Erkki Kankare and Takashi Moriya. Some of the highlights are summarised below.

Several of the luminous nuclear transients detected in the Catalina Real-time Transient Survey (CSS) have light-curves that show a clear difference between the pre- and post-flare luminosity. The reason is currently not fully understood. There is also often a second bump in the light-curve following the main flare. For example, CSS100217:102913+404220 shows a lower luminosity after the major flare whereas PS1-10adi shows a clear bump after the major flare. Nevertheless, in both cases the observed spectrum has not changed significantly between the pre- and post-flare epochs; that may be considered surprising. In the model of Moriya (see Sect. 5) a secondary bump could be expected to be less luminous because the previous event had already removed material

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from the system. Such events are rare, as they require the luminosity of the AGN to be close to the Eddingtion luminosity of the central black hole.

The nature of ASASSN-15lh is intriguing. Although there are some similarities to the other luminous nuclear transients, currently only one other transient like ASASSN-15lh has been observed. They are therefore either very rare, or we are not recognising them. It is not clear what can be said about the underlying TDE population, based on the currently observed sample and given the biases in their detection and selection. No TDEs in 'E+A' galaxies have been found by Gaia or OGLE, which is itself rather interesting.

The challenges to determining the types of near-IR transients detected within the dust-obscured nuclear regions of LIRGs are manifold. Spectroscopic observations are often not feasible (even at near-IR wavelengths) because the transients are often faint whereas the nuclear background is bright and complex, so their nature has to be determined from information based on near-IR light-curves. Optical imaging can provide upper limits that are useful for constraining the extinction.

It is uncertain whether the IR and radio observations of nuclear SN rates yield a consistent picture. The observational biases are different. Within the very innermost regions even the AO-assisted near-IR observations are not able detect transient events, whereas not all the core-collapse SNe become luminous radio SN. The two approaches effectively complement each other. On the other hand, optical observations are very efficient at detecting nuclear transients with low extinctions but over a very large volume, and will benefit from the large wide-field surveys that are now ongoing. Future observations at a range of wavelengths should provide interesting information on nuclear transients.

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