The AGN dance: astrometric variability as the result of supernova explosions in nuclear starbursts.

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Abstract. The starburst model of AGN predicts the supernova rates in the nuclear star clusters of low luminosity AGN to be less than one per year. The compact remnants of these explosions evolve in regions of very high density and thus radiate most of the energy in less than one year. Statistically, therefore, no more than one compact supernova remnant is expected to be active at any given time. The broad line region in the starburst model is produced in the compact supernova remnants so, for low luminosity objects, the BLR will typically consist of only one compact remnant.

Thus, a strong prediction of the model is that the BLR of low luminosity AGN should move at random with a typical step which depends on the luminosity of the nucleus. We call this motion the AGN dance.

1 AGN variability

One of the most powerful probes into the inner realms of AGN is their photometric variability which is observed to occur over a wide range of time scales and luminosities ranging from fast, low amplitude, flickering in X-rays on scales of hours, to flares of more than one magnitude lasting months to years in the optical. Variability poses one of the most stringent tests to any theory of the nuclear activity phenomenon and there is no single model that can account for all aspects of AGN variability.

Since the bulk of the energy radiated by AGN appears to be emitted in the blue/UV part of the spectrum [1], understanding the optical/UV variability appears to be the first and possibly the most important step towards understanding the energy generating mechanism in AGN.

1.1 Variability at Optical wavelengths

Lyutyi and his group (Lyutyi et al., 1984 and references therein) were the first to undertake massive photometric monitoring programmes of several active galaxies aimed at characterizing their optical variability. Lyutyi found that AGN variability at optical wavelengths can be described as flares characterized by a rapid rise in luminosity followed by a gradual decay lasting months to years modulated by

[1] This may not be the case for BL-Lacs where the geometry and the relativistic boosting factors are still not well understood

smooth similar amplitude variation with time scales of years. This results have been substantially confirmed by international monitoring campaigns of a few selected objects with excellent time resolution, notably the studies of NGC4151 by Penston et al., (1981) and of NGC 5548 by Korista et al., (1995, and references therein). Based on these studies, the main aspects of the photometric variability of AGN can be characterized as follows:

- Most AGN are variable. For radio-quiet AGN, the amplitude of variation correlates with luminosity in such a way that the least luminous nuclei are the most variable (Pica & Smith 1993, Hook et al., 1994, Cristiani et al., 1996)
- Variability appears to occur in discrete events or *flares* characterized by a rapid rise in luminosity followed by a slow decay, with typical time scales of weeks to months. (Lyutyi, 1963; Aretxaga 1993 and references therein).
- The light curves of the flares appear to be similar from event to event and from galaxy to galaxy (Cid-Fernandez, Terlevich and Aretxaga, 1996).

In addition to photometric monitoring, some of these international campaigns were also done spectroscopically so there is a wealth of fascinating information on the spectral variability of a few AGN. The results of these observations can be summarized as follows:

- Generally (but not always) there is a delay between the variation of the continuum and the lines, the latter *lagging* the continuum by 1-2 weeks (see Peterson 1993 for a review).
- The lines change intensity and shape. In some cases broad components develop in the permitted lines which radically change the classification of an object from Narrow Line/Seyfert 2 during quiescence, to Broad Line/Seyfert 1 during outburst (eg. Gregory et al., 1991, see Aretxaga & Terlevich 1994b for a compilation).
- The emission-line spectrum of the flares (after subtraction of the low state component) show a striking resemblance to the spectrum of peculiar type 2 supernovae (Terlevich and Melnick, 1988; Filippenko, 1989; Stathakis and Sadler, 1991 and references therein).
- The total energy released in each flare is close to 10^{51} ergs (Alloin et al., 1986).

1.2 AGN Variability in the *Starburst* model

The properties of AGN variability at optical wavelengths described above can be explained remarkably well by the so-called *Starburst model* that postulates nuclear activity to be the direct consequence of violent star formation activity in the nuclear regions of galaxies (Terlevich et al., 1987; 1992, 1995, Aretxaga & Terlevich 1994a, 1994b, Aretxaga et al., 1996). The model explains variability as due to supernova explosions in the high density environment of the nuclear regions of galaxies, and their subsequent evolution as (compact) supernova remnants (Terlevich et al., 1992).

1.3 The AGN dance

The *Starburst* model tells us that the Broad Line Region (BLR) is formed by compact supernova remnants (cSNRs; Terlevich et al., 1992). The supernova rates (ν_{SN}) predicted by the model for low luminosity AGN (e.g. those with $M_B > -21$) are $\nu_{SN} \leq 1\ yr^{-1}$ (Aretxaga & Terlevich 1994a). Since cSNR radiate their energy in about one year, for these objects the BLR will typically consist of only one cSNR and, therefore, as the cluster evolves and new stars explode as supernovae, the nucleus should be observed to move around the center of the cluster. We will refer to this predicted *astrometric* variability of low luminosity AGN as *the AGN dance.*

In this contribution we examine the possibility of observing the *dance* in nearby low luminosity AGN with the VLT(i).

2 Observing the AGN dance.

In order to calculate the mean distance between consecutive supernovae in a starburst cluster we will make the following simplifying assumptions:

1. Starburst clusters are spherical with a mass distribution characterized by a de Vaucouleurs law.
2. The mass to (blue) light ratio does not change with radius
3. The IMF is a Salpeter power-law of slope $\alpha = -2.35$ in the mass range $0.3 < M/M_{\odot} < 50$.

The probability of distribution of SN explosions is equal to the surface brightness distribution normalized to the total light,

$$P(r)dr = \frac{1}{3.61 R_e^2} 10^{-3.33[(r/R_e)^{1/4}-1]} r dr$$

where R_e is the effective radius of the cluster, this is so because the supernova rate per unit blue luminosity is a constant regardless of age or IMF of the cluster (Aretxaga & Terlevich 1994a). Clearly half of the supernovae explode within $0.5R_e$. The mean separation between consecutive explosions can be computed using the Monte Carlo method with this probability distribution. The resulting distribution of separations from one million explosions is shown in Figure 1

The model predicts that the optical nuclei of low luminosities should dance with a typical step close to the effective radius of the mass distribution R_e. This radius can be calculated from the relation (Poveda, 1957; Young, 1976),

$$M_T = 2073 R_e \sigma^2$$

where σ is the projected velocity dispersion of the cluster stars and M_T is the total mass (obtained from the cluster luminosity via the IMF, Aretxaga & Terlevich 1994a).

The light curve simulations of Aretxaga (1993) show that the minimum superposition (in time) between consecutive flares, and the maximum luminosity

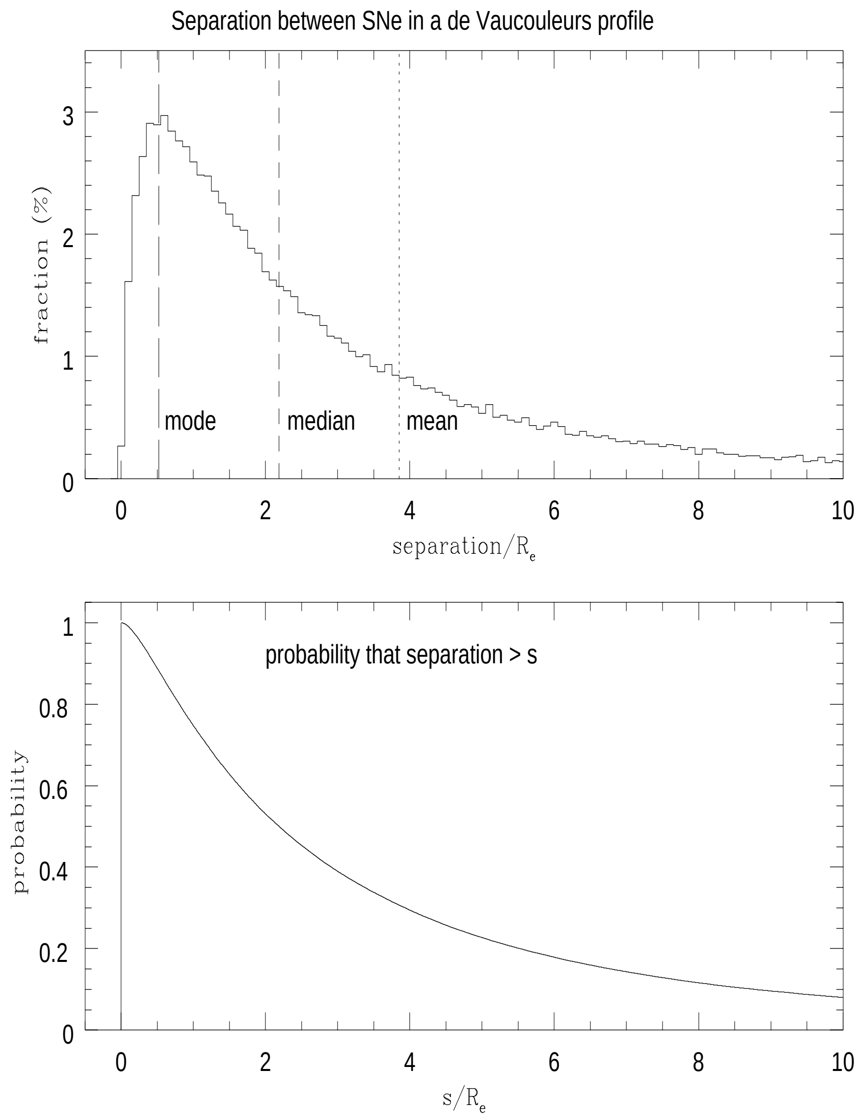

Fig. 1. *Top. Distribution of separations (in units of the effective radius R_e) of consecutive supernova explosions for a de Vaucouleurs mass distribution. Bottom. Cumulative distribution of separations for consecutive explosions.*

contrast of individual flares against the cluster occurs for supernova rates in the range 0.2 $<\nu_{SN}<$ 0.6 which correspond to blue luminosities between -19 and -21. These values are almost independent of the IMF parameters because the the blue luminosity is dominated by massive stars.

Table 1 gives the parameters for a few representative galaxies in the southern hemisphere selected from the list of Winkler et al. (1992) searching for southern objects of nuclear blue luminosities between -21 and -19 and redshifts lower than cz<20,000 $\mathrm{km\,s^{-1}}$

Table 1. Target galaxies

Galaxy	Distance (Mpc for H_0=75)	M_B	ν_{SN} (yr^{-1})	M_T ($M_\odot$)	R_e (pc)	θ_e (mas)
H0307-730	111	-20.7	0.4	1.3×10^9	16	30
NGC3783	37.3	-20.1	0.2	6.5×10^8	10	55
NGC4593	34.8	-19	0.1	1.0×10^8	1.5	9
E141-G55	147	-20.7	0.4	1.3×10^9	16	22

The table gives the distance to each galaxy calculated from the observed redshifts assuming H_0=75 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$, the absolute blue magnitude of the nucleus (M_B), the implied supernova rates (ν_{SN}), the total mass (M_T) calculated using $L_B/M_T = 15 L_\odot/M_\odot$ (Aretxaga & Terlevich 1994a), the effective radius R_e of the mass profile (calculated assuming a central velocity dispersion of 200 $\mathrm{km\,s^{-1}}$which appears to be typical of objects in this range of luminosities) and the corresponding angular radii in milli-arcseconds (θ_e).

The angular radii are well within the range of the VLTi and in fact could also be observed with a 8m unit telescope in the diffraction limited mode (active optics). However, in order to define an optimal observing strategy it is important to evaluate the uncertainties in these calculations.

2.1 Uncertainties...

There are several important unknowns that may have led us to overestimate the effective radii by rather large factors.

The first one is the velocity dispersion. We have assumed $\sigma = 200\,\mathrm{km\,s^{-1}}$which corresponds to the observed velocity dispersion of NGC4151 in the central $2''$. This must be considered as an upper limit since the expected effective radius of the nuclear cluster in this galaxy is only about 30 mas.

A second fundamental unknown is the IMF of the central cluster. The mass-to-light ratios (used to compute the total mass) may vary by factors of 2–3 depending on the lower mass limit. The variation may be even larger for IMF slopes steeper than Salpeter, but a factor of 2 is a reasonable estimate of the maximum error for ages in the type II supernovae phase ($> 2 \times 10^7$yrs).

A third perhaps even more fundamental uncertainty is mass segregation. HST observations of 30 Doradus (Malamuth and Heap 1994) indicate that the IMF in the core of the prototype starburst 30 Doradus appears to be significantly flatter than the IMF outside the core. If confirmed, these observations (taken before the refurbishement of HST) indicate that in starburst clusters the effective radius of the supernova progenitors may be significantly smaller than that of the overall mass distribution.

Together, these three effects imply that the values of R_e given in Table 1 may be overestimated by as much as a factor of 10. If these effects are not relevant, on the other hand, it will be possible to observe the dance with a single 8m telescope equipped with adaptive optics. Otherwise, the VLT interferometer will be required.

2.2 Observational strategy

The observational strategy will depend on whether the nuclear clusters can be directly resolved. If this is the case then individual supernovae (the optical nucleus) will stand out more clearly from the stellar background and their position will be easily measurable. Otherwise it will be necessary to measure the centroid of the light distribution, which will be the sum of an extended object (even in the worst case assumptions discussed above the characteristic size will be a few VLTi pixels) plus an unresolved spike. Thus, with a typical astrometric accuracy of $60\mu as$ the expected movement of the nucleus (a few mas) will be measurable. The questions of wavefront corrections and fringe tracking will require careful consideration. Most nuclei in the target list will be bright enough to allow fringe tracking and some even to do the wavefront corrections. But they will be resolved considerably reducing fringe contrast. Therefore, it will still be necessary to select AGN with bright nearby stars to use the interferometer. While there are galaxies in this configuration, it is clear that the availability of Laser Guide Stars is of considerable importance for this project.

The main problem will be the preparatory observations. VLT(i) observations of the AGN dance will require intensive monitoring with smaller telescopes. Spectra of all target objects must be obtained in order to classify the nuclear type (Seyfert 1 or 2). This requires a 2m class telescope. A systematic campaign of photometric monitoring must be conducted in order to determine ν_{SN} and thus characterize the variability of the nuclei with a sampling rate of one observation per AGN per month. A second epoch of spectroscopy together with a first epoch of astrometry with the VLT(i) should be conducted as soon as the photometric monitoring reveals galaxies that change luminosity above a certain threshold.

A 1m class telescope with adequate image quality is required for photometric monitoring. Such observations should begin as soon as possible in order to produce results by the time the VLT(i) is in full operation.

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