Star Formation through Time
*ASP Conference Series, Vol. **VOLUME**, 2003*
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AGN variability: the case for supernovae

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Abstract. We summarize the discussion session on the variability of Active Galactic Nuclei (AGN) held during the conference 'Star Formation through Time'. The presence of starbursts in type 2 AGN is now well established, and the production of supernovae (SNe) is a natural consequence of the age of their stellar populations. We review the possibility of detecting SNe in some type 1 AGN.

1. Introduction

One of the favourite research topics of Roberto Terlevich in the last 20 years has been to look for alternative ways to explain the phenomenology of AGN, in particular quantifying the ability of star formation to power the nuclear emission. Even before the presence of stars near the nuclei of some local AGN was firmly established (Terlevich et al. 1990, Oliva et al. 1995, Heckman et al. 1997, González-Delgado et al. 1998 ...) Roberto and his collaborators were exploring whether powerful massive starbursts could induce light variations that mimic those of AGN (Terlevich et al. 1987, Terlevich & Melnick 1988, Terlevich et al. 1992, 1995, Aretxaga & Terlevich 1994, Cid-Fernandes et al. 1996, Aretxaga et al. 1997).

The basic element invoked to explain AGN variability using starbursts is the explosion of SNe in dense circumstellar media, which are able to reprocess most of their kinetic energy into radiation on timescales of a few years. These particular SNe were first considered by Roberto in 1987 when he extrapolated the models of remnants evolving in dense media of $\sim 10^5$ cm^{-3} (Shull 1980, Wheeler et al. 1980). SN remnants in much denser media were soon found in the outer regions of nearby spiral galaxies (Filippenko 1989) and gave rise to a different SN spectroscopic class: type IIn SNe (Schlegel 1990).

2. Type IIn SNe or compact SN remnants (cSNRs)

The spectra of SN IIn are characterized by the presence of prominent narrow emission lines (hence the 'n') sitting on top of broad components of up to FWHM$\approx$ 15000 km/s at maximum light (see figure 1), and look extremely similar to the spectra of type 1 AGN (see a comparison in Filippenko 1989 and Terlevich 2001). They do not show the characteristic broad P-Cygni signatures of standard SNe, although narrow P-Cygni profiles are detected in some cases at high spectral resolution (e.g. SN 1997ab, Salamanca et al. 1998). SN IIn

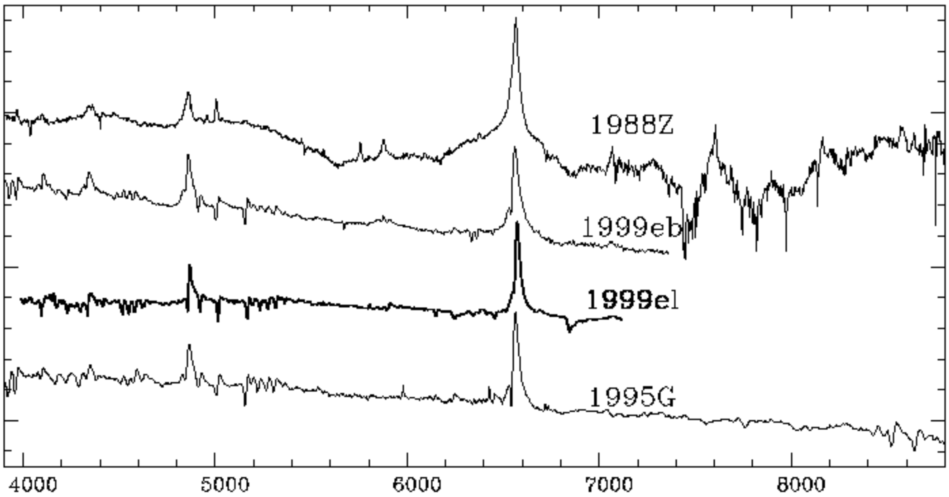

Figure 1. Rest-frame optical spectra of a collection of type IIn SNe (from Di Carlo et al. 2002): log flux (erg s^{-1} cm^{-2} $Å^{-1}$) + constant vs. wavelength (Å).

are normally associated with regions of recent star formation (Schlegel 1990). Despite these general characteristics, SN IIn as a group exhibit considerable heterogeneity (see also Filippenko 1997):

- some type IIn SNe have an extremely slow decay of luminosity after maximum light, which makes them, after 600 days, approximately 5 mag brighter in the V-band than standard SN IIP or SN IIL (e.g. SN 1988Z, Stathakis & Sadler 1991); however, others have a photometric behaviour much like standard type-IIL SNe (e.g. SN 1999el, Di Carlo et al. 2002);
- their peak luminosities ($M_V \sim -18.8$) are within the range of classical type IIP SNe (Richardson et al. 2002), and thus they are not particularly overluminous at optical wavelengths;
- some of those SNe that decay slowly are probably hypernovae, with kinetic energies in the range of $\sim 10^{52}$ erg (SN 1988Z, Aretxaga et al. 1999; SN 1997cy, Turatto et al. 2000; SN 1999E, Rigon et al. 2002), while other slowly decaying SNe have modest integrated energies of $\sim 10^{49}$ erg (e.g. SN 1995N, Pastorello et al., in prep);
- among the energetic type IIn SNe, two are probably connected with gamma-ray bursts (SN 1997cy, Germany et al. 2000; SN 1999E, Rigon et al. 2002);
- extremely bright radio and X-ray emission has been detected in a few type IIn SNe (e.g. SN 1988Z, van Dyk et al. 1993, Fabian & Terlevich 1995; SN 1995N, Fox et al. 2000), but emission at these wavelengths is not common in others (e.g. in SN 1997ab);
- whenever the forbidden-line ratios have been used to estimate the density of the narrow line producing region in type II SNe, values in the $\sim 10^6 -$

10^9 cm^{-3} range have been found (e.g. SN 1988Z, Stathakis & Sadler 1991; SN 1995N, Fransson et al. 2002.; SN 1995G, Pastorello et al. 2002).

It was soon recognized that the special characteristics of type IIn SNe are due to the strong interaction of the ejecta of the explosion with a dense circumstellar medium (Chugai 1991, Terlevich et al. 1992), probably created by the compressed winds of the progenitor star: slow decays and broad variable lines are originated in the dense ($> 10^{12}$ cm^{-3}) double shell structure created by the outer and inner shocks as they sweep the dense circumstellar medium and the ejecta, respectively; and the narrow lines are produced by the unshocked circumstellar medium which is ionized by the radiation coming from the shocks. In the case of strong interactions, like in SN 1988Z, where the estimated *radiated* energy from the radio to X-rays in the first 10 years of evolution exceeds 3×10^{51} erg (Aretxaga et al. 1999), i.e. two orders of magnitude more than typical SN events, the name 'supernova' does not do justice to the phenomenology we witness. The large radiated energies imply that most of the kinetic energy released in the explosion must be reprocessed into radiation within the first decade of evolution, much as classical SN remnants do over the course of thousands of years. These type IIn SNe are referred to as 'compact supernova remnants' (cSNRs) by Terlevich et al. (1992) to describe events where the energetics are dominated by the conversion of kinetic into radiated energy, and not by the thermal cooling of the expanding atmosphere of an exploding star.

3. Type IIn SNe in the inner circumnuclear regions of AGN?

There is little doubt that if a SN IIn explodes in the center of a normal galaxy, then the nucleus would be classified as a Seyfert 1, while the prominent broad lines remain visible. In fact, there has been a succession of theoretical studies that attempt to explain the phenomenology of lines and continuum at UV to near-IR wavelengths in Seyfert 1 nuclei in terms of a starburst that undergoes SN IIn explosions (e.g. Terlevich et al. 1992, 1995, Aretxaga & Terlevich 1994, Aretxaga et al. 1997).

Massive starbursts in the center of about 50% of all type 2 AGN have been discovered (Terlevich et al. 1990, Oliva et al. 1995, Heckman et al. 1997, González-Delgado et al. 1998, Cid-Fernandes et al. 2001). However, it is still to be determined that they also populate the centers of type 1 AGN, although the intensity of the calcium triplet absorptions provides some evidence in this direction (Jiménez-Benito et al. 2000). If starbursts are indeed present in the nuclei of type 1 AGN, they will produce a considerable number of SNe, and *if* these SNe are type IIn's, then they can reproduce the type 1 AGN phenomenology at IR-optical-UV wavelengths. The rates required to reproduce standard Sy 1s with pure starbursts are between 0.2 SN/yr for AGN of luminosities close to NGC 4151 and 0.5 SN/yr for those close to NGC 5548 (Aretxaga & Terlevich 1994). These correspond to masses of the starbursts around 10^8 to $10^9 M_\odot$ depending on the slope and lower end of the initial mass function.

The case of NGC 7582, a classical Sy 2, that suddenly mutated into a Sy 1 (Aretxaga et al. 1999b) is, probably, one of the most compelling examples where the SN explanation could work, although this is, by no means, a unique solution. Many of the nuclear properties of NGC 7582 support a unified scheme where the true Sy 1 nature is hidden by an obscuring torus: a sharp-edged [O III] outflow in the form of a cone is observed (Morris et al. 1985); optical spectropolarimetry does not reveal a hidden broad-line region, but since the far-IR colours $60\mu m - 25\mu m$ are very red, the absence has been taken as support for an edge-on thick torus able to block even the light scattered towards the observer (Heisler et al. 1997); indeed a large column density of neutral H ($N_H \sim 10^{24}$ cm^{-2}) also blocks the hard X-rays (Warwick et al. 1993), but this is variable and decreased at the time of the transition between Seyfert types (Turner et al. 2000). The presence of stars in the nucleus is also firmly established: Morris et al. (1985) found a steep gradient of Hα perpendicular to the [O III] cone, which they interpret as a 1 kpc disk of H II regions oriented at 60^o from the plane of the galaxy; the CO absorption lines and large near-IR light-to-mass ratio are similar to those of H II galaxies and a factor of 5 larger than those of normal galaxies, indicating that red supergiants dominate the light of the inner 200 pc at those wavelengths (Oliva et al. 1995); the expected SN rate of this starburst is 0.02 SN/yr (Aretxaga et al. 1999).

Hagai Netzer noted during the discussion that in the $N_H \sim 10^{22}$ cm^{-2} regime the X-ray flux increases and decreases constantly. When the X-rays increase, the obscuration similarly increases, the material becomes more opaque and it is possible that new dust can be formed. Beyond the central pc, the ionization front is weak, and the time scales of dust formation can be of order months to a year. Indeed the explanation for the variations in the level of dust obscuration is still plausible as the history of X-ray fluxes for NGC 7582 suggests: a change of $\sim 10^{23}$ cm^{-2} was observed shortly after the transition (Turner et al. 2000). The variations in the optical flux, however, were not compatible with the Goodrich test of the local reddening law (Aretxaga et al. 1999).

As Hagai Netzer explained, the problem with the SN explanation is not how it can explain the light curve, but how to avoid having SNe contaminating the AGN light curves. We should look carefully at the light curve of AGN and see whether we occasionally find the signature of a SN, and check the SN rates. It would be very surprising if, after 14 yr of careful observations, as in NGC 5548, there is not a single SN recorded. Roberto Terlevich pointed that the optical searches for SNe in starbursts has historically lead to null results, where none or very few SNe were found. In contrast the near-IR surveys of starbursts have discovered large numbers of SNe, suggesting that dust might be an important component of the circumstellar material. If we apply this reasoning to the starbursts in AGN, and look at their optical light curves, there is a possibility of failing to detect the SNe. It could also be that the SNe are normal type II's and not type IIn's.

Felix Mirabel suggested to look at the spectral signature at maximum flux in the hard X-ray regime, up to 500 keV. In his experience, the spectra of classical SN remnants are much softer, and can therefore be easily distinguished from the corona of an accreting supermassive black hole. Roberto Terlevich reminded the audience that X-ray observations for just two type IIn SNe (SN 1988Z and SN 1995N) have been made, and that the time allocation panels have not yet given sufficient time to characterize the flux levels and spectral properties of these objects. The only type IIn with an observed X-ray spectrum (SN 1995N), shows a hard component up to the upper-energy edge of ASCA (10 keV). Roberto

Cid Fernandes also made the point that we know very little about whether type IIn SNe have rapid X-ray variability, similar to that exhibited by AGN.

Dave Axon also underlined that using high-resolution interferometry to locate SN events, and then searching for broad-line regions which are displaced from the center, would shed light on the source of the variations.

Thaisa Storchi-Bergmann reminded the audience that there are other examples of type 2 to type 1 transitions in AGN, like the one experienced by NGC 1097, which are best explained by accretion processes, such as the disruption and capture of a star by a supermassive black hole (Storchi-Bergmann et al. 1995). In this case a double-peaked line profile is created, which is best reproduced by a disk geometry. Roberto Terlevich argued, that with only a single profile, it is difficult to decide whether the best explanation is a rotating disk or a precessing jet. Dave Axon replied that it could be distinguished with spectro-polarimetry. David Burstein claimed that the capture of a star by a supermassive black hole has also been invoked for the onset of weak AGN activity and UV flares in otherwise normal elliptical galaxies, like the one which occurred in NGC 4552 (Renzini et al. 1995).

A further point is whether the lag $\propto L^{1/2}$ relationship found in AGN can be reproduced by a correlation between the luminosity of the stellar cluster and the environment in which the SNe evolve. Observationally little is known about lags in type IIn SNe. Only SN 1988Z shows a delay of the Hα response to the continuum, of about two hundred days. In the rest of the SNe these large lags are not seen, and smaller ones, if present, cannot be characterized with the available data. On the other hand, the relationship is one of the outstanding predictions of the standard explanation of AGN lags, namely the reverberation of the accreting material onto a supermasive black hole (see Netzer in this volume). The question remains whether those AGN that do not satisfy this relationship have a different physical process to provide the variations.

The audience agreed that the Kα broad Fe line is one of the best pieces of evidence to support the suggestion that emission from a black hole dominates the X-rays. Hagai Netzer commented that, in his opinion, the presence of broad wing relativistic Kα lines in most Sy 1 has to be revised with new instrumentation, since many earlier claims have not been confirmed with more recent observations. Hagai also remarked that there is some confusion regarding the source of the hot ionized gas. This can be produced by a starburst, but once this gas is exposed to the central radiation field, it will become an AGN. The center of NGC 1068, for instance, has many discrete starburst regions, and we see their contribution in the form of very extended X-ray emission. Maybe starbursts are extremely important in producing the gas, which subsequently is then ionized by the central AGN.

Acknowledgments: IA would like to thank the organizers of the conference for partial support to attend it, and all the attendees for a vivid and interesting debate on AGN variability. IA's research is supported by CONACyT through grant E–32143.

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