THE STRUCTURE OF GALACTIC NUCLEI: RECENT OBSERVATIONS

S. M. Faber
Lick Observatory and Board of Studies in Astronomy and
Astrophysics, University of California, Santa Cruz

1. INTRODUCTION

Nuclei are often envisioned as sites for energetic and explosive phenomena in galaxies and may even be the birthplaces of quasars. Regardless of what models are chosen to represent such sources, a knowledge of the surrounding mass density and gravitational potential field is bound to be important for the creation and maintenance of the central engine. Moreover, galactic nuclei are worthy of close scrutiny even for their own sake. They constitute the brightest, most easily observed portions of galaxies and, in ellipticals, yield the central mass-to-light ratio, a quantity which cannot be determined for ellipticals using the ordinary rotation-curve method.

2. THE USUAL PICTURE: QUASI-ISOTHERMAL CORES

In the usual approach, galaxy nuclei are imagined to be rather like star clusters, having quasi-isothermal cores in which the velocity dispersion is virtually constant and the space density and surface-brightness profiles flatten out near the center. A family of such models, originally devised by King (1966) to fit star clusters, has been fitted to elliptical galaxies by King (1978) and Kormendy (1977). Near the center, the surface brightness I of these models is closely approximated by:

$$I = \frac{I_o}{1 + (r/r_c)^2} , \qquad (1)$$

The characteristic scale-length r_c is called the core radius. King and Kormendy determined values of I_o and r_c for 20 E and S0 galaxies by fitting to surface-brightness profiles measured by King (1978). Core radii ranged between 200 and 1000 pc and central surface brightness between 16.0 and 18.5 B magnitudes arcsec^{-2}, implying core densities from 15 to 100 $M_\odot$ pc^{-3}. No corrections for broadening of the luminosity profile due to seeing were applied.

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 135–142.

Core parameters like these were used by Faber and Jackson (1976) and by Schechter and Gunn (1979) to derive central blue mass-to-light ratios. The resultant values of M/L_B were remarkably uniform, ranging from 5 to 12 with a mean of ~ 9 (H_o = 50 km s^{-1} Mpc^{-1}). Faber and Jackson believed they detected an increase in M/L_B with absolute magnitude of the galaxy, whereas Schechter and Gunn saw no evidence for such a variation. Observations of more galaxies are required to settle this question.

3. DEPARTURES FROM QUASI-ISOTHERMAL CORES: CENTRAL MASS CONDENSATIONS

King (1978) has remarked that several galaxies studied by him are not well fitted by King models. In most of these objects, the core profile never completely flattens out near the center, and the turnover region near r_c is too broad to be fit by the rather sharp knee of a quasi-isothermal model. Let us assume that these departures from the isothermal model in the luminosity profile signify real departures in the mass density profile as well. We then conclude that near the center there is more mass interior to a given radius than the isothermal model would predict. In other words, M/L must increase near the center.

Just such an effect has been discovered in the luminosity profile of M87 by Young, Sargent, and co-workers (Young et al. 1978) and has since been confirmed by de Vaucouleurs and Nieto (1979). Young et al. were able to model the profile to high accuracy by adding a central point mass of 3 x $10^9 M_\odot$ to a quasi-isothermal core. In a companion paper, Sargent et al. (1978) analyzed the stellar velocity dispersion as a function of radius and showed that it increased markedly toward the nucleus (Fig. 1), again consistent with a central mass of a few times $10^9 M_\odot$. Limited by the seeing disk, Sargent et al. could estimate only that the central body is less than or equal to 110 pc in radius (at an assumed distance of 15 Mpc). However, in view of the presence of the jet and the nuclear activity in M87, it was natural to speculate that the mass is in fact a black hole which powers the non-thermal central source.

De Vaucouleurs and Capaccioli (1979) analyzed the light profile of the normal elliptical NGC 3379 and concluded that it, too, has excess light in the core relative to the quasi-isothermal model. NGC 3379 is much more difficult to study than M87 because its apparent King core radius is only 2$''$.8, much smaller than the 10" core radius of M87, in which the anomalous light distribution can be clearly resolved. Without correction for seeing, the core profile of NGC 3379 appears nicely isothermal, but de Vaucouleurs and Capaccioli believe that this is a fortuitous coincidence due to the severe broadening effects of image blurring. They successfully fit a de Vaucouleurs (1948, 1953) law:

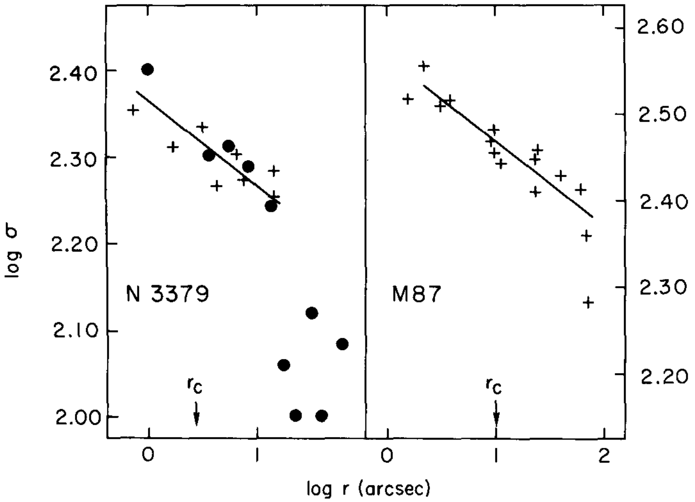

Figure 1. Radial trends in the velocity dispersion in NGC 3379 and M87. Dots: Davies (1978). Crosses: Sargent et al. (1978). The straight lines are drawn by eye and have identical slope.

$$\log(I/I_o) = -3.33\ [(r/r_o)^{1/4} - 1] \tag{2}$$

to the outer parts of the galaxy and argue that the same law fits the inner regions as well if seeing is allowed for. The de Vaucouleurs law cannot be valid at infinitely small radii since it predicts infinite central density. However, de Vaucouleurs and Capaccioli believe it could be valid well within the apparent core radius. The de Vaucouleurs law indicates an excess central cusp in luminosity relative to the best-fitting quasi-isothermal model.

Illingworth (private communication) has pointed out that the radial fall-off of the velocity dispersion in NGC 3379 appears quite similar to the fall-off seen in M87 if the two galaxies are compared in log-log coordinates (Fig. 1). This trend in dispersion might indicate a concentrated central mass, as in M87. NGC 3379 was one of the comparison galaxies to M87 analyzed by Young, Sargent, and co-workers, who found no central increase in M/L. However, the primary driver in M/L is the shape of the luminosity profile, and Kormendy's (1977) profile was used with apparently no allowance for seeing affects.

In summary, a substantial nuclear mass concentration over and above that predicted by the best-fitting isothermal model has been detected with certainty in the obviously peculiar elliptical M87. Considerable evidence suggests a similar concentration of mass in the otherwise totally normal elliptical NGC 3379. Furthermore, Davies (1978) has observed increases in the velocity dispersions near the nuclei of two other elliptical galaxies, indicating that nuclear mass concentrations may not be uncommon.

4. BROADENING BY SEEING

Schweizer (1979) expresses the view that nearly all of King's profiles are badly broadened by seeing and that the core characteristics inferred from them are therefore significantly in error. For sake of argument, he assumes the profiles to be de Vaucouleurs laws at all radii, convolves them with appropriate stellar broadening functions, and determines the apparent core radius, $r_{c,\ G+E}$, of the broadened profile. For many of King's galaxies, $r_{c,\ G+E}$ is only slightly smaller than the core radii of the observed profiles, as determined by King and Kormendy. Furthermore, NGC 4406, which had been badly fit by the quasi-isothermal model, agrees nicely with a broadened de Vaucouleurs law. Schweizer concludes that the de Vaucouleurs law could well hold inside the nominal core radii of many of these supposedly resolved ellipticals. Furthermore, for the nearby galaxies M32 and M31, he finds lower limits on the central stellar density of 3×10^5 and 10^6 $M_\odot$ pc^{-3} respectively, values which are 10^3 - 10^4 times higher than the central densities of more distant ellipticals found from the King and Kormendy core parameters (§2). He suggests that similar high-density cores could be present in the ellipticals as well but that they are hidden inside the seeing disk.

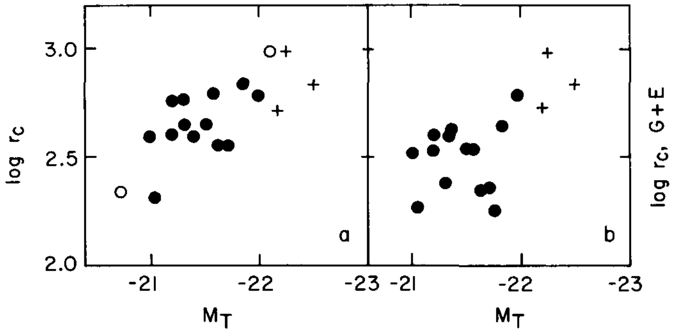

Figure 2. a) Core radii determined by Kormendy (1977) for King's (1978) ellipticals, versus absolute magnitude. b) Dots: core radii of seeing-convolved de Vaucouleurs profiles, as calculated by Schweizer for the galaxies represented by dots in a). Crosses: clearly revolved cores, for which Kormendy's radii are repeated. Schweizer radii for open circles in a) are not available and thus are not repeated in b). See text for further explanation.

Two arguments based on plausibility have been raised against the de Vaucouleurs law and in support of the quasi-isothermal model. Several workers have noted that the King and Kormendy core radii correlate well with other independently measured variables, notably central velocity dispersion and absolute magnitude (e.g., Fig. 2a). It would therefore appear at first sight that r_c must measure some physically meaningful parameter. However, these correlations might have arisen spuriously due to selection effects in the sample because smaller galaxies are most affected by seeing. This fact is illustrated graphically in Fig. 2b, where Schweizer's $r_{c,\ G+E}$ are plotted instead of r_c for all galaxies except the three most luminous objects, which all parties agree have been clearly resolved. (These three are indicated by crosses.) Since the smaller galaxies have small $r_{c,\ G+E}$ set by the seeing, a correlation nearly as convincing as that in Fig. 2a emerges.

Because the three most luminous galaxies have quasi-isothermal cores (setting aside for the moment the point mass in M87), economy of hypotheses might suggest that the smaller galaxies are also quasi-isothermal but with smaller core radii. Schweizer counters this argument with the fact that at least one very luminous elliptical, Fornax A, has an as-yet-unresolved core much smaller than any of these three and concludes that the total sample is still too small to allow any conclusions about correlations between core parameters and absolute magnitude. All in all, it would seem that the presence of at least some excess light and mass in the cores of even normal ellipticals is still an open question.

Binney (1979) has suggested that a measurement of the central velocity dispersion at high angular resolution could test whether de Vaucouleurs' law actually holds close to the center, since a decrease of 20-25% in the innermost velocity dispersion is predicted. NGC 3379 would be an excellent candidate to observe. The present angular resolution of 2"4 in the data of Sargent et al. (1978) is not quite adequate to reveal the effect, but a 1" measurement would provide a clear test.

Even if the quasi-isothermal model ultimately proves to be correct, Schweizer (1979) has shown that the raw core parameters of King and Kormendy require correction for seeing. For most galaxies, r_c has been overestimated by $\lesssim 25\%$ and I_o underestimated by a similar amount. However, for four objects the correction ranges between 50% and 100%. Curiously, even when broadening by seeing is severe, the quantity $I_o r_c$ remains nearly constant. Since M/L depends only on the product $I_o r_c$, the existing M/L estimates need virtually no revision even if based on uncorrected parameters, provided of course that the quasi-isothermal model holds.

5. OTHER RECENT OBSERVATIONS

Our remarks thus far have assumed that M/L for the stellar component is constant over the nuclear region and that the light distribution is therefore a good tracer for the mass density. From new measurements of the NaI 8190 absorption feature, Faber and French (1979) infer that the semi-stellar nucleus of M31 is enriched in M dwarfs relative to the bulge and that M/L_B is 3-4 times larger there than in the surrounding regions. Their suggestion is a revival of the original dwarf-rich population model of Spinrad and Taylor (1971), which they believe was never properly tested with observations at high enough angular resolution. Dwarf enrichment might resolve the longstanding puzzle of the large velocity dispersion in the nucleus relative to that in the bulge, which is impossible to model with constant M/L (Ruiz 1976). If M/L is allowed to vary, however, the nuclear structure is easy to account for. These results further suggest that the correspondence between light and mass in galactic nuclei may break down in some cases, even when purely stellar light and mass are involved.

Finally, it seems that a large fraction of the existing body of nuclear velocity dispersion measurements may be more homogeneous than has been thought (see Faber and Gallagher 1979 and references therein). R. L. Davies, R. Terlevich, D. Burstein and I have recently reanalyzed the luminosity-σ relation for elliptical and S0 galaxies. We include all velocities measured with the Fourier technique plus those of Faber and Jackson (1976). We find that the scatter in the L-σ relation is greatly reduced if "corrections" based on the nuclear metallicity are applied to the velocity dispersions. Fig. 3 shows the new relation between the corrected dispersions and luminosity, which is quite tight for the majority of galaxies. Systematic deviations of individual authors from the mean line in Fig. 3 are $\lesssim 5\%$, much smaller than had been suspected (e.g. Schechter and Gunn 1979).

Our corrections to σ are in turn related to the observed ellipticities in the sense that, at a given luminosity, flatter galaxies have lower dispersions and metallicities. A similar correlation between metallicity and ellipticity has also been discovered independently by van den Bergh (1979) and by G. Knapp and J. Cardelli (private communication). These new results suggest that ellipticity is in some sense a "second parameter" for elliptical galaxies, a fact potentially important to theories of galaxy formation.

6. SUMMARY

In this review, I have scarcely mentioned spiral nuclei, about which little is known. Even for ellipticals, the discussion in the literature and recent preprints suggests that the observational data are not yet adequate to establish the central run of luminosity and density with certainty. For the present, however, I find the

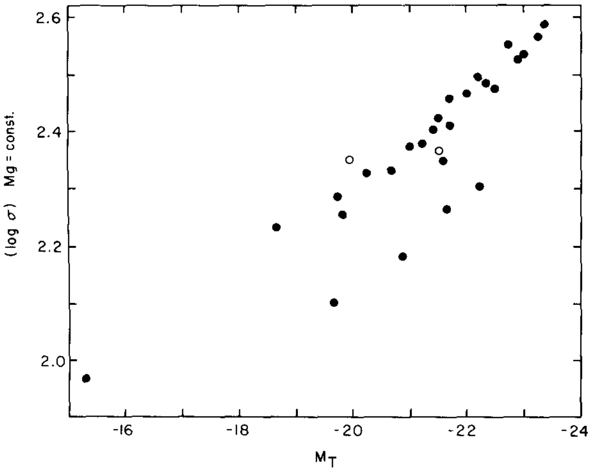

Figure 3. Velocity dispersions corrected to standard mean metallicity (Mg = const.), versus absolute magnitude. Deviant objects below mean line are NGC 720, 1052, 1172, and 1426. Dots: ellipticals. Open circles: S0's.

structure of the inner region of M31 appealing as a model for other galaxies. In M31, there exists a diffuse, quasi-isothermal bulge which, if viewed at the distance of Virgo*, would have a core radius of only 0.″6. Imbedded in this bulge, there is a second, denser, quasi-isothermal core (Light, Danielson, and Schwarzschild 1974), which is usually called the semi-stellar nucleus. Schweizer has shown that this entire structure would be indistinguishable from a de Vaucouleurs law convolved with the seeing when viewed at the distance of the Virgo cluster. Hence, if M31 is a valid model, the marginally resolved core radii in ellipticals represent diffuse bulge components. Semi-stellar nuclei within the bulges might then be the source of excess central light. This interpretation has also been put forward as one alternative by Schweizer.

If this picture holds, mass-to-light ratio estimates of elliptical bulges would remain substantially correct, but estimates of the innermost mass density and velocity dispersion could be seriously in error. At the very least, Schweizer's work has alerted us to the possibility of highly compact structures within nuclei, which can only be hinted at with ground-based techniques. Study of galactic nuclei is clearly one of the prime projects to be carried out with Space Telescope.

REFERENCES

Binney, J. 1979, preprint.
Davies, R. L. 1978, Ph.D. thesis, Cambridge University.
de Vaucouleurs, G. 1948, Ann. d'Ap., 11, 247.
de Vaucouleurs, G. 1953, M.N.R.A.S., 113, 134.
de Vaucouleurs, G., and Capaccioli, M. 1979, preprint.
de Vaucouleurs, G., and Nieto, J.-L. 1979, Ap. J., 230, 697.
Faber, S. M. and French, H. 1979, preprint.
Faber, S. M. and Gallagher, J. S. 1979, Ann. Rev. Astron. Ap. 17, in press.
Faber, S. M. and Jackson, R. E. 1976, Ap. J., 204, 668.
King, I. R. 1966, Astron. J., 71, 64.
King, I. R. 1978, Ap. J., 222, 1.
Kormendy, J. 1977, Ap. J., 218, 333.
Light, E. S., Danielson, R. E., and Schwarschild, M. 1974, Ap. J., 194, 257.
Ruiz, M. T. 1976, Ap. J., 207, 382.
Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R., and Hartwick, F. D. A. 1978, Ap. J., 221, 731.
Schechter, P. L., and Gunn, J. E. 1979, Ap. J., 229, 472.
Schweizer, F. 1979, preprint.
Spinrad, H., and Taylor, B. J. 1971, Ap. J. Suppl., 22, 445.
van den Bergh, S. 1979, Ap. J. Letters, 230, L161.
Young, P. S., Sargent, W. L. W., Boksenberg, A., Lynds, C. R., and Hartwick, F. D. A. 1978, Ap. J., 222, 450.