Integral-field Spectroscopy of Galactic Nuclei

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Abstract. High-resolution imaging and long-slit spectroscopy obtained with HST, combined with ground-based integral-field spectroscopy, provides the kinematics of stars and gas in nearby galactic nuclei with sufficient accuracy to derive the intrinsic dynamical structure, and to measure the mass of the central black hole. This has revealed that many nuclei contain decoupled kinematic components and asymmetric structures, and that nuclear and global properties of galaxies are correlated. Higher spatial resolution and significantly increased sensitivity are required to cover the full range of galaxy properties and types, including the nearest powerful active radio galaxies, and to study the evolution of galactic nuclei as a function of redshift. The prospects in this area are discussed.

1. Integral-field spectroscopy

The past decade has seen a revolution in instrumentation for spatially resolved spectroscopy of galaxies and their nuclei. At many observatories, traditional long-slit spectrographs have been replaced by integral-field devices which produce spectra over an area, fully spatially sampled, in many cases taking advantage of adaptive optics capabilities (see, e.g., Emsellem & Bland–Hawthorn 2002 for a recent summary). These instruments are very efficient in use of telescope time, and allow complete reconstruction of the intensity distribution from the spectra, so that errors in the registration of the spectra relative to the galaxy image, familiar from aperture and long-slit spectroscopy, are avoided.

2. Galactic nuclei with HST

HST has revealed that most early-type galaxies have centrally cusped luminosity distributions, often containing nuclear stellar and gaseous disks as well as asymmetries. FOS aperture spectroscopy and STIS long-slit spectroscopy of stars and gas has demonstrated that nearly all these nuclei contain a supermassive black hole, with masses ranging between $10^6$ and a few times $10^9 M_\odot$ (e.g., Kormendy & Gebhardt 2002). Global and nuclear properties appear to correlate. Examples include a correlation of cusp-slope with total luminosity, and of black hole mass with host galaxy velocity dispersion (e.g., Gebhardt et al., 2000, Ferrarese & Merritt 2000). We discuss four examples of HST studies of nuclei to illustrate the need for two-dimensional spectroscopic coverage, the need for measurement of the absorption-line kinematics, and the need for high spatial resolution.
Figure 1. The nucleus of M31. Clockwise from top left: deconvolved WFPC2 $I$-band image, stellar velocity $V$, stellar velocity dispersion $\sigma$, and intensity $I$ derived from OASIS integral-field spectroscopy near the Ca triplet (Bacon et al. 2001a). The brightest peak in the WFPC2 image is P1, the secondary peak is P2. The dashed line indicates the symmetry axis of the $V$-field. The field-of-view is 3.5 by 2.5.

2.1. The nucleus of M31

Stratoscope II discovered that the nucleus of M31 is asymmetric (Light, Danielson & Schwarzschild 1974). HST imaging revealed two peaks in the brightness distribution, labeled P1 and P2 by Lauer et al. (1993), separated by 0.49. The ground-based integral-field spectroscopy with modest spatial resolution obtained with TIGER showed a nearly symmetric stellar velocity field, with P1 offset from the kinematic center, and a velocity dispersion peak near P2 but offset from it in the direction away from P1 (Bacon et al. 1994). Multiple FOS pointings (Ford, unpubl.), and long-slit spectroscopy with both FOC (Statler 1999) and STIS (GTO 8018, PI Green, see Bacon et al. 2001a) showed an asymmetric velocity curve, and confirmed the velocity dispersion peak near P2, presumably caused by a $7 \times 10^7 M_\odot$ black hole. AO-assisted integral-field spectroscopy with OASIS on the CFHT, with an effective resolution of 0.45, clarified these puzzling asymmetries (Bacon et al. 2001a). As Figure 1 shows, the velocity field is regular, and the dispersion peaks near P2, but a slit through P1 and P2 (a natural choice based on the WFPC2 image) neither coincides with the kinematic symmetry axis nor intercepts the true $\sigma$ maximum: without the OASIS data, the STIS profiles are difficult to understand. The nature of the M31 nucleus is not fully understood, but the N-body models of Bacon et al. (2001a), which build on Tremaine’s (1995) eccentric disk model, show that a near-Keplerian $m = 1$ density wave provides a good qualitative fit. Future models will have to deal with all the constraints established from two-dimensional spectroscopy.
Figure 2. Dynamical models for M32. The panels show contours of $\Delta \chi^2$, which measures the goodness of fit of the dynamical models to the kinematic measurements, as a function of black hole mass $M_{\text{BH}}$, stellar mass-to-light ratio $M/L$ and inclination $i$, taken from Verolme et al. (2002). The thick contour is the $3\sigma$ confidence level for three degrees of freedom, at a $\Delta \chi^2$ of 14.2 above the minimum. The intrinsic flattening $q$ of the models is indicated in the lower-right corner of each panel.

Left: model fits to the Joseph et al. (2001) STIS major-axis data and the SAURON integral-field measurements over $9'' \times 11''$ sampled with $0''28$ pixels in $0''95$ seeing. This allows accurate measurement of $M/L$, $M_{\text{BH}}$ and $i$. Right, model fits which include again the STIS major axis-data, but now only the SAURON measurements along 4 slits (major and minor axis, and at $\pm 45^\circ$). This shows that the traditional kinematic coverage provides almost no constraint on $i$, and that the resulting uncertainties on the inferred values of $M/L$ and $M_{\text{BH}}$ are significantly larger.
2.2. The E3 galaxy M32

M32 is a high-surface brightness inactive E3 companion of M31, and has long been suspected of harboring a central black hole of about $3 \times 10^6 M_\odot$ (e.g., Tonry 1984). This dominates the observed kinematics inside $0'' 15$, and as a result a reliable mass measurement had to await FOS and the development of general machinery for the construction of axisymmetric dynamical models with the full range of orbital anisotropies (van der Marel et al. 1998). Verolme et al. (2002) compared the STIS major axis kinematics (Joseph et al. 2001), as well as SAURON integral-field spectroscopy of the inner $9'' \times 11''$ of M32 (Bacon et al. 2001b; de Zeeuw et al. 2002) with general axisymmetric dynamical models, varying stellar mass-to-light ratio $M/L$, black hole mass $M_{BH}$ and the inclination $i$. All three parameters are well-constrained, with $M_{BH} = (2.5 \pm 0.5) \times 10^6 M_\odot$ (3$\sigma$-error), $M/L = 1.85 \pm 0.15 M_\odot/L_\odot$ in the $I$-band, and $i = 70^\circ \pm 5^\circ$ (Figure 2, left panel). Experiments showed that the traditional approach of using ground-based kinematics along a few slits significantly degrades the measurement accuracy: it does not allow meaningful determination of $i$ and as a result causes a larger uncertainty on $M_{BH}$ (Figure 2, right panel). Even in the case of an object as dynamically simple as M32, two-dimensional coverage is of key importance.

2.3. Kinematics of gas or stars?

Much work has been done on obtaining kinematics of emission-line gas of nearby nuclei (Kormendy & Gebhardt 2002). This is attractive as it allows kinematic measurements with only a few HST orbits at excellent spatial resolution. Often three parallel slits are used to mimic integral-field capability. The results are not always easy to interpret, as the gas is rarely in a simple disk, and even if it is, the kinematics may be asymmetric, or the gas velocity dispersion so large that modeling becomes problematic (e.g., Ho et al. 2002).

Black hole masses and nuclear properties derived independently from the kinematics of gas and stars are available for only a few nearby galaxies. Cappellari et al. (2002) carried out a detailed comparison for the E3 galaxy IC 1459. Dynamical modeling of the stellar kinematics (using STIS and multiple-position angle ground-based data) allows a decomposition/identification of the counter-rotating stellar core in phase space, and shows that it is a disk with a mass of about $3 \times 10^6 M_\odot$. The best-fit model has a black hole mass of about $2.6 \times 10^9 M_\odot$, somewhat larger than the value expected from the $(M_{BH}, \sigma)$-relation. Models of the gas velocities suggest $M_{BH} \approx 3.5 \times 10^8 M_\odot$ if the gas is in circular motion in a principal plane, while simple models of the velocity dispersion suggest $M_{BH} \approx 1 \times 10^8 M_\odot$ for a spherical distribution of the gas. This leaves significant uncertainties about the reliability of the gas as a tracer of the galaxy gravitational potential. Studies of NGC4335 (Verdoes Kleijn et al. 2002), and NGC4697 (Gebhardt priv. comm.) reach similar conclusions. While simple modeling of the observed gas kinematics can probably be trusted when the gas has a smooth and regular morphology, symmetric kinematics, and low velocity dispersion (e.g., Barth et al. 2001), in many nuclei this will not be the case.

Much effort has gone into obtaining stellar kinematics with STIS for nearby galactic nuclei (e.g., Pinkney et al. 2002). These studies have typically been restricted to objects with velocity dispersions larger than about 140 km/s, and cusped luminosity profiles. In some cases the $0'' 2$ slit is required to reach suffi-
cient signal-to-noise. In combination with multi-position-angle or integral-field ground-based stellar kinematics, these measurements provide reliable black hole masses (e.g., Gebhardt et al. 2002; Verolme et al. 2002). STIS cannot probe the nuclei of the giant ellipticals in Virgo because of their modest surface brightness, and cannot resolve the black hole sphere of influence in low-luminosity ellipticals, because at 15 Mpc its radius is smaller than 0′′1.

2.4. Active galaxies

Most nearby galaxies contain a quiescent or only weakly active nucleus (Ho et al. 1997). There are few powerful nuclei within 20 Mpc: Cen A at ≈3 Mpc (but its nucleus is heavily obscured), as well as classical Seyferts such as NGC1068, and FR I radio galaxies such as M84 and M87 in the Virgo cluster. More powerful active nuclei appear at even larger distances, with Cyg A, the classical FR II at ∼200 Mpc. 3C273, the nearest quasar, is another factor 2.5 or so more distant.

HST imaging by Verdoes Kleijn et al. (1999) of a complete sample of 21 northern nearby FR I galaxies (18 of which are beyond 40 Mpc) revealed that all of them have nuclear emission-line gas, as well as dust disks or dust lanes. Comparison with imaging of inactive galaxies shows that the trigger of activity must lie on scales smaller than resolved by WFPC2, even in the nearest active nuclei. STIS emission-line kinematics is now available for these FR I objects but, as we have seen above, the derived $M_{\text{BH}}$ will have to be treated with caution, in particular because the gas kinematics may be influenced by non-gravitational motions (in- and outflows). Beyond 40 Mpc the spatial resolution is insufficient to detect all but the largest black holes. Measurement of the stellar kinematics in nearby active nuclei is difficult, as these often reside in low-surface brightness giant ellipticals, and contain a bright nuclear emission-line spike. Increased resolution in both imaging and spectroscopy is required.

3. Requirements for next steps

HST Studies of nearby galactic nuclei have raised interesting questions, including: why are nuclear and global properties correlated, what is the role of nuclear disks and asymmetries, do galaxies evolve dynamically from the inside out on interesting time scales, why is only a small fraction of the black holes currently active, how does the $M_{\text{BH}}$ mass function evolve with time? In order to answer these, we need to extend the studies that are currently possible only for Local Group galaxies to a representative sample. This leads to four requirements:

- Integral-field spectroscopy to obtain the two-dimensional kinematics (and line-strengths), which provides key constraints not only for asymmetric nuclei such as the one in M31, but also in ‘simple’ galaxies such as M32;
- Sufficient sensitivity to be able to measure the stellar absorption-line kinematics over the full range of central surface brightness seen in Virgo galaxies, in order to have a reliable tracer of the gravitational potential;
- Increased spatial resolution, to probe the nuclei of the smaller galaxies in Virgo, and to carry out a representative census to larger distances which also contains the rarer types, in particular the radio-loud galaxies.
- A coronographic capability to probe near bright central spikes.
4. Prospects on the ground

Galactic nuclei are interesting targets for AO-assisted studies from the ground. The OASIS results on M31 in the I-band shown in Figure 1 provide a case in point. This instrument is being upgraded, and will move to the WHT on La Palma in 2003. The enhanced throughput, and a laser guide star (planned for 2005) should provide the stellar kinematics in objects like M87 with unprecedented spatial resolution.

Integral-field spectrographs operating at near-infrared wavelengths will soon be available on 8m class telescopes. Examples include SINFONI on the VLT and NIFS on Gemini, with first light for both expected in 2004. These instruments allow measurement of the stellar kinematics through observations of the CO bandhead at 2.3µm. With the tenfold increase in collecting area over HST, and the potential to provide spectra at a spatial resolution of better than 0.1 at 2µm, this will allow a significant step beyond STIS in the study of normal and dusty objects, including some of the nearest active nuclei.

Adaptive optics in the visible range on 8m telescopes can in principle improve on the current HST resolution by a factor two or more over a small field of view. This will be hard to achieve in practice, but there is much ongoing effort in this direction, and galactic nuclei are among the natural targets. This will not only involve imaging but also spectroscopy. An example is provided by the proposed second generation VLT instrument MUSE (PI Bacon). While its main aim will be MC(AO) assisted panoramic integral-field spectroscopy of ultra-deep fields in the I and R bands, MUSE will have a mode for spectroscopy at the highest spatial resolution provided by adaptive optics in a small field. Phase A is in progress, and the instrument could be on the VLT by 2007.

Development of interferometry at infrared wavelengths is being pursued actively at Keck and at ESO (VLTI). Interferometry is also an important component of the planned scientific use of the LBT. Galactic nuclei (including the Galactic Center) are among the main drivers to go faint and reach K of 20 mag. The anticipated VLTI spatial resolution of order 0.015 at 10 µm would allow imaging of the dusty broad-line regions of the nearest active nuclei at these wavelengths. Obtaining spectroscopic information on these scales would be very exciting, but is an extremely challenging goal.

Design studies are underway for optical telescopes with filled apertures ranging from 30 (CELT and GSMT) to 100m (OWL). If (MC)AO can be made to work at near-infrared and eventually at optical wavelengths, then these extremely large telescopes will provide the increase in resolution over HST, combined with sufficient sensitivity, to carry out studies of galactic nuclei satisfying the requirements outlined in section 3. A 30m telescope would allow detailed study of nuclei in most Hubble types. Larger apertures (70–100m) operating at visible wavelengths would in principle allow detailed studies out to beyond Virgo with the sensitivity and resolution now achievable only for Local Group galaxies. Furthermore, because the angular diameter versus distance relation has a minimum at z = 1, these ELT’s could make it possible to estimate black hole masses in large galaxies throughout the Universe from emission-line kinematics.
5. Prospects in space

The first question to consider is whether significant progress could already be made by equipping HST with an integral-field spectrograph for near-UV and optical wavelengths. Efficient high-throughput designs exist, but this option would require an additional servicing mission. The reward would be the enhancement of the spectroscopic efficiency of HST by about a factor of 50 beyond STIS, including a relaxation of the roll-angle requirements on the observatory. Applications would range from resolved spectroscopy of Io and of proplyds in star-forming regions to resolved kinematics of gravitationally lensed arcs at high redshift. For galactic nuclei, this would provide exquisite capabilities for studying the nuclei of Local Group galaxies, and for measuring the gas kinematics in many nuclei. It would also enlarge the sample for which stellar kinematics can be measured with sufficient resolution.

The current plans have NGST as a 6m class observatory, with spectroscopic capabilities in the near and mid-infrared. An integral-field capability on NIRSPEC would allow study of normal and dusty nearby nuclei, provided it has a spectral resolution of a few thousand. The main gain over HST would not be spatial resolution (because of the longer wavelengths) but an order of magnitude in sensitivity, so that one might obtain stellar kinematics of giant ellipticals at 0″1 resolution. MIRI integral-field spectroscopy will provide emission-line diagnostics of dusty starbursts and active nuclei, and may probe the nuclear stellar populations of high-z galaxies as the CO bandhead moves to the mid-IR for z > 1.5.

A 6-8m class space telescope with integral-field capabilities in the optical (and perhaps near-UV) would allow stellar absorption-line spectroscopy of many galactic nuclei at 0″1 resolution or better, and a sufficient gain over HST in sensitivity that the giant ellipticals in Virgo can be studied at this resolution. A coronograph would allow unique studies of active nuclei (e.g., Seyferts). This would be a truly fantastic resource, which would benefit broad areas of astronomy. However, for galactic nuclei it might not provide a huge gain over the results expected from HST imaging combined with AO-assisted ground-based integral-field spectroscopy on 8m class telescopes, except in UV diagnostics. A space telescope of significantly larger aperture would provide a major leap in this area, and allow absorption-line studies in a representative sample of galaxy types with sufficient spatial resolution and sensitivity, and emission-line studies to the highest redshifts.

6. Conclusions

The combination of HST imaging and ground-based integral-field spectroscopy is very powerful for the study of the nuclei of normal and active galaxies, and provides a compelling argument for integral-field capabilities in space. Much progress in our understanding of galactic nuclei is expected on the ground in the next decade, and this may continue if near-diffraction limited observations become possible on telescopes with apertures of 30m or larger. While the study of galactic nuclei is not the main science driver for a 6-8m class space telescope, even a smaller aperture equipped with an integral-field spectrograph would yield a rich scientific harvest.
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