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Conference Summary

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1.1 Introduction

In the past decade, much effort was devoted to measure the masses of supermassive black holes in galactic nuclei, to establish the relation between black hole mass and the global/nuclear properties of the host galaxy, and to understand the role of these objects in the formation and subsequent dynamical evolution of galaxies. This whole area of research is an appropriate and timely topic for the first in this series of symposia. I congratulate the organizers, and in particular Luis Ho, for putting together such an interesting program of talks and posters.

Nearly half the contributions were devoted to the various methods that are being used to estimate masses of central black holes, from nearby globular clusters all the way to quasars at redshifts $z > 6$. This work forms the foundation of our understanding of black hole demography, and provides constraints on scenarios for black hole formation and growth, and on their connection to the formation and properties of the host galaxy. I will address these topics in this same order.

1.2 Black Hole Masses

The basic principle is to deduce the mass distribution in a galactic nucleus from the observed motions of stars or gas, and compare it with the luminous mass associated with the observed surface brightness distribution. If this requires a central mass-to-light ratio M/L larger than anything that can be produced by normal (dynamical) processes, the associated dark mass is considered to be a black hole.

Depending on the nature of the nucleus, and on its distance, one may employ the kinematics of individual stars, the spatially-resolved kinematics of the absorption lines of the integrated stellar light, or of the emission lines of gas (optical/maser), or the unresolved kinematics from reverberation mapping and modeling of line profiles. It is useful to review the contributions on all these approaches by starting with the nearest black holes, and working to larger distances. This takes us from what could be called "primary" black hole mass indicators to "secondary" and "tertiary" estimators.

1.2.1 The Galactic Center

The nearest supermassive black hole is located at the Galactic Center. Despite the large foreground extinction, it is possible to detect individual stars near it in the infrared, and to measure their proper motions and radial velocities. Ghez showed us beautiful results based on adaptive-optics-assisted near-IR imaging with a spatial resolution of $\sim 0\farcs05$. The velocities of stars this close to the Center are large: the five-year coverage to date already defines accurate three-dimensional stellar orbits for at least six stars, some of which are very eccentric. The stars appear to have early-type spectra, so may be massive and young. The current record holder recently passed pericenter at only 60 AU from the black hole, with a velocity of $\sim$9000 km s^{-1}!

With data of this quality, measuring the mass at the Galactic Center reduces to the classical astronomy of binary orbits. The current best estimate is $3.6 \times 10^6 M_\odot$. The spatial resolution achieved allows probing well inside the radius of influence of the black hole. The Galactic Center hence provides a unique laboratory for measuring the properties of a star cluster in the regime where the black hole dominates the gravitational potential, and allows studying the formation and evolution of massive stars under atypical conditions (see contributions by Alexander and Scoville).

The generally friendly but nevertheless intense rivalry between the groups at Keck (Ghez) and at ESO (Genzel/Eckart) promises further interesting results in the near future. In particular, the near-IR integral-field spectrographs `SINFONI` and `OSIRIS`, and hopefully `NIFS` on Gemini, will provide proper motions and radial velocities from the same observations, and will push these studies to fainter magnitudes.

1.2.2 Globular Clusters

Measurement of the resolved stellar kinematics is also possible in nearby globular clusters, which might contain "intermediate-mass" black holes, i.e., with masses in the range $10^3 - 10^4 M_\odot$. Ground-based proper motion and radial velocity studies generally lack the spatial resolution to observe the kinematic signature of such black holes, but the *Hubble Space Telescope (HST)* can detect them.

Van der Marel discussed the recent measurement of radial velocities in the central arcsecond of M15 obtained with `STIS`. The interpretation of the observed radial velocity distribution has led to significant controversy, which centers around the nature of the measured inward increase of M/L. Because dynamical relaxation has been significant in M15, dark remnants must have aggregated in its center. The initial estimate of a black hole of $\sim 3 \times 10^3 M_\odot$ had to be revised because of errors in previously published figures describing a Fokker-Planck model for the cluster. The revised figures suggest that the observed M/L increase could be due entirely to dark remnants, but leaves room for a black hole of $\sim 10^3 M_\odot$. Whatever the final word, this work suggests that it might be profitable to scrutinize other globular clusters, and it pushes the groups that have been producing detailed dynamical models for globular clusters to provide them for specific objects, while fitting all kinematic data.

HST proper motions might also reveal central black holes in globular clusters. The case of ω Centauri is of particular interest. It is a massive cluster that may be the remnant of a galaxy that fell in long ago, shows little evidence of mass segregation, and has ground-based kinematics for $\sim 10^4$ stars. It is the target of an extensive `WFPC2` proper motion study (King & Anderson 2002) which should detect a black hole if it has a mass as large as expected from the $M_\bullet - \sigma$ relation for galaxies (see below).

1.2.3 Stellar Absorption-line Kinematics

We cannot resolve motions of individual stars in the nuclei of other galaxies, but it is possible to measure the stellar kinematics from the integrated light at high spatial resolution. Ground-based integral-field spectroscopy is crucial for constraining the stellar M/L and the intrinsic shape of the galaxy. The orbital structure in these systems is rich, so a true inward increase of M/L must be distinguished from a possible radial variation of the velocity anisotropy. This requires measuring the shape of the line-of-sight velocity distribution as a function of position on the sky, and then fitting these with dynamical models. Recent work in this area was reviewed by Gebhardt and Richstone, with assists by Kormendy and Lauer.

A number of independent codes have been developed to construct dynamical models with axisymmetric geometry. These are by now all based on Schwarzschild's (1979) numerical orbit superposition method (Rix et al. 1997; van der Marel et al. 1998). The consensus view is that they give consistent black hole masses, as long as one is careful to obtain smooth solutions (by maximum entropy or via regularization, or by including very large numbers of orbits). A case study is provided by M32, which has been modeled by many groups over the past 20 years. The latest analysis is by Verolme et al. (2002), who model major-axis `STIS` data as well as `SAURON` integral-field kinematics. This produces an accurate M/L, for the first time fixes the inclination of M32, and sets the mass of its black hole at $2.5 \times 10^6 M_\odot$.

It is useful to keep in mind that two other nearby nuclei differ considerably from that in M32. The nucleus of M31 has long been known to be asymmetric (Light, Danielson & Schwarzschild 1974). `TIGER` and `OASIS` integral-field spectroscopy revealed its stellar kinematics (Bacon et al. 2001), and allowed understanding of previous long-slit work, including `FOS`, `FOC` and `STIS` data (Kormendy, Emsellem). Long-slit absorption-line spectroscopy of the nucleus of the Sc galaxy M33 shows that it cannot contain a black hole more massive than $1.5 \times 10^3 M_\odot$ (Gebhardt et al. 2001).

To date, nearly 20 early-type galaxies with distances up to 20 Mpc have been studied in this way. Dynamical modeling of ground-based and `STIS` spectroscopy provides evidence for black holes in all of them. More than half the determinations come from the long-running *HST* program by the Nuker team, and are based on edge-on axisymmetric models (Gebhardt et al. 2003). Additional cases can be found in the poster contributions (e.g., Cappellari, Cretton). The black hole masses usually lie in the range $5 \times 10^{7-8} M_\odot$, and may be accurate to 30% on average. The inferred internal orbital structure suggests tangential anisotropy near the black hole. This constrains black hole formation scenarios (Sigurdsson, Burkert). However, many of these objects display kinematic signatures of triaxiality, and surely not all of them are edge-on. This casts doubt on the accuracy of the individual masses. Application of the same modeling approach, but now for triaxial geometry, will show how severe these biases are. The machinery for doing this is now available (Verolme et al. 2003).

Detection of stellar kinematic evidence for black holes smaller than $5 \times 10^7 M_\odot$ in galaxies at the typical distance of Virgo requires higher spatial resolution than *HST* offers. Here other methods will be needed. The central surface brightness in the giant ellipticals is too low for the 2.4-m *HST* to provide spectroscopy of sufficient signal-to-noise ratio at high spatial resolution. They are prime targets for near-infrared integral field spectroscopy of the CO bandhead at 2.3 μm, with 8-m class telescopes.

1.2.4 Optical Emission Lines

The nuclei of active early-type galaxies, and those of most spirals, contain optical emission-line gas. Its kinematics can be used to constrain the central mass distribution, as long as the spatial resolution is sufficient to resolve the region where the gravity field of the black hole dominates the motions. It is important to account for the proper observational set-up. Maciejewski showed that not doing so can change an inferred black hole mass by a factor as large as 4! It is also important to confirm that the gas is in regular motion, by using an integral-field spectrograph, or by taking multiple parallel slits.

To date, the emission-line gas in about 100 nuclei has been observed with *HST*, for galaxies to distances of up to 100 Mpc (see contributions by Axon, Barth, Marconi, Sarzi, Verdoes Kleijn). Only $\sim$20% of these seem to have circular rotation, and so far only a few black hole masses derived in this way have been published, all of them larger than $\sim 10^7\,M_\odot$. NGC 3245 is a textbook example (Barth et al. 2001).

The accuracy of these black hole masses is not easy to establish. To date, there are very few cases for which a black hole mass has been determined by more than one independent method. While good results are claimed for NGC 4258 (stellar kinematics/maser emission—see below), the mass derived for the black hole in IC 1459 from gas motions is significantly lower than that derived from stellar motions. It will be very useful to carry out such comparisons for other nuclei, as this is the only way to put the masses determined by different methods onto the same scale, a prerequisite for an unbiased analysis of the black hole demography. It seems clear that the kinematic model of circular rotation for the gas is nearly always too simple. In many cases the gas velocity dispersion increases strongly inward. This is evidence for "turbulence," presumably caused by nongravitational motions, which probably include in/outflows, winds, and genuine turbulence in the gas near the central monster (similar to what is seen in the simulations reported by Wada). An improved (hydrodynamic) standard model for analysis of the gas motions would be very useful.

1.2.5 Masers in Seyferts and LINERs

VLBI measurements of H_2O maser emission allow probing the gas kinematics to very small scales, and have provided the cleanest extragalactic black hole mass determination, for NGC 4258. This method achieves the highest spatial resolution to date, but is possible only when the circumnuclear disk is nearly edge-on. A search of $\sim$700 nuclei has revealed maser emission in 21 additional cases, and regular kinematics on VLBI scales in four of these, to distances of up to 70 Mpc. The inferred black hole masses range from $(1-40)\times 10^6 M_\odot$. This mass range is currently very difficult to probe otherwise.

1.2.6 Reverberation Mapping

The observed time-variation of broad emission lines (e.g., Hβ) relative to the continuum in nearby Seyfert 1 nuclei and quasars can be used to estimate the radius of the spatially unresolved broad-line region by means of the light travel-time argument. In combination with simple kinematic models for the motion of the broad-line clouds, the observed width of the lines then provides a typical dispersion, so that an estimate of the mass of the central object responsible for these motions follows (Green, Peterson).

This is a powerful method in principle, as it allows probing nuclei out to significant distances. Early mass determinations appeared to be statistically systematically lower than those obtained by other means, but this discrepancy has now disappeared. However, there is not yet a truly independent calibration of the mass scale. The nearest well-studied case is too faint for obtaining, e.g., the resolved stellar kinematics of the nucleus, and for this reason the simple kinematic model is calibrated by requiring results to fit the local $M_\bullet - \sigma$ relation, so that the masses agree by definition. This makes reverberation mapping effectively a "secondary" mass indicator.

1.2.7 Line Widths

A number of contributions (e.g., Vestergaard, Kukula, Jarvis & McClure) advocated using the widths of the Hβ, Mg II, or C IV emission lines to estimate a velocity dispersion σ, and to infer a typical radius R from a locally observed correlation between luminosity and broad-line region size, so that a black hole mass follows. These authors set the overall scale by calibrating versus reverberation mapping masses, which in turn is calibrated by the local $M_\bullet - \sigma$ relation, making this a tertiary mass indicator, which may still contain significant systematic uncertainties. This approach is potentially very useful, as it can be applied even to the highest redshift quasars. The method suggests that some of the $z > 6$ quasars may contain $5 \times 10^9 M_\odot$ black holes. If true, this would require very rapid growth of any seed black hole to acquire so much mass at such early times. It will be very useful to calibrate this method more directly.

1.2.8 X-ray Emission

Recently, it has become possible to measure the profile of the Fe Kα line at 6.4 keV in the nuclei of Seyfert galaxies such as MCG-6-30-15 and NGC 3516. The early *ASCA* results have now been superseded by *XMM-Newton* spectra (Fabian et al. 2002). The data reduction effort is significant, but the asymmetric line profile shows a width of about 10^5 km s^{-1}, a sure sign that the emission must originate near 10 Schwarzschild radii of a (rotating) relativistic object. The radius where the emission originates is not measured independently, so these observations do not provide the mass of the black hole.

1.3 Black Hole Demography

1.3.1 $M_\bullet - \sigma$ Relation

Early attempts to relate measured black hole masses to global properties of the host galaxy focused on $M_\bullet$ versus bulge luminosity L_B (e.g., Kormendy & Richstone 1995). Following a suggestion by Avi Loeb, two groups showed that there is a tighter correlation between $M_\bullet$ and host galaxy velocity dispersion σ (Ferrarese & Merritt 2000; Gebhardt et al. 2000). This generated many follow-up papers either explaining the relation, or "predicting" it afterwards, and also sparked a remarkable (and sometimes even amusing) debate about the slope of the correlation, and the proper way to measure it (see Tremaine et al. 2002 for a recent summary, and contributions by Gebhardt, Kormendy, and Richstone).

We have seen that the black hole masses that form the foundation of the $M_\bullet - \sigma$ relation may still contain significant errors. The black hole masses for high-σ galaxies (giant ellipticals) generally rely on gas kinematics, and these should be treated with caution until we have independent measurements derived from stellar kinematics. Many of the available stellar dynamical measurements in E/S0 galaxies cover black hole masses in the range 5×10^7 to $5 \times 10^8 M_\odot$, but rely mostly on edge-on axisymmetric dynamical models. Many of the host galaxies show signs of triaxiality, which must cause considerable changes in the anisotropy of the orbital structure relative to that in an axisymmetric model. Depending on the direction of viewing, one might observe more or less of this anisotropy in the line-of-sight kinematics, and accordingly ascribe less or more of a higher central velocity dispersion to the presence of a black hole. This may be a significant effect for any given galaxy (Gerhard 1988). While the resulting shifts in black hole mass may tend to average out when observing a sample of galaxies with random orientations, there may still be residual systematic errors in $M_\bullet$ when derived with an axisymmetric model. If the distribution of intrinsic shapes of early-type galaxies varies with luminosity (or σ) then relying on axisymmetric models may introduce a bias in the slope of the $M_\bullet - \sigma$ relation.

The number of reliable black hole masses below $4 \times 10^7 M_\odot$ is still modest, especially for spiral galaxies. The expectation is that the spirals with classical spheroidal bulges should all contain a black hole, in agreement with the fact that a very large fraction of them also contains a low-luminosity active nucleus (Heckman, Ho, Sadler). The smallest reported black hole masses for spheroidal systems are those for the Galactic globular cluster M15 and for the M31 companion cluster G1. While both are consistent with an extrapolation of the $M_\bullet - \sigma$ relation to small σ, the mass determinations are not yet secure, in particular for M15.

In view of this, it seems to me premature to consider the $M_\bullet - \sigma$ relation ironclad over the entire range of $10^3 - 3 \times 10^9 M_\odot$, *and* valid for all Hubble types to all redshifts, as some speakers assumed, and as appears to have become almost universally accepted outside the immediate field. Rather than debating the details of finding the slope of the correlation, it seems more productive to measure more reliable black hole masses, and indeed to work out why this correlation should be there, especially if it were to extend all the way from giant ellipticals to globular clusters.

1.3.2 Galaxies with Pseudo-bulges

Many spiral galaxies do not have a classical $R^{1/4}$ spheroid, but instead contain a separate central component that has many properties resembling those of disks (Kormendy 1993; Carollo 1999), and is commonly referred to as a pseudo-bulge. Carollo reviewed recent work on these objects, based on large imaging surveys with *HST*. She showed that all pseudo-bulges in her sample contain nuclear star clusters that are barely resolved at *HST* resolution (e.g., Carollo et al. 2002). The example of M33 mentioned in the above suggests that these galaxies may not have a central black hole, consistent with the almost complete absence of emission-line signatures of activity (Heckman, Ho). The sole exception appears to be NGC 4945 which has a black hole mass based on maser emission. It will be very interesting to establish what the demography of black holes is in galaxies with pseudo-bulges. The presence of the tight central cluster will make it very difficult to measure central black hole masses by stellar dynamical methods.

1.3.3 Quasars

We heard much about recent work on quasars, driven by new and large samples, notably that provided by the Sloan Digital Sky Survey. This has produced accurate and detailed luminosity functions (Osmer, Fan), and also tightened the limits on the typical lifetime of the quasar phenomenon derived from the spectacular decline in numbers at redshifts below two, to $\sim 4 \times 10^7$ yr (Martini).

The $z > 6$ quasars seen in the Sloan Survey are interesting objects for a number of reasons. The most luminous of these demonstrate that the central black hole responsible for the observed activity must have grown about as fast as possible. The spectrum shortward of Lyα also provides evidence for a Gunn-Peterson trough, suggesting the tail end of reionization occurred a little above a redshift of six.

Many apparently conflicting opinions were stated on the nature of the host galaxies of quasars. Lacy, Kukula and Haehnelt argued that the high-z quasars are located in (boxy) ellipticals. Peng reported a mix of host galaxy types at $z \approx 1$, Heckman argued for "very luminous galaxies," and Scoville presented evidence that many of the nearest low-luminosity quasars reside in disks. This underlines the importance of careful sample definition and nomenclature before drawing strong conclusions on host-galaxy evolution with redshift.

A number of speakers revisited Sołtan's (1982) line of reasoning, and used recent data to work out the mean density in black holes versus the mean density in extragalactic background light. Fall derived that the quasar contribution is 1% of that of stars. The consensus value for the mean density of black holes is $\sim 2.5 \times 10^5 M_\odot$ Mpc^{-3}. This assumes an efficiency of about 0.1, and agrees with the local census in average value. However, the comparison of the quasar luminosity function and the current estimate of the local black hole mass function is less straightforward, and requires more work (Yu, Richstone).

Fabian addressed the possibility that the recent measurements of the X-ray background with *Chandra* and *XMM-Newton* indicate a black hole density a factor of 4 larger than the above estimate. This would either require a much-increased accretion efficiency (which seems hardly possible), or over two-thirds of the active nuclei being obscured. He however also presented evidence that the X-ray objects evolve differently with redshift than do the quasars, and in the end concluded (or, as some pointed out, recanted) that any discrepancy might be less than a factor of 2. In my primitive understanding of this issue this means that we are close to having the correct census of black holes in the Universe.

1.4 Black Hole Formation and Growth

Rees (1984) published a celebrated diagram illustrating that the formation of (seed) black holes early on during galaxy formation is essentially inevitable. Many of the processes he discussed were considered also during this conference.

1.4.1 Formation

Recent work on the formation of the first objects in the Universe suggests that the initial collapses occurred as early as $z \approx 20$. Whether these lead to mini-galaxies or mini-quasars is less clear (Haiman), but either way, the reionization of the Universe must have started about this time. The theorists seemed in agreement that most of the mass in the black holes that power the active nuclei must have grown from seeds formed around $z \approx 15$ (Phinney). Clarke argued for competitive accretion (by analogy with the normal star formation process), while others considered the collapse of a supermassive star to a Kerr black hole (Shapiro) and the dynamical evolution of dense stellar clusters (Freitag, Rasio). It is clear from the existence of the $z \approx 6$ quasars that whatever happened, the process was able to build black holes with masses larger than $10^9 M_\odot$ very quickly.

1.4.2 Adiabatic Growth

A number of speakers considered processes that cause (secular) growth and evolution of a central black hole, with as ultimate aim to deduce (or at least constrain) the formation history of the black hole from the observed morphology and kinematics of the host nucleus. Sigurdsson considered the problem of adiabatic growth through accretion of stars. This process is well understood in spherical geometry, and produces a power-law density profile with a range of slopes, as well as tangential orbital anisotropy near the black hole. However, the same observed properties can be produced by other formation mechanisms, such as violent relaxation around a pre-existing black hole (Stiavelli 1998). The problem of adiabatic growth in axisymmetric or triaxial geometry deserves more attention. There is a fairly wide-spread expectation of inside-out evolution of the shape toward a more nearly spherical geometry, but recent numerical work by, e.g., Holley-Bockelmann et al. (2002) suggests that this may not occur on interesting time scales. Construction of dynamical models of galaxies with measured black hole masses can provide significant constraints on the intrinsic shapes and orbital structure, and hence may shed further light on this problem.

1.4.3 Mergers, Binary Black Holes, and Gravitational Waves

In the currently popular scenario of hierarchical galaxy formation, the giant ellipticals with extended cores had their last major merger many Gyr ago, and since then accreted mostly small lumps. An infalling galaxy will lose its steep central cusp if the host contains a massive black hole. This tidally disrupts the cusp, and transforms it into a nuclear stellar disk of the kind seen by *HST* in nearby galaxies. The core itself was formed during the last major merger that presumably involved two cusped systems, each containing a black hole. Dynamical friction causes the black holes to form a binary, after which star-binary interactions remove many of the stars from the central region, generating an extended low-surface brightness core, or even a declining central luminosity profile (Lauer). The dynamical interactions harden the black hole binary, which eventually may reach the stage where gravitational radiation becomes effective so that rapid black hole coalescence follows (e.g., Begelman, Blandford & Rees 1980). Overall triaxiality of the host galaxy increases the black hole merging rate because a large fraction of stars are on orbits that bring them close to the center so that the binary evolution speeds up (e.g., Yu 2002).

Merritt and Milosavljević reported on recent progress in this area. No reliable *N*-body simulations of the complete process of formation of a core-galaxy via a binary black hole merger of two cusped systems are available yet, and not much is known about the expected shape of the resulting core, but this situation should change in the next few years. To date, it remains unclear whether black hole coalescence goes to completion in less than a Hubble time, or whether the binary stalls. If the process is slow, then binary black holes might be detectable with high spatial resolution spectroscopy in nearby systems such as Centaurus A, and they would provide a natural explanation for the twisted jets seen in some radio galaxies (Merritt & Ekers 2002). In this case repeated mergers will cause three-body interactions of the black holes, which may eject one of them from the galaxy altogether, and hence generate a population of free-floating massive black holes hurtling through space. If, on the other hand, black hole coalescence is fast, then giant ellipticals will contain a slowly rotating single black hole (Hughes & Blandford 2003), and many binary black hole mergers must have occurred in the past. A number of speakers discussed the exciting possibility of detecting the gravitational wave signature of these black hole mergers with LISA, the planned ESA/NASA space observatory to be launched in the next decade (Armitage, Backer, P. Bender, Phinney).

1.4.4 Fueling

The bulk of the fuel for the central engine that powers an active nucleus must be in gaseous form. While transporting gas inward to about 100 pc from the nucleus is fairly straightforward, it is not at all clear how to get it inside 1 pc. Shloshman, Frank & Begelman's (1990) bar-in-bar scenario has been updated, but observational evidence suggests that large-scale bars may not be very important for fueling. However, Emsellem presented intriguing kinematic evidence for inner density waves, perhaps related to central bars, which may hold the key to efficient gas transport into the nucleus.

Three-dimensional simulations of the structure of nuclear gas continue to improve. Wada showed a beautiful example in which the gas is turbulent and filamentary, but is in ordered motion with a significant velocity dispersion, in qualitative agreement with observations. The morphology of his simulated disk resembles that of the celebrated Hα disk in M87 (Ford et al. 1994). It will be interesting to see how well the kinematic properties compare. The turbulent filamentary structure in the simulated disk is caused by local energy input which corresponds to an assumed supernova rate of 1 per year. While this may be appropriate for the peak of activity in high-luminosity quasars, it is less evident that this would apply to, say, M87.

1.4.5 Accretion Physics and Feedback

Blandford reviewed recent progress in our understanding of accretion physics. The basic paradigm for an active nucleus—an accretion disk surrounding a supermassive black hole—has been agreed for over 30 years, but detailed models have been fiendishly difficult to construct as they require inclusion of a remarkable range of physical phenomena in the context of general relativistic magneto-hydrodynamics. The goal is to model the morphology and spectra of individual objects in detail, and to reproduce the full zoo of the AGN taxonomy, where inclination of the accretion disk to the line of sight, but also age and accretion mode are parameters that can be varied (e.g., Umemura). Theory has identified three viable modes of accretion. In the "low" mode, accretion is adiabatic. This is likely to apply to "inactive" nuclei (low-luminosity AGNs), including Sgr A* in our own Galaxy. The "intermediate" mode may apply to Seyferts (Heckman) and corresponds to the classical thin disk (Shakura & Sunyaev 1973), while the "high" mode is again adiabatic, and may be most relevant for obscured quasars. Amongst the adiabatic models much work has been done on advection-dominated accretion flows (Narayan & Yi 1994), which are radiatively inefficient. There is disagreement as to whether this ADAF model fits the spectrum of, e.g., Sgr A*. The theory of the more recent convection-dominated accretion flow (CDAF) variant is less well developed, and in particular the magneto-hydrodynamic flow in these models has not been worked out in full. The adiabatic inflow-outflow solution (ADIOS) of Blandford & Begelman (1999) was developed to overcome some of the difficulties encountered by the ADAF models, but more work on this is needed as well.

Begelman reminded us that much of the output of an active nucleus is in kinetic form (outflows, jets), which may inhibit accretion and affect the surroundings. Some of this feedback may be observable in radio galaxies, as episodic activity that he argued is buoyancy-driven, with the energy distributed by effervescent heating. It will be interesting to work out in more detail how feedback operates in the formation of the luminous high-z quasars. We have seen that these require rapid and efficient growth of their central supermassive black hole. It is likely that efficient cooling is required to bring in enough gas to grow the black hole efficiently. Statistical evidence from the Sloan Survey suggests that powerful active nuclei may be accompanied by a significant population of young and intermediate-age stars, and that the most powerful ones may well reside in massive young galaxies (Heckman, Kauffmann). The combined effects of feedback by the growing nucleus, and of the massive accompanying starburst, may well be reponsible for lifting the obscuration provided by the dust and gas revealing the quasar for all the Universe to see.

1.5 Black Holes and Galaxy Formation

It has been clear for some time that nuclear and global properties of galaxies correlate. This includes the correlation of cusp slope with total luminosity, the $M_\bullet - \sigma$ relation, and also the relation between $M_\bullet$ and the Sersic index n that characterizes the overall (rather than the central) luminosity profile (Graham, Erwin). Understanding these correlations, and establishing which of these is fundamental, is a key challenge for galaxy formation theories.

The current galaxy formation paradigm is based upon hierarchical merging, where the dark matter clumps through gravitational instability in the early Universe, after which the primordial gas settles in the resulting potential well, in the form of a disk, and starts forming stars. These produce heavier elements that they return to the gas at the end of their lives, so that subsequent generations of stars are increasingly metal rich. The proto-galactic disks experience frequent interactions, ranging from infall of smaller clumps that hardly disturb the disk to equal-mass mergers that result in a spheroidal galaxy, which may reacquire a stellar disk by further gas infall.

Somerville and Haehnelt suggested that during the first collapse, the low angular momentum material may already form a bulge, containing a black hole, and that its properties are related to those of the dark halo. In this view, the main disk would form/accrete later, and its properties may have little to do with the black hole, so that correlations between nuclear and global properties arise naturally for galaxies with classical bulges. The theorists have various scenarios to reproduce the $M_\bullet - \sigma$ relation. The models also predict the evolution of the black hole mass function, and could in principle provide the expected LISA signal for merging massive black holes once the vexing details of black hole binary coalescence have been sorted out.

The observed range of central cusp slopes in ellipticals, lenticulars, and classical spiral bulges is larger than predicted by simple adiabatic growth, but qualitatively consistent with successive merging of smaller cusped systems with their own black holes. It will be very interesting to compare detailed numerical simulations of this merging history with the internal orbital structure derived from dynamical modeling for individual galaxies. Burkert reported that the observed tangential orbital anisotropy is not (yet?) seen in his merger simulations.

This leaves the disk galaxies with pseudo-bulges, which show little evidence for nuclear activity. Could they have formed late, as a stable disk in an isolated dark halo, and without a central black hole? It has been argued that the pseudo-bulges might be the result of bar dissolution, but despite earlier reports to the contrary, stellar bars appear to be robust against dynamical evolution caused by a central "point mass," as long as its mass is as modest as that of the observed central star clusters (Carollo, Sellwood, Shen). Understanding the formation and subsequent internal evolution of these disks is an area that deserves much more attention.

1.6 Challenges

Rather than summarize this summary, or repeat suggestions for future work made in the above, I conclude by mentioning two areas where progress is most needed.

It will be very useful to measure more black hole masses, to (i) establish the local demography over the full mass range from globular clusters to giant ellipticals, (ii) settle whether or not the galaxies with pseudo-bulges contain central black holes, and (iii) calibrate the secondary and tertiary mass estimators that can then hopefully be used to estimate reliable black hole masses to high redshift. On the theoretical side, it will be interesting to see if the measured black hole masses can help pin down the models for the various active nuclei, e.g., to establish accretion mode and age.

Pressing projects related to galaxy formation include (i) establishing what are the fundamental parameters underlying the various correlations between global and nuclear properties of galaxies, (ii) understanding the evolution of the black hole mass function, from the formation of the first seed black holes to the present day, including the role of binaries, and (iii) working out where the galaxies with pseudo-bulges fit in.

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