Supermassive Black Holes Can Hardly Be “Silent”

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Abstract. There is now ample evidence that most - perhaps all - galactic spheroids host a supermassive BH at their center. This has been assessed using a variety of observational techniques, from stellar and/or gas dynamics to megamasers. Yet another promising technique is offered by the case of the Virgo elliptical NGC 4552, in which early HST/FOC observations revealed a central low-luminosity flare. Subsequent HST/FOS observations with a 0.21 arcsec aperture have revealed a rich emission-line spectrum with broad and narrow components with FWHM of 3000 and 700 km/s, respectively. This variable, mini-AGN at the center of NGC 4552 is most naturally the result of a sporadic accretion event on a central BH. It has a Hα luminosity of only \( \sim 10,000 \, L_\odot \), making it the likely, intrinsically faintest AGN known today. Only thanks to the superior resolution of HST such a faint object has been discovered and studied in detail, but adaptive optics systems on large ground-based telescopes may reveal in the future that a low level of accretion onto central massive BHs is an ubiquitous phenomenon among galactic spheroids. FOC/FOS observations of a central spike in NGC 2681 reveal several analogies with the case of NGC 4552, while yet another example is offered by a recent exciting finding with STIS by R.W. O’Connell in NGC 1399, the third galaxy in our original program.

1 Discovery of a Central Flare in NGC 4552

Sophisticated techniques have been used to infer the presence of supermassive black holes (BH) at the center of galactic spheroids: from detailed stellar dynamical modeling fitting 2D spectroscopy data cubes to megamaser observations, all aspects widely discussed at this meeting. Here I will present observational evidence concerning three randomly-selected galactic spheroids, showing that high spatial resolution imaging and/or spectroscopy can reveal sporadic mini-AGN activity likely related to the presence of a central BH.

To investigate the UV upturn of ellipticals, in 1993 HST/FOC images in several UV bands were obtained for the central regions of the elliptical galaxies NGC 1399 and NGC 4552 and of the bulge of the S0/a galaxy NGC 2681. A point-like source – or spike – was evident at the center of both NGC 4552 and NGC 2681, with their photometric profile being indistinguishable from the PSF of the pre-COSTAR HST (Paper I [1]).

Comparison with another FOC image of NGC 4552 taken in 1991 [2] showed that this spike had increased its luminosity in the U band (F342W) by a factor \( \sim 7 \pm 1.5 \) between the two epochs, reaching \( \sim 10^6 L_\odot \) (Paper I). A second point-like source is also present in the 1991 image, \( \sim 0''.14 \) from the
central spike and with nearly the same luminosity. While both sources were
detected at the $\sim 4\sigma$ level in the 1991 image, the offcenter source was not
detectable in the 1993 image at the $\sim 2.5\sigma$ level.

In Paper I several possible interpretations were discussed for the origin
of this flare at the center of NGC 4552, favoring an accretion event onto
a central massive black hole (BH). The accreted material could have been
tidally stripped from a star in a close fly-by with the BH, though alternative
ways of feeding the BH were also considered. The low luminosity of the spike
was nevertheless at variance with the predicted luminosity in the case of a
total stellar disruption [3,4], hence the case of partial stripping was favored,
being also such an event much more frequent than total disruptions.

2 More HST Follow Up Reveals a Mini AGN in
NGC 4552

If the flaring spike was due to accretion onto a BH, its spectrum should show
prominent, rotationally broadened emission lines, typical of an accretion disk.
To test this expectation further HST observations were obtained in 1996, both
in imaging with FOC and in spectroscopy with FOS. The results of these later
HST observations are extensively reported in Paper II [5].

2.1 FOC Imaging

The 1991, 1993, and 1996 observations were made with different telescope-
instrument configurations and therefore differences in detector efficiency and
non-linearity effects were carefully treated along with an adequate modeling
of the PSF. The analysis revealed that the center spike in NGC 4552 increased
its $U$-band luminosity by a factor of 4.5 from 1991 to 1993 and faded from
1993 to 1996 by a factor $\sim 2$ at all observed wavelengths (1700–3500 Å)
(Paper II). In 1996 the UV fluxes indicated a black body temperature of $T \sim
15,000$ K (assuming the emission to be thermal) implying a spike bolometric
luminosity of $\sim 3 \times 10^5 L_\odot$ (at a distance of 15.3 Mpc). The offcenter spike
that was present in 1991 did not appear in any of the later images.

2.2 FOS Spectroscopy

The 1996 FOS spectra were obtained through a $0''.21 \times 0''.21$ square aperture
centered on the spike and covering the range from $\sim 2200$ to $\sim 8500$ Å. Fig.
1 compares the 1996 FOS spectrum of this central region with a composite
spectrum meant to represent the spectrum of the inner $r \leq 7''$ of this galaxy.
This composite spectrum is a good match to the SED of the FOS spectrum,
with two notable exceptions: 1. the FOS spectrum shows strong emission
lines that are absent in the composite spectrum, and 2. shortward of 3200 Å
the FOS spectrum is far stronger than the IUE SED.
The overall 1996 FOS spectrum of NGC 4552 within the $0'' .21 \times 0'' .21$ aperture centered on the spike (thin line), is superimposed to a scaled combination of the IUE $10'' \times 20''$ aperture of NGC 4552 [6] matched to ground-based optical spectrum of NGC 4649, a giant elliptical whose SED is virtually the same as that of NGC 4552 [7] (thick line). The spectra have been normalized to the visual region. The FOS spectrum show a strong UV excess and prominent emission lines.

The most prominent emission lines include C II $\lambda 2326$, Mg II $\lambda 2800$, [O II] $\lambda \lambda 3727$, [S II] $\lambda 4072$, H$\beta$, [O III] $\lambda \lambda 4959, 5007$, [N I] $\lambda 5700$, [O I] $\lambda 6300$, [N II] $\lambda \lambda 6548, 6583$, H$\alpha$ and [S II] $\lambda \lambda 6717, 6731$. The emission line ratios of the narrow components place the spike among extreme AGNs, while the [O III]/H$\beta$ ratio falls just on the borderline between Seyferts and LINERs.

The emission line profiles were fitted with gaussian components, reaching the following main conclusions: 1. Good fits of the emission lines can be obtained only with a combination of broad and narrow components for both the permitted as well as the forbidden lines. 2. The emission lines are very broad, with very high velocity widths for both the broad (FWHM $\simeq 3000$ km s$^{-1}$) and narrow components (FWHM $\simeq 700$ km s$^{-1}$). 3. The shape of the H$\alpha$+[N II] complex has definitely changed from the 1996 spectrum to a FOS spectrum taken 8 months later, indicating a shift to the blue of $\sim 230$ km s$^{-1}$ of the whole (narrow + broad) H$\alpha$ line.

2.3 Interpretation

This complex phenomenology clearly points towards the presence of a very weak AGN at the center of this galaxy, most likely powered by a low level of accretion onto a central BH. Other interpretations were already considered unlikely, given the early evidence (Paper I). The additional evidence gathered in 1996 was conclusive in this respect. The mass of the supermassive BH at the center of NGC 4552 was then estimated to be between $3 \times 10^8$ to $2 \times 10^9$
The observed [O I], [N II], Hα, and [S II] lines in the red region of the FOS G780H spectrum (top) together with their gaussian decomposition into narrow and broad components (middle) and the corresponding residuals (bottom). The narrow and broad components have FWHM $\approx 700$ and $\approx 3000$ km s$^{-1}$, respectively.

$M_\odot$, consistent with other ground-based estimates as well as with the BH mass-bulge mass (or -bulge luminosity) relation [8,9].

With the adopted distance of 15.3 Mpc the broad Hα luminosity is $\sim 5.6 \times 10^{37}$ erg s$^{-1}$, a factor of two less than the broad Hα luminosity of the (previously) faintest known AGN, the Seyfert 1 nucleus of NGC 4395, and a $\sim 20$ times fainter than M81, the next faintest Seyfert 1 nucleus [10].

As suggested in Paper I, this phenomenology is generically consistent with a scenario in which the flare is caused by the tidal stripping of a star in a close flyby with a central supermassive BH. From the theoretical side, only the extreme case of the total disruption of a $\sim 1 M_\odot$ main sequence star has been widely investigated so far (e.g., [3,4,11]). The frequency of such events is estimated to be of one every $\sim 10^3 - 10^4$ yr in a giant elliptical galaxy [3]. The flare is predicted to be very bright for several years ($\sim 10^{10} L_\odot$), much brighter than the observed flare. This indicates that if the flare in NGC 4552 was caused by a tidal stripping in a BH-star flyby, then this flyby was rather wide and led to only partial stripping. One expects wider flybys to be vastly more frequent than the hard ones causing total disruption. To be consistent with the observed luminosity, only $\sim 10^{-3} M_\odot$ should have been stripped (Paper I), perhaps more if an ADAF is established (?).

Tidal stripping of a star is but one possible way to feed matter to a massive central BH at a low rate. Other mechanisms mentioned in Paper II include: a) Roche lobe overflow from a star in bound orbit around the BH; b) accretion from a clumpy interstellar medium which is actually seen near the nucleus (see Fig. 12 in Paper II); or c) gas fed to the BH via a cooling flow within the X-ray emitting hot interstellar medium. Concerning alternative c), occasional cooling catastrophes lead to transient major cooling flow that can feed the central BH, while mini-inflows may be active most of the time. Such
flows can lead to sizable excursions in the (mini-)AGN luminosity (flickering), reminiscent of the behavior of the spike in NGC 4552 [12,13].

It may well be that each of these mechanisms operates from time to time in the central regions of elliptical galaxies like NGC 4552, and in all these options an accretion disk is established, hence no clear cut discrimination can easily be achieved. However, some evidence favoring the tidal stripping option comes from the noticed shift in the broad Hα emission between 1996 and 1997. Tidal stripping/disruption is indeed predicted to produce an elliptical accretion disk which precession results in Hα line profile variations [14]. Finally, in Paper II it was speculated that the offcenter spike seen only in the 1991 image could be due to a relativistic jet emerging from the central mini-AGN having shocked the dense dusty ring seen at nearly the same distance, with the jet having been possibly produced by a previous accretion event.

3 Also NGC 2681 and NGC 1399 Display Central Activity

In 1997 FOC and FOS observations were secured also for the central spike in NGC 2681, with a virtually identical strategy to that used for NGC 4552 (Paper III [15]). The main results can be summarized as follows.

The photometric profile is well represented by a Nuker-law of the power-law type, from the innermost 0''005 up to ~ 100'' from the center. Given the very high surface brightness of the central regions, a transient UV spike such as that in NGC 4552 would have not been revealed in either the FOC images (see Fig. 3) or in the FOS UV continuum. The UV continuum and the presence of Balmer absorptions indicate that the central region of NGC 2681 is dominated by the light of a relatively young stellar population (1–2 Gyr).

Contrary to the case of NGC 4552, the FOS spectrum of the innermost 0''21 × 0''21 region matches very well the IUE UV spectrum, in spite of the much larger (a factor of ~4000) area sampled by the IUE aperture. Together with the absence of gradients in the (Far-UV)–(Near-UV) and UV–IR colors, this implies the homogeneity of the stellar population within r<10''. The FOS shows emission lines whose ratios indicate that the nucleus is a LINER. The emission lines are well-modeled by a single Gaussian with FWHM~ 480 km s\(^{-1}\), which is a factor ~ 2 higher than that measured from the ground, within a 2'' × 4'' aperture, indicating the presence of a central mass concentration.

This steepening of the (gas) velocity dispersion is not accounted for by a spherical isotropical dynamical model with constant M/L, derived by deprojecting the Nuker-law. The same kind of model gives a good fit to the FOS data when assuming a central dark mass (BH) with M•≤6 × 10\(^7\) M\(_{\odot}\), consistent with the BH mass-bulge luminosity relation [9]. This holds under the assumptions that the emitting gas has an isotropic velocity-dispersion tensor and that its density is proportional to the stellar density. Models without a
BH can also fit the data if these assumptions are relaxed, e.g. either the nuclear gas is in a disk, or gas clouds are on radially-anisotropic orbits close to the nucleus. In summary, there are quite many analogies between the central spikes in NGC 4552 and NGC 2681. The possibility that the line emission in the NGC 2681 spike originates in an accretion disk seen more face on than in NGC 4552 cannot be ruled out.

Fig. 3. The FOC $U$-band surface brightness profiles of the innermost $3''$ of NGC 4552 (lower lines) and NGC 2681 (upper lines). The dashed lines represent the best fit Nuker laws and the solid lines their convolution with the PSF of the FOC, with a point-like source being added in the case of NGC 4552.

On 1993 FOC images the central $\sim 20''$ of NGC 1399 appear as smooth as silk, i.e. no spike similar to either that of NGC 4552 or that of NGC 2681 is present. Indeed, NGC 1399 is well fit by a Nuker law of the core type, and its central surface brightness is much lower than that of NGC 2681. However, a STIS far UV spectrum of NGC 1399 recently obtained (R.W. O’Connell private communication) appear to contain a distinct nuclear point source—definitely above the background light of the galaxy’s core—which may be even brighter than the spike in NGC 4552. A very nice surprise indeed!

4 No Supermassive Black Hole Can Be Totally Silent

The case of the flare in NGC 4552 adds yet another option at our disposal to gather evidence for supermassive BHs lurking at the center of apparently in-active galactic nuclei. Supermassive BHs in galactic spheroids sit at the bottom of their gravitational potential well, where stellar and ISM densities reach their maximum, and where any cannibalized material tends to converge. As such, one is tempted to say that the real problem is how to avoid a low, fluctuating level of accretion onto a massive BH — hence of low level AGN
activity — rather than how to produce it. After all, it must be hard for guests as bulky as $10^8$ or $10^9 \, M_\odot$ to really hide at the center of galaxies: wherever a massive BH exists, its presence is likely to be betrayed by at least a low level of AGN-like activity.

The case of NGC 4552 offers a lesson in this respect. Thanks to its angular resolution, HST observations in either UV or optical imaging or narrow aperture spectroscopy allow to reveal a mini-AGN activity which would be essentially invisible to similar ground based observations. However, a high resolution comparable to that of HST is now possible also from the ground at near-IR wavelength thanks to adaptive optics (AO). AO-fed, near-IR, 1D and 2D spectroscopy of the center of galactic spheroids (e.g., with SINFONI at the VLT) might reveal broad emission lines of the Paschen and Brackett series, hence potentially offering additional opportunities for the demography of central BHs in galactic spheroids. The generic prediction is that virtually all galactic spheroids (and especially those for which dynamical evidence exists) should show a low-level AGN activity similar to that so clearly detected by HST in NGC 4552.

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