PERSPECTIVES: ASTRONOMY (Submitted July 21, 2000 to *Science*)

MONSTERS AT THE HEART OF GALAXY FORMATION[1]

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Black holes with masses of $10^6 - 10^{9.5}$ solar masses ($M_\odot$) were invented in the 1960s to explain active galactic nuclei (AGNs) such as quasars (1 – 4). These supermassive black holes (BHs) stand in sharp contrast to ordinary black holes with masses of a few $M_\odot$ that are well known to form when massive stars die. Supermassive black holes are more mysterious. Their origin is unknown, and their existence was a hypothesis. But it was a very successful hypothesis, and by the mid-1980s, an enormously complicated AGN paradigm had been developed based on BH engines (5, 6). The most immediate need then was to test whether dynamical evidence of BHs could be found. In the following decade, much effort was invested in looking for dark objects in galactic nuclei (7, 8). The evidence for them is now strong, and in two objects – our Galaxy and NGC 4258 – the dark mass must live inside such a small radius that astrophysically plausible alternatives to a BH can be excluded (9). Still, the emphasis was on checking and further developing the AGN paradigm. That is, the subject had not progressed much beyond its roots. BHs were studied mainly to understand the spectacular but restricted phenomena of AGNs.

This situation is changing rapidly. Surveys with the *Hubble Space Telescope* (HST) are finding BHs in every galaxy that has an elliptical-galaxy-like "bulge" component (10). This strengthens hints from ground-based spectroscopy (11) that BHs are standard equipment in galaxy bulges. The observations imply that BH growth and galaxy formation are closely linked. The result is a profound change in how astronomers view BHs. More than just exotica needed to explain rare AGNs, they are becoming an integral part of our understanding of galaxy formation.

This change in perspective was much in evidence in an all-day session on BHs held on June 6, 2000, at the 196$^{\rm th}$ meeting of the American Astronomical Society. At least 15 new detections were reported, bringing the total number of BHs available for study to at least 34.

The big news at the meeting was a new correlation between BH mass $M_\bullet$ and host galaxy properties that was announced independently by Karl Gebhardt (12, 13) and by Laura Ferrarese (14) and collaborators. More massive BHs live in galaxies whose stars have larger random velocities σ. The figure shows this correlation together with an older correlation (15, 7) between BH mass and the total luminosity $L_{\rm bulge}$ – surrogate for total mass – of the bulge. More massive BHs live in more massive bulges. This is not surprising: many properties of astronomical objects scale with mass. In the present case, more massive galaxies are expected to have more fuel to feed BHs. But the scatter in the $M_\bullet - L_{\rm bulge}$ correlation is substantial, and a few galaxies stand out as having anomalously large or small BHs. Remarkably, the new correlation has essentially zero scatter. The figure shows all BH detections, but if the sample is restricted to the galaxies with the most accurate mass measurements, then the scatter is consistent with the error bars.

Tight correlations in astronomy have a history of leading to fundamental advances. In this case, the correlation implies a connection between galaxy formation and the process that feeds BHs, building them up to their present masses while making them shine as quasars. To be accreted onto a BH, fuel must be robbed of almost all of its angular momentum. This is difficult, so the process of "feeding the monster" is poorly understood (16). But tying BH growth to galaxy formation is useful progress. This is what the new correlation so nicely accomplishes.

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[1]Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, operated by AURA, Inc., under NASA contract NAS 5-26555

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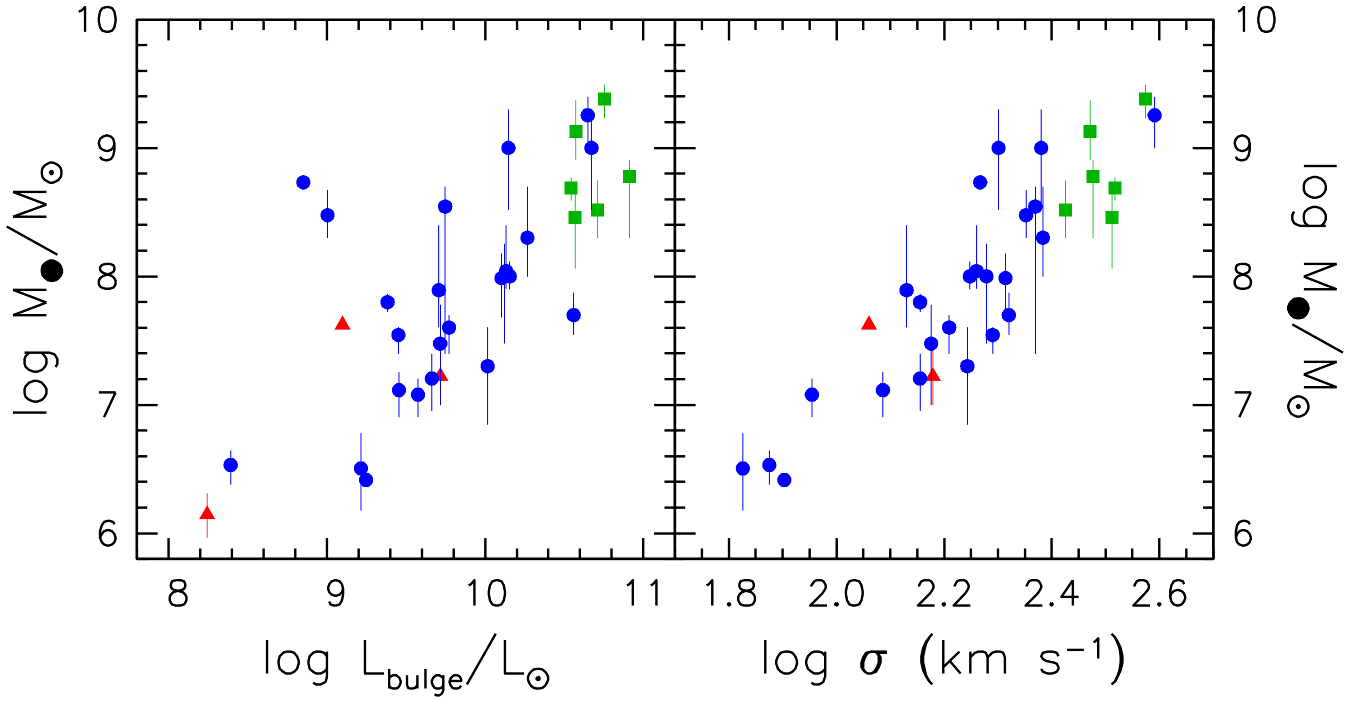
The argument is as follows (17). The two correlations in the figure are almost equivalent, because bulge mass is proportional to σ^2. But the $M_\bullet$ – σ correlation contains new information. BH mass is so closely connected with this new information that it fixes up the imperfect correlation with total mass and produces a correlation with σ that has almost no scatter. What is this new information? Why, when a BH is unusually massive for its luminosity, is it also high in σ, so that exceptions in the left panel of the figure are not exceptions in the right panel? There are several possibilities. The stellar mass-to-light ratio could be anomalously large; by the virial theorem, equilibrium demands more velocity for more mass. This proves not to be the main effect. Instead, bulges with unusually high velocity dispersions are unusually compact: they have higher surface brightnesses and smaller radii than normal for their luminosities. Then the stars are closer together, so their gravitational forces on each other are larger, so they must move faster. We conclude that, when a galaxy is hotter than average, it underwent more dissipation than average and collapsed inside its dark halo to a smaller size and higher density than average. But if BHs are unusually massive whenever their bulges are unusually collapsed, then this strongly suggests that BH masses were determined by the bulge formation process.

In sharp contrast to their correlations with bulge properties, BHs do not correlate with galaxy disks. Pure disk galaxies – ones that lack a bulge component – must have BH mass fractions that are much smaller than the canonical 0.2 % that is implied by the $M_\bullet$ – $L_{\rm bulge}$ correlation. The best studied pure disk galaxy is our neighbor in the Local Group of galaxies, Messier 33. If disks contained BHs like bulges do, then M 33 should have a black hole of mass $M_\bullet \sim 3 \times 10^7\ M_\odot$. But



Correlations of BH mass with properties of the bulge component of the host galaxy, i. e., (left) total luminosity in units of the luminosity of the sun and (right) mean velocity dispersion σ inside the radius r_e that contains half of the light of the bulge (13, 17). It is important that the radius used be large enough so that σ is not inflated by the BH. Apart from this, the dispersion could be averaged in radii that are substantially larger or smaller than r_e without affecting the results. In both panels, filled circles indicate $M_\bullet$ measurements based on stellar dynamics, squares are based on ionized gas dynamics, and triangles are based on maser disk dynamics. Note that exceptions to the $M_\bullet$ – $L_{\rm bulge}$ correlation are not exceptions to the $M_\bullet$ – σ correlation.

HST spectroscopy shows that it cannot contain a BH more massive than 2000 $M_\odot$. So BH growth is connected only with the process that forms bulges.

Bulges and elliptical galaxies (i. e., diskless bulges) form when galaxies collide and merge in a hierarchically clustering universe. Gravitational violence during mergers mixes orbits and redistributes energies and angular momenta; the result is that quiescently formed systems such as disks are turned into ellipsoids. At least in the nearby universe, gas dissipation is required to produce the high densities observed in bulges out of the low densities in disks. The new results on BHs suggest that the major events that form a bulge and the major growth phases of its BH – when it shone as an AGN – were the same events. The likely formation process is a series of dissipative mergers that fuel both starbursts and AGN activity.

The exact relationship between BH growth and bulge formation is not known. Some authors have suggested that BH growth happens before galaxy formation. For example, Silk and Rees (18) explore the idea that giant black holes come first and then regulate how much galaxy can form around them via the radiation pressure and gas outflows from the AGN. We also know that some BH mass is accreted after galaxy formation, because we observe low-level AGN activity in some old galaxies. What fraction of the mass is accreted before, during, and after galaxy formation is likely to be a subject of debate in the years to come.

However, a clear observational guide is provided by our best examples in the local universe of the formation of giant ellipticals. These are "ultraluminous infrared galaxies" or ULIRGs; i. e., infrared-bright galaxies with luminosities $L \gtrsim 10^{12}\ L_\odot$. They are known to be mergers in progress that involve large-scale dissipative collapse. Sanders *et al.* (19, 20) have suggested that ULIRGs are quasars in formation. This idea led to a decade-long debate about whether ULIRGs are powered by active nuclei or by starbursts. Observations now suggest that both sides are correct: about 2/3 of the energy comes from starbursts and about 1/3 comes from nuclear activity (21, 22). In addition, submillimeter observations are finding high-redshift versions of ULIRGs from the quasar era (23). Again, many show AGN activity. ULIRG properties are entirely consistent with the suggestion that bulge formation, BH growth, and quasar activity all happen together.

Black holes affect galaxy formation in other ways, too. For example, some ellipticals have "cuspy cores", i. e., density distributions that break at small radii from steep outer power laws to shallow inner power laws. Faber *et al.* (24) suggest that these cores may be produced via the orbital decay of binary BHs. When two galaxies merge, their BHs form a binary once violent relaxation has finished making an elliptical. After that, the BHs sink toward the center by flinging stars away. This reduces the stellar density and may produce a break in the density profile.

Another possible way to make cores involves energy feedback from AGNs (18). If BHs are fed by the same dissipative collapse that makes bulges, then the resulting AGN is easily energetic enough to affect the gas that is trying to collapse toward the BH. It may prevent enough collapse to produce the deficit of stars that we see as the core.

Neither process is well studied, and neither is known to be the correct explanation of cores. But both are examples of how BHs may be a necessary ingredient in our understanding of galaxy formation. The developing interconnection between BHs and other work on galaxy formation is one reason why the combined picture is compelling.

Further progress is likely to be rapid. We have just entered one of the major payoff periods of the *Hubble Space Telescope*. The search for supermassive black holes was always a major goal of the telescope. Since the 1997 installation of the Space Telescope Imaging Spectrograph (STIS), the search has become much more efficient, because STIS samples light from a one-dimensional slit rather than from a single aperture. Many groups are conducting BH surveys. The next few years should produce more detections than we have had in the past 15 years of the BH search.

I thank the Nuker team (D. Richstone, PI) for many years of fruitful collaboration and stimulating discussion of the above topics. The Nuker team is supported by HST data analysis funds through grants GO-02600.01-87A and GO-07388.01-96A.

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