THE CENTERS OF GALAXIES

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1. Introduction

This report has two major purposes. First, we summarize here work by our team on the determination of the density of stars near the centers of a large sample of galaxies observed with the Hubble Space Telescope. There appear to be two varieties of elliptical galaxies (and bulges). The stellar densities near the centers of small elliptical galaxies exceed those of globular clusters and the density of the universe at the recombination epoch. The radial dependence of density and implied gravitational force seems inconsistent (at least in the case of the smaller elliptical galaxies) with a long-lived triaxial configuration. It therefore seems likely that the central regions of less luminous elliptical galaxies are axisymmetric. For the more luminous ellipticals, the central densities are far more modest and the presence of a distinct core (defined below) is generally well established. Even in these

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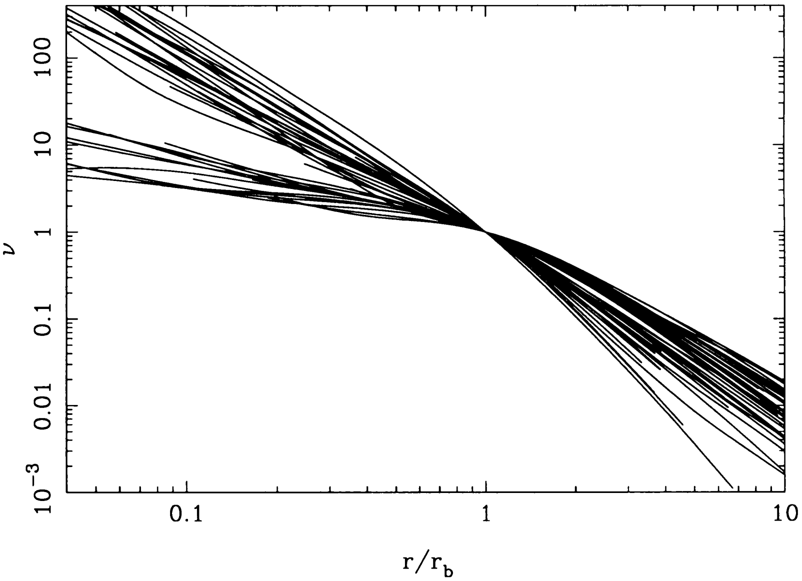
cases, however, we find few if any galaxies with analytic (Taylor expandable) stellar densities near the center.

Second, we discuss some of the recent results on the detection of massive black holes in the centers of galaxies. In our view, the presence of *massive dark objects* with only upper limits to their radii and without visible emission, is now well established. In the case of NGC 4258 alternative models involving clusters of faint or degenerate stars appear to be ruled out. In other important cases that goal remains elusive.

2. Light Profiles of Centers of "Hot" Stellar Systems

We begin with an illustration of the emissivity distribution $\nu(r)$ (or density of stars) near the centers of $\sim$ 60 ellipticals and S0 bulges based on Lucy-Richardson deconvolved images from the (optically uncorrected) Hubble Space Telescope (Figure 1). The reduction techniques are described in Lauer *et al.* 1995, Lauer *et al.* 1992a, and references cited therein. Most of the sample comes from Lauer *et al.* , although it has been enlarged as described in Gebhardt *et al.* 1996.



The stellar density ν shown in this figure has been deprojected from the observed surface brightness by the non-parametric technique of smoothing splines as described in Gebhardt *et al.* The galaxies have been superimposed by scaling both ν and r to unit density and length at the radius of maximum logarithmic curvature $dS/d\log r$ where $S = d\log\nu/d\log r$.

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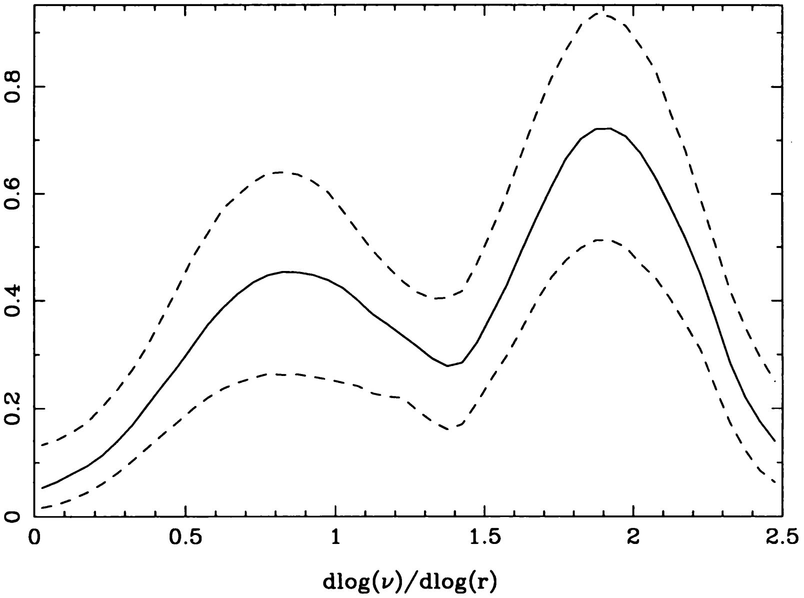
Two interesting results can be instantly seen in Figure 1. First, in no case does the best estimate of S reach zero at small radii (in all cases the density estimates are made only for $r \geq 0''.1$). Hence few if any of these objects can be approximated, even at HST resolution, by $\nu = A - Br^2$ near $r = 0$ and hence they are not *analytic cores* (Tremaine 1995). By contrast King models and nonsingular isothermal spheres (both sometimes used in the analysis of globular clusters — the primary subject of this book) do have analytic cores.



Second, considering only the light profiles inward from the position of maximum slope, these objects separate into two groups of galaxies. The distribution of logarithmic slopes at $0''.1$ from Gebhardt *et al.* supports this impression, at about the 2σ level (see Figure 2 above). The physical significance of this difference is buttressed by its correlation with properties of the main bodies of these galaxies including total luminosity, rotation (v/σ), and departures from elliptical isophotes (boxiness or diskiness). These relationships are discussed in detail in Faber *et al.* 1996. As an illustration of this point we display the relationship between the logarithmic slope at $0''.1$ and the galaxy (or bulge) magnitude from Gebhardt *et al.* (see Figure 3 overleaf). We advocate the use of the terms "core" and "power law" to describe these two kinds of galactic centers. The term "core" (borrowed from its earlier usage in connection with isothermal spheres and King models) here refers to the presence of a clear break in the density distribution seen in the left-hand group in Figure 2. The term "power law" emphasizes the

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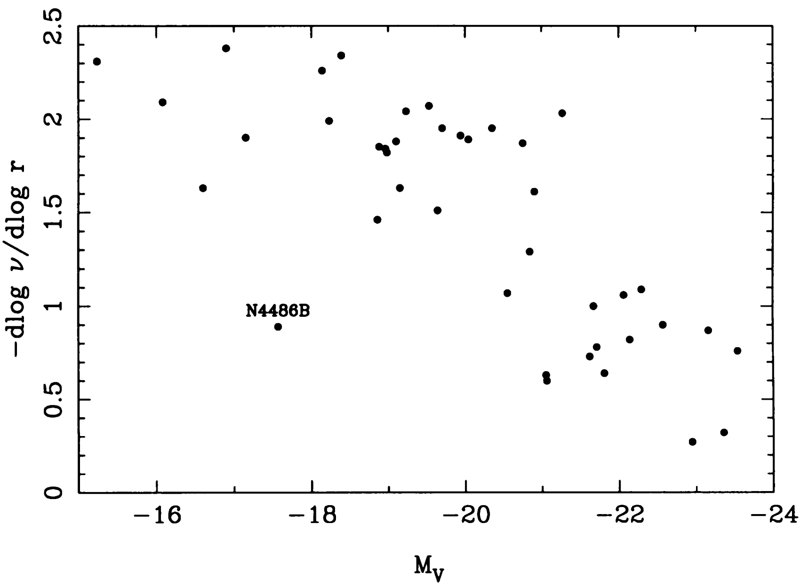
far less marked break in slope in the other group of galaxies. It remains to be seen, of course, whether the discovery of new objects will conform to this division into two clear groups, or will instead show that we have been overly impressed by extreme members of a continuous distribution.



These logarithmic slopes can be immediately compared to a recent study by Merritt and Fridman (1995) of the regularity of orbits in triaxial mass distributions. They show that in profiles with $\rho \propto r^{-2}$ there are insufficient regular box orbits (flattened in the same direction as the mass distribution) to create an equilibrium configuration. With milder density cusps ($\rho \propto r^{-1}$), the critically necessary box-like orbits are still chaotic, but they mimic regular behavior for a long time before mixing in phase space. Such galaxies may be in equilibria that last a substantial fraction of a Hubble time. While Merritt and Fridman's work only investigated two density profiles and one particular set of axial ratios, the results seem very likely to be generic. Using these results as a guide, it seems very likely that the steep profile (low luminosity) elliptical galaxies in our sample are not triaxial anywhere near the center (although, since many are known to rotate they are probably oblate).

In the case of the shallow profile (and high luminosity) galaxies the situation is more complex. Even though these ellipticals and bulges are slightly more shallow then $\rho \propto r^{-1}$ case investigated by Merritt and Fridman, they do not approach the analytic case that would correspond to a Stäckel potential where regular box orbits are known to exist. The presence

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of a massive dark object would further steepen the potential and accelerate the stochastic mixing of orbits in such a system. There appear to be two possibilities in this case. The galaxies may be evolving slowly under the influence of orbit diffusion, and may still be triaxial. Or they may be axisymmetric near the center.

In either profile family, it seems doubtful that experience gained from the analysis of orbits in static Stäckel potentials or of triaxial objects with analytic cores is likely to have much connection to the real galaxies illustrated in figures 1, 2 and 3.

3. Some Thoughts on Formation and Survival of Galaxy Centers

The comments above were based only on the profile shapes of the observed galaxies, but now we consider also the densities at $0\farcs1$, as illustrated in figure 4 overleaf (only objects with filled symbols are resolved). The object with the largest density is M32, which is also plotted as it would appear if observed at the distance of the Virgo cluster (the distance of most of the galaxies in the sample). Its position in the figure shows that there is every reason to believe that all of the low luminosity ellipticals reach that same stellar density of nearly $10^6 L_\odot \mathrm{pc}^{-3}$. Moreover, this is a luminosity density. Using a reasonable M/L of 2 and fitting a model to this object, Lauer *et al.* 1992b concluded that the M32 reaches densities of at least $10^7 M_\odot \mathrm{pc}^{-3}$. This mass density may be typical of low luminosity hot stellar systems and it exceeds the density of even the densest globular clusters (see Djorgovski 1993).

Taking $10^7 M_\odot \mathrm{pc}^{-3}$ as a useful fiducial number, we may compute the redshift at which the mean cosmic density of the universe was equal to this. That redshift is

$$1 + z = 3.3 \times 10^4 h^{-2/3} \Omega_0^{-1/3}, \tag{1}$$

an epoch before recombination, and even before matter domination! The first moment of matter domination occurs at $1 + z_{eq} = 2.3 \times 10^4 \Omega_0 h^2$ (Padmanabhan 1995).

Since galaxy scale fluctuations could not have grown at that time they must have formed later and at lower densities. It therefore seems probable that dissipational processes played an important role in the formation of the densest parts of these low luminosity galaxies.

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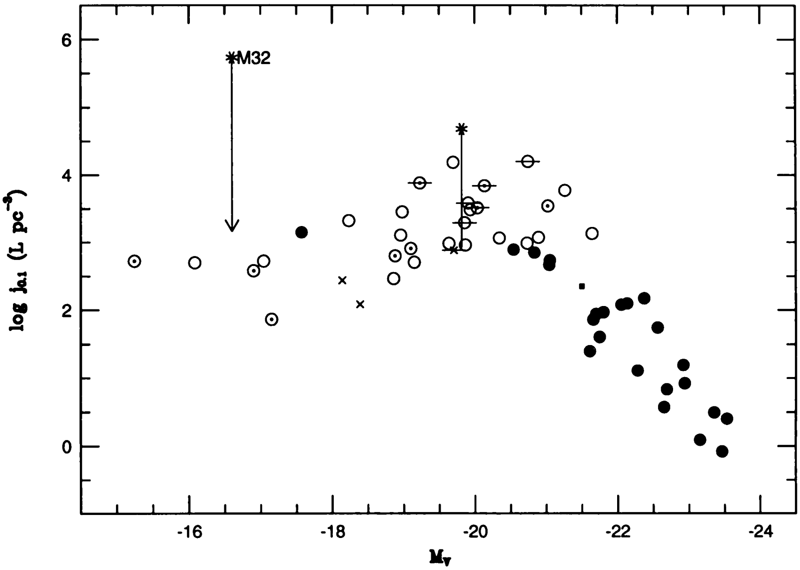

The low density centers of high luminosity galaxies offer a separate problem. It is well known that high luminosity galaxies accrete low luminosity galaxies, although the accretion rate is controversial. All of the low luminosity galaxies in our sample have high central densities and all of the quite high luminosity galaxies have very low densities, as much as six orders of magnitude smaller than M32. Since, during an accretion event the low luminosity objects never encounter tidal forces sufficient to destroy them, it is hard to understand the absence of M32-like nuclei in at least some of our luminous objects. Yet these are not seen. In cosmological simulations of formation of collisionless gravitating objects, (see, for example, Hernquist (1993) and Crone, Evrard and Richstone 1995), objects with well defined low density cores do not form because during the merger of small, dense objects with larger more diffuse ones there is quite incomplete energy redistribution among the particles. Hence, the most tightly bound subsystems retain their form, even when incorporated into much larger objects.

A possible resolution of this difficulty might be the presence of massive black holes in, at least, the more luminous ellipticals, which could provide the tidal forces necessary to disrupt the dense infalling dwarfs and scatter their stars over a large volume (and hence at low density). Although this explanation is consistent with all black hole detections in large ellipticals, it is nonetheless quite speculative.

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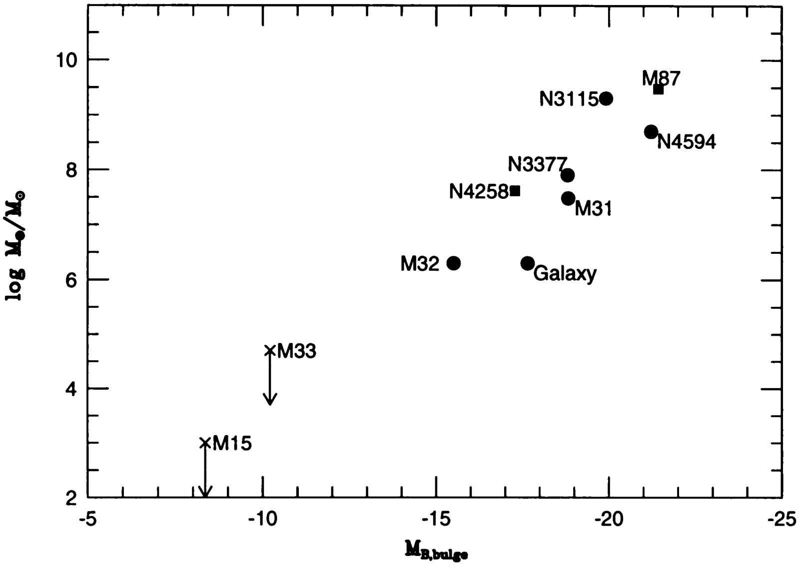
4. The Case for Massive Black Holes



Finally, we turn to the question of evidence for massive black holes in galactic nuclei. As summarized by Kormendy and Richstone (KR, 1995), there are now several secure cases of objects in the literature, illustrated in Figure 5, in which there is strong dynamical evidence for unseen mass (or a sharp rise in M/L) at the center of the galaxy and on a scale whose upper limit corresponds to the spatial resolution of the data. As noted by KR, the mass of these objects appears to be proportional to the luminosity of the elliptical galaxy or spiral bulge in which they are located.

The demonstration that these mass concentrations are in fact black holes could really only be achieved through the observation of relativistic velocities. Failing that, the elimination of alternative possibilities, as attempted in the case of M32 by Goodman and Lee 1989, Richstone, Bower and Dressler 1990, and Lauer *et al.* 1993b, would be useful. By far the most spectacular example of this approach was achieved in the case of NGC 4258 by Maoz 1995. NGC 4258 is observed to have maser emission features over a range of radii from 0.13 pc to 0.25 pc, with an apparently Keplerian velocity dependence (Miyoshi *et al.* 1995). The mass enclosed within .13pc is $3.6 \times 10^7 M_\odot$. Maoz was able to show that if the enclosed mass had been a cluster of stars of individual masses greater than $.03 M_\odot$, the cluster would have evaporated in less than a Hubble time (even if the objects were degenerate). If, on the other hand, the cluster was composed of stars of still lower mass, the physical collision/merger timescale would be exceedingly short and more massive objects would build up rapidly, either leading to a

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single object or to evaporation. Hence, a dark cluster of stars appears to be ruled out in the case of NGC 4258 and we are left with the prospect of a massive black hole or of something not yet invented.

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