IKKβ in epithelial cells (*7*). Neish *et al.* now show that nonpathogenic bacteria have also evolved ways to interfere with NF-κB activation. These investigators took advantage of a cultured cell line derived from a human colon cancer that has most of the features of normal colon epithelium. When they added nonpathogenic (commensal) *Salmonella* to the apical surface of this cell layer, they found that the bacteria prevented ubiquitination and hence degradation of phosphorylated IκB; NF-κB remained bound to IκB in the cytoplasm, and so the genes encoding inflammatory cytokines were not switched on (see the figure). The observations of Neish *et al.* need to be confirmed in vivo and the bacterial products that prevent ubiquitination of IκB identified. Future studies should also address how the default "no NF-κB activation" state maintained by nonpathogenic bacteria is overridden so that the gut epithelium is able to mount an immune response against pathogenic bacteria.

What is the physiological significance of the effect of commensal bacteria on NF-κB activation? Two recent reports suggest that oral administration of nonpathogenic bacteria (probiotics) may be effective in the treatment of some patients with inflammatory bowel disease (*8*, *9*). Although the way in which probiotics work is largely unknown, these bacterial species may also be able to abrogate NF-κB activation and quell the host's inflammatory response. A better understanding of how the normal gut microflora remains largely invisible to the host intestinal epithelium may provide a clearer picture of the molecular pathways of chronic inflammation. Indeed, dysregulated interactions between microbe and host might underlie many of the poorly understood chronic inflammatory disorders of the gastrointestinal tract.


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PERSPECTIVES: ASTRONOMY

# Monsters at the Heart of Galaxy Formation


**John Kormendy**


Black holes $10^6$ to $10^{9.5}$ times as massive as the sun were first invoked in the 1960s to explain the enormous energy output of active galactic nuclei (AGNs) such as quasars (*1–4*). These supermassive black holes (BHs) stand in sharp contrast to ordinary BHs, which have masses of only a few solar masses ($M_\odot$) and which are well known to form when massive stars die. The origin of supermassive BHs is unknown, and their existence long remained a hypothesis. By the mid-1980s, BH "engines" had become part of the theoretical framework for understanding AGN activity (*5*, *6*), but evidence for their existence was still lacking. In the following decade, much effort was invested in looking for dynamical evidence of dark objects in galactic nuclei (*7*, *8*). That evidence 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*).


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Until recently, BHs were studied mainly to understand the spectacular but restricted phenomena of AGNs. But the 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*, *11*). These observations strengthen hints from ground-based spectroscopy (*12*) that BHs are standard equipment in galaxy bulges. They indicate that BH growth and galaxy formation are closely linked. These results have profoundly changed astronomers' views of BHs: More than just exotica needed to explain rare AGNs, BHs 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 6 June 2000 at the 196th meeting of the American Astronomical Society. Detections of at least 15 new BHs were reported, bringing the total number available for study to at least 34. The big news was a new correlation between BH mass, $M_\bullet$, and host galaxy properties, announced independently by Karl Gebhardt and coworkers (*13*, *14*) and by Laura Ferrarese (*15*) and collaborators. Both groups have found that BHs are more massive in galaxies whose stars have larger random velocities σ (see the right panel of the figure). A similar correlation (*7*, *16*) was previously observed between BH mass and the total luminosity $L_{\rm bulge}$ of the bulge (a surrogate for its total mass): More massive BHs live in more massive bulges (see the left panel of the figure). This is not surprising because many properties of astronomical objects scale with mass and because 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 have anomalously large or small BHs. In contrast, the new correlation has essentially zero scatter. The figure shows all BHs detected to date. If the sample is restricted to the galaxies with the most accurate mass measurements, then the scatter in the right panel is consistent with the error bars.

In astronomy, tight correlations have a history of leading to fundamental advances. The correlation between $M_\bullet$ and σ 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 (*17*). But tying BH growth to galaxy formation is useful progress.

Why is a BH that is unusually massive for its luminosity 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 (*18*). For example, the stellar mass-to-light ratio could be anomalously large; equilibrium demands more velocity for more mass. This, however, proves not to be the main effect. Instead, bulges with unusually high velocity dispersions are observed to be unusually compact. That is, they have higher surface brightnesses and smaller radii than is normal for their luminosities. Therefore, the stars are closer together, so their gravitational forces on each other are larger and they must move faster. This means that when a galaxy is hotter than average, it has undergone more dissipation than average and has collapsed inside its dark halo to a smaller size and higher


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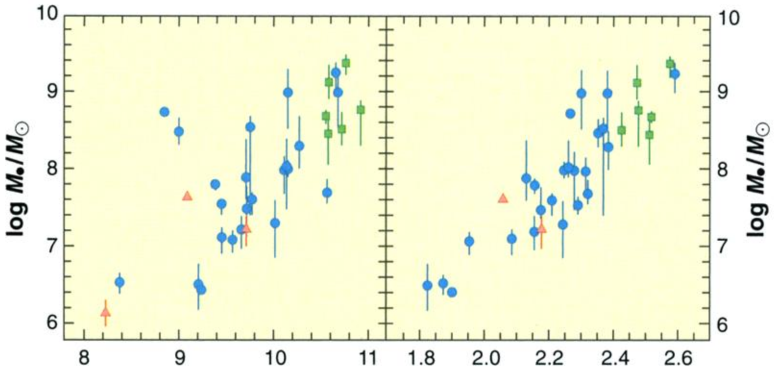


**Correlations of BH mass with properties of the bulge component of the host galaxy.** Correlation of BH mass with (**left**) total luminosity in units of the luminosity of the sun and (**right**) mean velocity dispersion σ in the main body of the galaxy (*14, 18*). In both panels, filled circles indicate $M_\bullet$ measurements based on stellar dynamics, squares are based on ionized gas dynamics, and triangles are based on maser disk dynamics. Exceptions to the $M_\bullet$-$L_{bulge}$ correlation are not exceptions to the $M_\bullet$-σ correlation.

density than average. But if BHs are unusually massive whenever their bulges are unusually collapsed, this strongly suggests that BH masses were determined by the bulge formation process.

In sharp contrast to bulges, the properties of disk galaxies do not correlate with BH masses. Pure disk galaxies (ones that lack a bulge component) must have BH mass fractions that are much smaller than the canonical 0.2% implied by the $M_\bullet$-$L_{bulge}$ 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 M33 should have a BH of mass $M_\bullet \sim 3 \times 10^7$ $M_\odot$. But HST spectroscopy shows that M33 cannot contain a BH more massive than 2000 $M_\odot$. BH growth is thus connected only with the process that forms bulges.

Bulges and elliptical galaxies (that is, diskless bulges) form when galaxies collide and merge. 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 suggest that the major events that form a bulge are the same as the major growth phases of its BH, when it shines as an AGN. 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 BHs grow before galaxy formation. For example, Silk and Rees (*19*) explore the idea that preexisting giant BHs regulate how large a galaxy can form around them through the radiation pressure and gas outflows from the AGN. We also know that some BH mass is accreted after galaxy formation, because low-level AGN activity has been observed in some old galaxies. How much of the mass is accreted before, during, and after galaxy formation remains to be seen.

However, observational guidance is already provided by the best studied examples of the formation of giant ellipticals in the local universe. These "ultraluminous infrared galaxies" (ULIRGs) are infrared-bright galaxies with luminosities $L \geq 10^{12}$ $L_\odot$. They are known to be mergers in progress that involve large-scale dissipative collapse. Sanders *et al.* (*20, 21*) 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 two-thirds of the energy that powers ULIRGs comes from starbursts, and the rest comes from nuclear activity (*22, 23*). High-redshift versions of ULIRGs have now been found in the quasar era (*24*). Again, many show AGN activity. ULIRG properties are entirely consistent with the suggestion that the same processes are responsible for bulge formation, BH growth, and quasar activity.

Black holes affect galaxy formation in other ways, too. For example, some ellipticals have a "core," which is a central region where the density gradient is much shallower than the steep power law observed at large radii. Faber *et al.* (*25*) suggest that these cores may be produced through orbital decay of binary BHs. When two galaxies merge, their BHs form a binary and then sink toward the center by flinging stars away. This reduces the stellar density and may produce a break in the density profile. Alternatively, cores may form through energy feedback from AGNs (*19*). 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.

We do not yet know whether one of these processes is the correct explanation of cores. However, in both of them, BHs are a necessary ingredient in our understanding of galaxy formation. This example illustrates the developing interconnection between BHs and galaxy formation that makes the combined picture so compelling.

Further progress is likely to be rapid. We have just entered one of the major payoff periods of the HST. Since the 1997 installation of the Space Telescope Imaging Spectrograph (STIS), the BH search has become much more efficient, because STIS samples light from a one-dimensional slit rather than from a single aperture. The next few years should produce more BH detections than we have had in the past 15 years.

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