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LINE FORMATION IN THE INNER STARBURST REGIONS OF AGN

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RESUMEN

Revisamos la evidencia de que existan poblaciones estelares jóvenes en las regiones centrales ($\lesssim 200\,$pc) de los núcleos galácticos activos, y los mecanismos que los cúmulos estelares tienen a su alcance para crear las líneas de emisión que caracterizan la actividad nuclear.

ABSTRACT

We review the evidence for young stellar populations in the inner $\lesssim 200\,$pc of Active Galactic Nuclei (AGN), and the physical mechanisms through which the stars can potentially create the emission lines that characterize AGN.

Key Words: **ACTIVE GALACTIC NUCLEI — STARBURSTS — SUPERNOVAE**

1. INTRODUCTION

The last two decades have seen a significant advance in our understanding of the phenomenology of various classes of AGN. The effect of the nuclear orientation on the classification of AGN has been particularly important (see Goodrich 2001 for a review). Unified schemes postulate that the broad-line region (BLR) and the continuum emitting zone of an AGN are obscured, when observed edge-on, by a dusty obscuring torus with a size of order ~ 1 to 100 pc. Under this scenario, and depending on the line of sight to the nucleus, identical objects can be classified as a Seyfert 2 (Sy 2) or Seyfert 1 (Sy 1).

This configuration can explain several observables of Sy 2 nuclei, for example the detection of broad lines in polarized light (Antonucci & Miller 1985; Miller & Goodrich 1990) which are directly detected in near-IR light (Goodrich, Veilleux, & Hill 1994), the presence of kpc-scale ionizing cones (Pogge 1988, 1989; Tadhunter & Tsvetanov 1989), the large columns of neutral hydrogen that absorb the X-ray emission (Mushotzky 1982; Bassani et al. 1999; Risaliti, Miaulino, & Salvati 1999), and the cold far-IR colors (Pérez-García, Rodríguez-Espinosa, & Santolaya Rey 1998). However, the scheme, taken at face value, has some difficulty in incorporating other observables: the high polarization levels observed in the broad polarized lines of Sy 2s compared to the modest polarization of the continuum (Goodrich & Miller 1989; Tran 1995; Cid Fernandes & Terlevich 1995), the similarity of the observed UV-continuum slopes of Sy 1 and Sy 2s (Kinney et al. 1991), the rich $\sim 100\,$kpc environments surrounding Sy 2s but not Sy 1s (Dultzin-Hacyan et al. 1999), the transient development of broad lines in otherwise classically quiescent type 2 AGN (Storchi-Bergmann et al. 1995; Aretxaga et al. 1999a), and the absence of type 2 QSOs (Hill, Goodrich, & De Poy 1995).

Unified schemes, nevertheless, have survived 20 years of detailed observational tests. Sensible variations on the simple-minded statement "all Sy 2s are obscured Sy 1s seen edge-on" have been made, and the current consensus is that even if orientation is not a unique factor in creating the variety of all AGN types, it certainly is an important one to consider.

2. YOUNG STELLAR POPULATIONS IN THE INNER REGIONS OF AGN

The study of the ages of the stellar populations in the inner parts of AGN has been a source of debate over the last decade. We will define the inner regions as those at distances $\lesssim 200\,$pc from the gravitational center of the galaxy. In most cases, these regions are regarded as *nuclear* by the limitations of the resolution ($\sim 1''$) regularly achieved from ground-based optical facilities. Powerful circumnuclear starbursts at distances of $\sim 1\,$kpc from the nucleus have been known to exist in many Seyfert galaxies for a long time (e.g., NGC 1068). The nature of the stellar populations in the inner regions of the AGN, however, are still a matter of active research.

In the early 90s the age determinations focused on using near-IR absorption lines, where contamination by powerful line emission was minimal. The absorption features due to the Ca IR triplet $\lambda\lambda\,8494,8542,8662\,$Å in nearby Sy 2 and Sy 1s were shown to be statistically stronger than the absorptions of normal spiral (S) and elliptical (E) galaxies, once the possible presence of dilution by the power-law emission of an accretion disk had been accounted for (Terlevich, Díaz, & Terlevich 1990;

Jiménez-Benito et al. 2000; and see the figures by Nelson & Whittle in Terlevich 2001). This was interpreted as direct evidence for a population of red supergiant stars that dominates the near-IR light. The high mass-to-light ratios $L(1.6\,\mu\mathrm{m})/M \gtrsim 3\,L_\odot/M_\odot$ inferred from the photospheric CO $\lambda\,1.62$, $\lambda\,2.29\,\mu$m absorptions of a sample of Sy 2 nuclei confirmed that red supergiants dominate the nuclear continuum emission in $\sim 50\%$ of Sy 2s (Oliva et al. 1995), whilst a similar conclusion could not be drawn for a Sy 1 sample.

With the advent of blue-sensitive detectors in many optical facilities, by the late 90s, the focus shifted to the detection of the UV and Balmer absorptions of massive stars. UV imaging and spectroscopy of 4 Sy 2s selected by their strong [O III] $\lambda\,5007$ Å and 1.4 GHz fluxes (which, in principle, are intrinsic AGN properties) show a $\lesssim 100$ to 200 pc resolved and broken-knot structure whose continuum spectrum is 100% that of a starburst, as derived from the strength of the absorption lines (Heckman et al. 1997; González Delgado et al. 1998). The properties of the starbursts are $L_{\rm SB} \approx 10^{10}$ to $10^{11}\,L_\odot$, $M_{\rm SB} \approx 10^6$ to $10^7\,M_\odot$ and ages 3 to 6 Myr. Even in the low-luminosity type 2 AGN (LINERs and Sy 2s) where the major component of UV light is unresolved, the continuum is totally dominated by the photospheres of OB stars (Maoz et al. 1998; Colina et al. 2002). The most complete surveys to date show that 50% out of 35 Sy 2s have a continuum which is dominated by the emission of starbursts or post-starburst populations (Cid Fernandes et al. 2001). A similar study for Sy 1s has not been attempted, due to the difficulty of decontaminating the UV-optical absorption-line spectrum from the corresponding emission-line spectrum.

In smaller samples of radio-loud AGN a similar picture is starting to emerge: about 40% of the spectra of narrow-line radio galaxies show undiluted starburst features (Aretxaga et al. 2001; Tadhunter et al. 2002), but the position of these starbursts cannot be determined to better than ~ 1 kpc from the center.

Starbursts regions confined to the inner ~ 200 pc can explain some of the paradoxes that the unified scheme faces, like the different levels of polarization of broad lines and continuum and the similarity of the UV slopes between Sy 1 and Sy 2s, if the AGN is not only obscured by the torus, but the torus is forming stars (Cid Fernandes & Terlevich 1995).

A starburst-AGN connection has been proposed in at least three scenarios: starbursts giving birth to massive black holes (e.g., Scoville & Norman 1988); black holes being fed by surrounding stellar clusters (e.g., Perry & Dyson 1985; see also Pittard et al. 2003); and also pure starbursts without black holes (e.g., Terlevich & Melnick 1985; Terlevich et al. 1992). The evidence for starbursts in Seyfert nuclei strongly supports some kind of connection. However, it is still to be demonstrated that starbursts can explain some of the phenomenology characteristic of AGN, specifically the line emission spectrum, which ultimately is what defines an AGN (Seyfert 1943; Baldwin, Phillips, & Terlevich 1981).

3. AGN NARROW-LINE EMISSION SPECTRUM FROM STARBURSTS

Early attempts to reproduce the AGN emission-line spectrum, using stars as the only source of ionization, have met with only moderate success and much controversy. Terlevich & Melnick (1985) proposed the existence of evolved massive stars of $T_{\rm eff} \gtrsim 100,000$ K (extremely hot WC or WO stars, which they named *warmers*), by directly applying the stellar evolutionary models in vogue at the time. These stars, present in a 3 to 8 Myr starburst, had enough hard-UV photons to reproduce the diagnostic lines of AGN. It was the addition of an optically thick stellar wind to the stellar interior models (Maeder 1990; Schaerer et al. 1993) that suggested the extremely-luminous blue phase did not exist, and since then the idea of warmers as a source of ionization in AGN has slowly been disregarded by its proposers (Cid Fernandes 1997; Terlevich 2001).

Normal starbursts can reproduce some of the lines observed in AGN. In particular, the inferred properties of the nuclear/circumnuclear starbursts that reproduce the observed UV absorption spectra of Sy 2s (§ 2) have enough photons to ionize the whole Balmer emission series (González Delgado et al. 1998; Colina et al. 2002), but the photospheres of those young stars cannot, in general, account for the higher-ionization emission-line species, like [Ne V] $\lambda\,3426$ Å or He II $\lambda\,4686$.

Low-ionization species, however, can be reproduced with the ionizing power of hot stars. A starburst with normal OB stars, in dense media ($\gtrsim 5\times10^3\,\mathrm{cm}^{-3}$), can reproduce weak [O I] $\lambda\,6300$ Å/Hα LINERs (Shields 1992; Filippenko & Terlevich 1992).

4. TYPE IIN SNE OR COMPACT SN REMNANTS

The modest success of using only stars to ionize the gas in an AGN was soon to be replaced by the by-products of their evolution in pure starburst models: the supernova explosions and the quick reprocessing of their kinetic energy by dense circum-

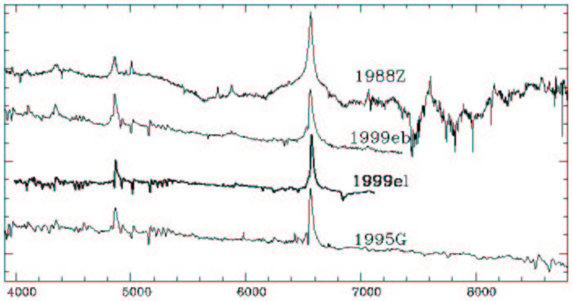

Fig. 1. Rest-frame optical spectra of a collection of type IIn SNe (Di Carlo et al. 2002): constant + log flux ($\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$) versus wavelength (Å).

stellar media. These particular SNe were first considered by Terlevich, Melnick, & Moles (1987) when they extrapolated the models of remnants evolving in dense media of $\sim 10^5\,\mathrm{cm^{-3}}$ (Shull 1980; Wheeler, Mazurek, & Sivaramakrishnan 1980). SNe exploding in much denser media were soon found in the outer regions of nearby spiral galaxies (Filippenko 1989; Stathakis & Sadler 1991) and gave rise to a different SN spectroscopic class: type IIn SNe (Schlegel 1990). These objects can potentially explain the high-ionization narrow emission lines seen in type 2 AGN (§ 6), and also provide the broad emission lines and UV–optical–IR light variations, which, over long timescales ($\gtrsim$ 1 month), resemble those of type 1 AGN (§ 5).

The spectra of SN IIn are characterized by the presence of prominent narrow emission lines (hence the "n") sitting on top of broad components with FWHM $\lesssim 15{,}000\,\mathrm{km\,s^{-1}}$ 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 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, see Figure 2); 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.

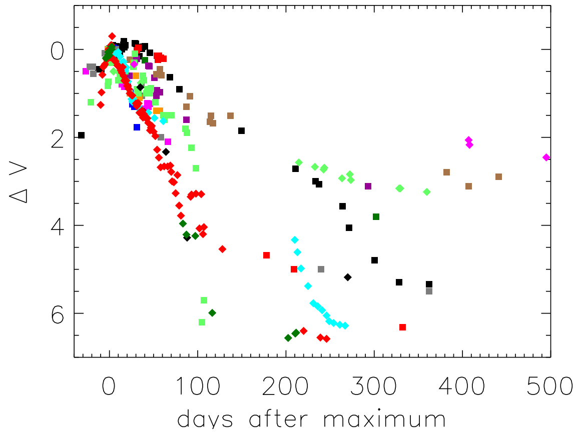

Fig. 2. V-band light curves of 16 type IIn SNe with known optical maxima, normalized to maximum light (Aretxaga et al. 2003).

- 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. 1999b; SN 1997cy: Turatto et al. 2000; SN 1999E: Rigon et al. 2003), while other slowly decaying SNe have modest integrated energies of $\sim 10^{49}$ erg (e.g., SN 1995N: Pastorello et al. 2003).

- Among the energetic type IIn SNe, two are probably associated with gamma-ray bursts (SN 1997cy: Germany et al. 2000; SN 1999E: Rigon et al. 2003);

- Extremely bright radio and X-ray emission has been detected in some type IIn SNe (e.g., SN 1988Z: van Dyk et al. 1993, Fabian & Terlevich 1996; SN 1995N: Fox et al. 2000), but emission at these wavelengths is not common in others (e.g., 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 range 10^6 to $10^9\,\mathrm{cm^{-3}}$ 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 from the explosion with a dense circumstellar medium (Chugai 1991; Terlevich et al. 1992), the origin of which is probably the compressed winds of the progenitor star: slow decays and broad variable lines originate in the dense ($\gtrsim 10^{12}\,\mathrm{cm^{-3}}$) double shell structure created by the outer and inner shocks as they sweep the dense ($\sim 10^7\,\mathrm{cm^{-3}}$) 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, and is probably close to 10^{52} erg (Aretxaga et al. 1999b), i.e., two orders of magnitude larger 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 behave over the course of thousands of years. These type IIn SNe are referred to as "compact supernova remnants" (cSNRs) by Terlevich et al. (1992), which 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.

5. 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, the nucleus would be classified as a Sy 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 optical wavelengths in Seyfert 1 nuclei in terms of a starburst that undergoes SN IIn explosions (Terlevich et al. 1987, 1992, 1995; Aretxaga & Terlevich 1994; Aretxaga, Cid Fernandes, & Terlevich 1997).

Massive starbursts in the center of $\sim$ 50% of type 2 AGN have been discovered (§ 2). However, it is still to be determined whether they also populate the centers of type 1 AGN. 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, and have similar ages to those of type 2 AGN, they will produce a considerable number of SNe, and *if* these SNe are type IIn, then they potentially can reproduce the type 1 AGN phenomenology at IR–optical–UV wavelengths. Since starbursts are subject to a scaling relationship, where the SN rate ($\nu_{\rm SN}$) and the optical luminosity coming from stars ($L^*_{\rm B}$) are related along the lifetime of the SN II explosion phase ($\sim$ 10 to 70 Myr) by $\nu_{\rm SN}/L^*_{\rm B} \approx 2 \times 10^{-11}\,{\rm yr}^{-1} L^{-1}_{{\rm B}\odot}$ (Aretxaga & Terlevich 1994), the rates required to reproduce standard Sy 1s with pure starbursts are between $0.2\,{\rm SN\,yr}^{-1}$ for AGN of luminosities close to NGC 4151 and $0.5\,{\rm SN\,yr}^{-1}$ for those close to NGC 5548. 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. These proposed starbursts are thus 1 to 2 orders of magnitude more massive than those found in Sy 2s to date. The light curve that a cluster of luminosity similar to the nucleus of NGC 4151 would produce, if all SNe were type-IIn, is represented in Figure 3 together with the historically observed light curve of NGC 4151 for comparison. The simulation, although not identical to the observed object (since it is produced stochastically), can reproduce the basic long-term properties such as mean luminosity, rms and power spectrum, with just one free parameter: the density of the circumstellar medium in which the cSNRs evolve (Aretxaga & Terlevich 1994).

The theoretical models of cSNRs show that the UV and Balmer lines respond to variations of the continuum on timescales of a few days to several tens of days, depending on the line species, and that these lags are similar to those found in NGC 5548, but they are not created by time-travel delays (Terlevich et al. 1995). However, the lags have not been explored in real type IIn SNe since the sampling of the light variations in these sources is still very scarce. The only lag clearly detected is that of the Hα line in SN 1988Z (Turatto et al. 1993), but the lag is $\sim$ 200 days, and these values are not seen (although they could have been detected) in other type IIn.

The case of NGC 7582, a classical Sy 2 that suddenly mutated into a Sy 1 (Aretxaga et al. 1999a), is probably one of the most compelling examples where the SN explanation works, 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 colors 60 μm to 25 μm 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, Lumsden, & Bailey 1997); indeed, a large column density of neutral H ($N_{\rm H} \sim 10^{24}\,{\rm cm}^{-2}$) also blocks the hard X-rays (Warwick et al. 1993), but this absorption is variable and decreased ($\Delta N_{\rm H} \sim 10^{23}\,{\rm cm}^{-2}$) 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° from the plane of the galaxy; the CO absorption

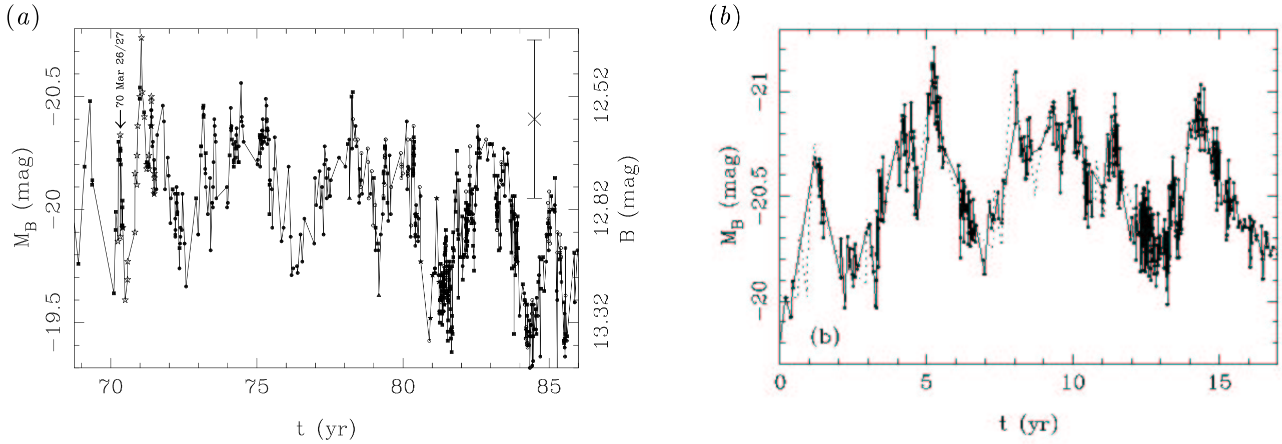

Fig. 3. (a) Light curve of NGC 4151 in absolute B-band magnitudes. The uncertainties in the derivation of the radial velocity of the galaxy are shown as the point with error bars at the upper-right corner of the panel. (b) Simulated light curve for a starburst which undergoes a SN rate $\nu_{\rm SN} = 0.3\,{\rm yr}^{-1}$, with energy of explosions $E = (3.0 \pm 0.1) \times 10^{51}$ erg evolving in a medium of $n = (1.0 \pm 0.3) \times 10^7\,{\rm cm}^{-3}$. The sampling of points in the simulated light curve is identical to that in the top panel. Observational errors of $\sigma^{\rm obs} = 0.1$ mag are included. The dotted lines represent the simulated light curve (Aretxaga & Terlevich 1994).

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 $0.02\,{\rm SN\,yr}^{-1}$ (Aretxaga et al. 1999a). The light variations in the optical were not consistent with a standard reddening law variation (the Goodrich 1989 test), which could be the result of nuclear light traveling through a region of less obscuration in the torus. The flare, which was followed for a few months, had a similar decaying law as that of SN 1983K (retrospectively classified as a type IIn, and a fast decayer like SN 1999el) and line-width variations of $\sim 12{,}000\,{\rm km\,s}^{-1}$ to $5000\,{\rm km\,s}^{-1}$ in a few months are also typical of type IIn (Aretxaga et al. 1999a). The X-ray data taken during the flare are consistent with both explanations, either a change in reddening in the torus or a type IIn SN onset (Turner et al. 2000).

6. DISCUSSION

Starbursts in type 2 AGN have been directly found on scales which could correspond to the surroundings of a dusty torus. We also could be seeing the outskirts of a massive cluster embedded within the dusty torus. The stars in the best studied cases (e.g., González Delgado et al. 1998) can reproduce all the observed Balmer line emission and continuum, but they do not have enough ionizing photons to produce the high-ionization lines that characterize AGN. Some type IIn SNe provide hard energy photons in sufficient quantities to produce the high-ionization lines of AGN, and also coronal lines like [Fe X] $\lambda\,6375$ Å, [Fe VII] $\lambda\,5159$ Å, [Fe VII] $\lambda\,6086$ Å ... (Turatto et al. 1993; Fox et al. 2000). If these SNe are mixed with the dust, or if they are located in the central region of the AGN and are hidden by the torus, they could reproduce the rest of the ionization characteristics of the Sy 2s. The black hole should still be responsible for properties such as the relativistic broad Fe Kα lines that are present in many Sy 2s (Turner et al. 1997), but it does not necessarily have to be responsible for the UV-optical emission.

In turn, some type IIn SNe in the outskirts of the torus could be directly visible, mimicking the phenomenology of AGN (e.g., NGC 7582).

If one is to extrapolate this result to classical Sy 1, the masses of the stellar clusters required are 1 to 2 orders of magnitude larger than those directly detected in type 2 AGN. These could *per se* be larger, or we could be seeing more of the cluster as part or all of the dust in Sy 1s is blown up or dispersed, as suggested by Dultzin-Hacyan et al. (1999). Type IIn SNe do mimic many of the characteristics of AGN, but there are still many of their properties that are unexplored, e.g., the lags of their emission lines or the small-scale variations. The lag $\propto L^{1/2}$ relationship found in AGN is one of the most outstanding predictions and successes of the standard model of AGN (e.g., Wandel, Peterson, & Malkan 1999), where the lines originate in (or near) an accretion disk that surrounds the supermassive black hole. Observationally little is known about lags in type IIn SNe. Only SN 1988Z shows a delay of the

Hα response to the continuum, of $\sim$ 200 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. A variation of the lag with the environment of the circumstellar material is predicted, and one can conceive of a link with the total luminosity of the cluster. The details, however, have not been worked out, and most importantly, they haven't been tested against bona-fide isolated SN IIn.

It might also be the case that the stellar clusters in AGN do not produce type IIn SNe at all, but instead normal type IIs. It would still be important, however, to learn how to distinguish the optical variations of type IIn SNe from those of accretion processes in AGN, and estimate the true SN rate in the clusters.

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