The nuclear orbital distribution in galaxies as a fossil record of black hole formation from integral-field spectroscopy

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Abstract
In the past decade, most effort in the study of supermassive black holes (BHs) has been devoted to measuring their masses. This led to the finding of the tight $M_{\text{BH}}-\sigma$ relation, which indicates the existence of strong links between the formation of the BHs and of their host spheroids. Many scenarios have been proposed to explain this relation, and all agree on the key role of BHs’ growth and feedback in shaping their host galaxies. However, the currently available observational constraints, essentially BH masses and galaxy photometry, are not sufficient to conclusively select among the alternatives. A crucial piece of information on black-hole formation is recorded in the orbital distribution of the stars, which can only be extracted from high-resolution integral-field (IF) stellar kinematics. The introduction of IF spectrographs with adaptive optics on large telescopes opens a new era in the study of BHs by finally allowing this key element to be uncovered. This information will be complementary to what will be provided by the LISA gravitational wave satellite, which can directly detect coalescing BHs. Here, an example is presented for the recovery of the orbital distribution in the centre of the giant elliptical galaxy M87, which has a well-resolved BH sphere of influence, using SAURON IF kinematics.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction
In recent years, there has been tremendous progress, primarily from space-based observations, in our understanding of the distribution of central black-hole (BH) masses and the relation between BHs and their host galaxies (see de Zeeuw (2004) for a review). The resulting
picture of BH demography is summarized by the correlation between BH mass and absolute spheroid luminosity (e.g., Magorrian et al 1998) and the much tighter correlation between BH mass and galaxy central velocity dispersion (the $M_{\text{BH}}-\sigma$ relation; Ferrarese and Merritt 2000, Gebhardt et al 2000). It is now clear that BHs are nearly ubiquitous in galaxies, and there is increasing evidence that BH formation plays a key role in driving galaxy formation, via feedback processes. The correlations obtained from nearby galaxies are also being extended to study the high-redshift universe. To date, however, the only observable constraints on the BH formation process are the BH masses and the nuclear stellar density profiles of nearby galaxies. Until now, very little is known about the nuclear orbital distribution of the stars, which constitutes a fossil record of the BH formation process. The advent of high spatial resolution integral-field spectroscopic observations is opening a new era in the study of BHs by allowing this crucial piece of information to be reliably extracted.

2. Observable constraints on black hole formation scenarios

Spheroidal components of galaxies are thought to form through a series of hierarchical mergers of smaller systems, which themselves have central BHs. As two systems merge, their central BHs rapidly fall to the minimum of the potential well due to dynamical friction, and create a binary system at the centre of the remnant. The binary loses energy and shrinks by capturing stars on radial orbits which pass nearby, and ejecting them at much higher velocities, thus dynamically heating the central regions and lowering its stellar density, scouring out a ‘core’ of radius $R_c$ in the photometric profile (Quinlan and Hernquist 1997, Milosavljević and Merritt 2001). In this way, a coalescing BH binary can eject a total mass of stars similar in order to its own mass, and influence the orbital structure of the remnant nucleus out to the radius $R_e$, which is several times larger than the actual BH radius of influence. The imprint of this process is found in the central orbital structure, which can be quantified, e.g., in terms of the ratio of radial to tangential orbits (figure 1). BHs can also grow by acquiring gas which sinks via dissipation to the bottom of the galaxy potential well. In this case, simulations show that a cusp forms in the density profile when the gas subsequently forms stars, while the orbital distribution is only weakly affected. These two black-hole formation mechanisms have been proposed as an explanation for the dichotomy of central luminosity profiles of early-type galaxies (Faber et al 1997). While the details of the theoretical predictions for the effects of the BH growth on the orbital distribution are still under lively debate (Merritt and Milosavljević 2004, Makino and Funato 2004), due to the difficulty of constructing accurate $N$-body simulations with very large numbers of stars near the BH singularity, it already appears clear that BHs have a profound influence on the structure of galaxy nuclei, which retain the fossil record of the formation process. One of the strongest observable constraints on the BH formation scenarios is its effect on the central orbital structure.

3. Limitations of high-resolution long-slit studies

Probing the BH radius of influence demands sub-arcsecond spatial resolution, even for nearby galaxies. For this reason, STIS onboard HST has been used for many well-determined BH masses measured from dynamical modelling of the kinematics of stars or gas. There are also several studies currently in progress to establish black-hole masses using adaptive optics (AO)-assisted long-slit measurements from the ground, using NAOS–CONICA (VLT) and NIRI–Altair (Gemini). There are strong limitations, however, to what can be achieved by long-slit studies. A single-slit observation is not sufficient to detect possible signs of
non-axisymmetry in the kinematics, resulting from a nuclear bar, for example. Therefore, the symmetry assumptions generally made in the dynamical models, used to measure BH masses, cannot be tested.

More importantly, the orbital distribution (e.g., the anisotropy) cannot be recovered without knowledge of the line-of-sight velocity distribution (LOSVD) of the stars at all spatial positions on the galaxy image projected on the sky (figure 2). Integral-field kinematic data are therefore the only way to reliably constrain the orbital structure (Cappellari et al. 2004), and general orbit-based methods can then be used in realistic conditions, for a given potential, to extract the orbital distribution from the two-dimensional (2D) kinematics (Krajnović et al. 2005). Ignorance of the anisotropy due to only having a single long slit directly translates into large uncertainties in the BH mass determination (Verolme et al. 2002), as well as invalidating any constraint on the BH formation scenario. Although observational studies of the velocity anisotropy around BHs exist (Gebhardt et al. 2003), these are based on single-slit information, from HST/STIS, and so cannot place tight constraints on the orbital structure. Avoiding these issues by obtaining multiple slit positions is a prohibitive observational expense, and no such studies exist.

Until now, no instrument could provide integral-field kinematics at the resolution of HST (but see Bacon et al. (2001a)), so it was impossible to reliably infer the orbital distribution near the nuclear black holes. The advent of AO-fed IF units on large telescopes, such as SINFONI (VLT), OASIS (WHT), NIFS (coming on Gemini) and OSIRIS (coming on the Keck telescopes), is finally going to change this situation. In particular, the future prospect of laser guide star-based AO systems on these instruments will allow statistically meaningful samples to be obtained. Observations from such instruments, combined with general dynamical models, will provide the first reliable determination of the effect of a black hole on the nuclear stellar orbits, giving a unique insight into the formation of BHs and their host systems.
4. Nuclear orbital distribution of M87 from integral-field kinematics

To demonstrate what IF observations can provide, we present here the recovery of the orbital distribution from general axisymmetric three-integral dynamical modelling of the IF stellar kinematics of M87, which is part of the SÃOÐN survey (Bacon et al. 2001b, de Zeeuw et al. 2002). This galaxy is an ideal candidate for this ground-based study as its BH sphere of influence $R_{\text{BH}} \approx 1.4''$ is resolved even in natural seeing. Moreover, the core, whose structure is thought to have been shaped by the BH binary, has a radius $R_c \approx 7.5''$ (Faber et al. 1997) and is very well sampled by the observed SÃOÐN kinematics.

The observations were presented in Emsellem et al. (2004) and we refer to that paper for details. In brief, the SÃOÐN IF observations were spatially binned to a minimum $S/N \approx 60$ using the Voronoi 2D-binning algorithm by Cappellari and Copin (2003) and the stellar kinematics were subsequently extracted with the penalized pixel-fitting (pPXF) method of Cappellari and Emsellem (2004). This provided, for each Voronoi bin, the mean velocity $V$, the velocity dispersion $\sigma$ and the higher order Gauss–Hermite moments of the velocity, including $h_3$–$h_6$ (van der Marel and Franx 1993, Gerhard 1993). For the three-integral dynamical modelling, we adopted Schwarzschild’s (1979) numerical orbit-superposition method, which can fit all kinematical and photometric observations (Rix et al. 1997, van der Marel et al. 1998, Cappellari et al. 2002). A similar approach was adopted by other groups to measure the black-hole (BH) masses in galaxy nuclei (e.g., Gebhardt et al. 2003, Valluri et al. 2004).
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Figure 3. Each column from left to right shows the kinematic moments: mean velocity, $\sigma$, and higher Gauss–Hermite moments $h_3$–$h_6$. Top row: Voronoi 2D-binned and symmetrized SAURON observations of the giant elliptical galaxy M87. Bottom row: three-integral Schwarzschild model fit to the above kinematics.

Figure 4. Radial profile of the orbital anisotropy $\sigma_r/\sigma_t$ in M87. The different solid lines are measured along different polar angles, in the galaxy meridional plane, and provide an indication of the model uncertainties. The dotted horizontal line corresponds to an isotropic model. The dashed vertical line indicates the radius $R_{BH}$ of the BH sphere of influence, while the solid vertical line corresponds to the location of the break radius $R_c$, which is indicative of the core size. The main galaxy body is mildly radially anisotropic until well inside the sphere of influence of the BH (at the limit of our spatial resolution), where the orbits become tangentially anisotropic.

Our best fitting model with constant stellar mass-to-light ratio $M/L$ (figure 3; for an assumed inclination $i = 90^\circ$) is able to reproduce all the details of the observed kinematics. As our kinematic measurements do not have enough spatial resolution to provide tight constraints on the BH mass, we assume $M_{BH} \approx 3 \times 10^9 M_\odot$ as derived from the HST gas kinematics (Harms et al. 1994, Macchetto et al. 1997). The anisotropy profile of the model is presented in figure 4. It shows that the main galaxy body is mildly radially anisotropic even inside $R_c$, and it is not until well inside $R_{BH}$ (at the limit of our spatial resolution) that it becomes tangentially anisotropic. This result is consistent with previous models by Dressler and Richstone (1990), van der Marel (1994) and Merritt and Oh (1997) which only made use of the velocity dispersion along a single-slit position. This is not surprising given the near circular symmetry of the projected observables of this galaxy in the central regions. In a nonrotating spherical stellar system, if the potential is given, the anisotropy is uniquely specified by the velocity dispersion alone (Binney and Manon 1982). Therefore, the fact that our model is able to fit the higher
order moments of the velocity as well, gives us confidence that the orbital distribution is being correctly recovered.

Although little can be learned from a single object and a specific simulation, it is still interesting to see how the observations and the predictions compare. We find that the observed distribution of M87, which is the prototypical giant core elliptical galaxy, is not obviously explained by current simulations of the BH binary core-scouring mechanism. In fact, although the observed anisotropy is consistent with the predicted one at the time of the formation of the hard BH binary (figure 1(b)), the steep surface brightness profile (figure 1(a)) is inconsistent with the observations (figure 7 of van der Marel et al 1994). The observed surface brightness profile is better reproduced by the simulations at later times, when the binary had time to scour a deeper core, but the anisotropy profile at that time (figure 1(c)) is inconsistent with the observed one. This discrepancy may be due to the effect of multiple merger events (Milosavljević and Merritt 2001), making the simulations and the observations difficult to compare in detail. This practical example demonstrates the method, and highlights the need to perform this kind of study for larger samples of objects, in order to tightly constrain the BH formation mechanism of these massive ($M_{BH} > 10^6$) BHs in nearby galaxies, and uncover fossil signatures of BHs binaries, which can be compared with detailed predictions from simulations. This information will be complementary to what will be provided by the LISA gravitational wave satellite, which can directly detect coalescing BHs (if this happens) in the smaller mass range $M_{BH} < 10^6 M_{⊙}$, and in a much larger redshift range (up to $z ∼ 10$). Understanding the BH growth is expected to shed light on the feedback processes by which BHs shape galaxy evolution.

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