A Hole in the Hat or Evidence for a Black Hole in the Sombrero Galaxy?

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1. Introduction

Studies of the nuclei of normal galaxies have received renewed interest in the past few years partially due to new detector technology, particularly CCD's, used in both direct imaging and spectroscopic modes. This has led to the understanding that the nuclei of some of these galaxies are dynamically complex systems exhibiting unusual kinematic and photometric behaviour compared to the surrounding bulge. The most notable examples are M87 (eg. Sargent et al., 1978), M31 (eg. Kormendy, 1988) and M32 (Dressler and Richstone, 1987). High spatial resolution kinematic data of the nuclei of these galaxies revealed the presence of large increases in velocity dispersion and large velocity gradients over the central few arcseconds. Both of these studies concluded that a central black hole most adequately explained the very large increase in central mass-to-light ratio.

The likely presence of black holes in two of the closest galaxies with bulge-like components compels us to look at the nuclei of other nearby or large galaxies to see if they also show evidence for supermassive objects. We report here the initial results of new kinematic data for the major axis of NGC 4594 (M104) which are shown to have large kinematic similarities with those galaxies already believed to possess black holes.

2. Observations and Reduction Procedures

The long-slit spectroscopic data were obtained with the Boller and Chivens spectrograph attached to the 3.6-m telescope at La Silla, Chile. The detector was an RCA CCD (512 × 320 pixels) with pixel sizes of 1.74 Å by 1".17. We used a grating with a dispersion of 59 Å mm^{-1} which gave an instrumental dispersion of 60 km s^{-1} with a 2" slit. Our spectra covered about 900 Å centred on the Mg b absorption lines at 5175 Å. See Jarvis et al. (1988) for a more detailed description of the instrumental setup. We observed a total of 5 × 1,020 s (= 5,100 s) exposures with the slit aligned along the major axis of the galaxy passing through the nucleus at a position angle of 270°. The reduction and analysis followed now fairly standard procedures for this type of data and the reader is again referred to Jarvis et al. (1988) for details.

Our final absorption line velocity and dispersion data are shown in Figure 2. The major axis kinematic data obtained by Kormendy and Illingworth (1982; hereafter KI) are also plotted for comparison as open circles. In an attempt to preserve the signal-to-noise ratio of the data with increasing r, we have averaged together groups of adjacent rows in the outer parts of the galaxy. These are shown as horizontal bars in the figure.

3. Discussion

The first point to note is the overall excellent agreement between the independent data sets of KI and that of this paper. This was our original and only motivation for observing this galaxy, to check our reduction and analysis techniques against those of others before proceeding on another programme. We have arbitrarily assigned a radius of zero to the brightest row in our spectra which due to the large spatial scale of 1".17 $pixel^{-1}$ probably accounts for most of the difference between the velocity of the inner rotation peaks at $r \simeq \pm 15''$. Previous independent measurements of the central velocity dispersion of NGC 4594 range from 215 ± 35 km s^{-1} by Williams (1977) to 263 ± 32 km s^{-1} measured by Whitmore et al. (1979). In comparison, Schechter (1983) found 248 ± 29 km s^{1} and KI found 256 ± 22 km s^{-1}. Our final value of 249 ± 15 km s^{-1} is in good agreement with both these last measurements. In view of the rapid decrease of velocity dispersion within the central few arcseconds, it is apparent that the major sources of difference between the above measures are probably due to small centring errors of the spectrograph slit and seeing differences. We conclude, therefore, that our measurement of the central velocity dispersion is likely to be a lower limit due to our mediocre seeing, fairly large slit width and coarse spatial scale.

There appears to be at least two distinct dynamical components in both the rotation and dispersion profiles. It is clear that exterior to $|r| \simeq 15''$, where the bulge is dominating the observable light, we are measuring the rotational motion of the large spheroidal bulge component. Interior to $|r| \simeq 15''$, the situation is more complex. It appears that the kinematics are dominated by a rapidly rotating nucleus which has a fairly constant velocity gradient of 38 km s^{-1} $arcsec^{-1}$ for $|r| \leq 3''.5$. Additional information on the detailed shape of the nucleus requires kinematic data at different position angles.

The most striking feature of the velocity dispersion profile is the sharp increase in the central few arcseconds.

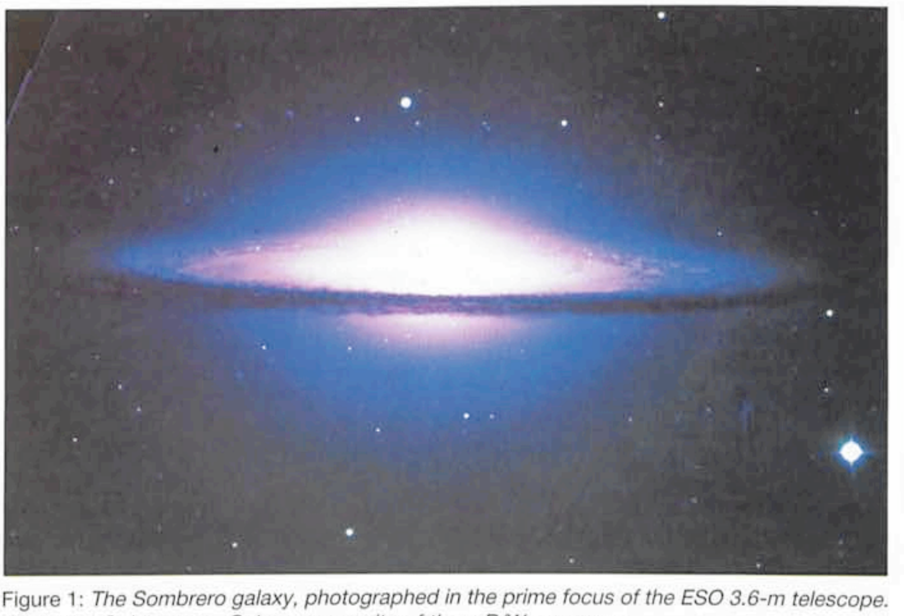

Figure 1: *The Sombrero galaxy, photographed in the prime focus of the ESO 3.6-m telescope. Observer: S. Laustsen. Colour composite of three B/W exposures.*

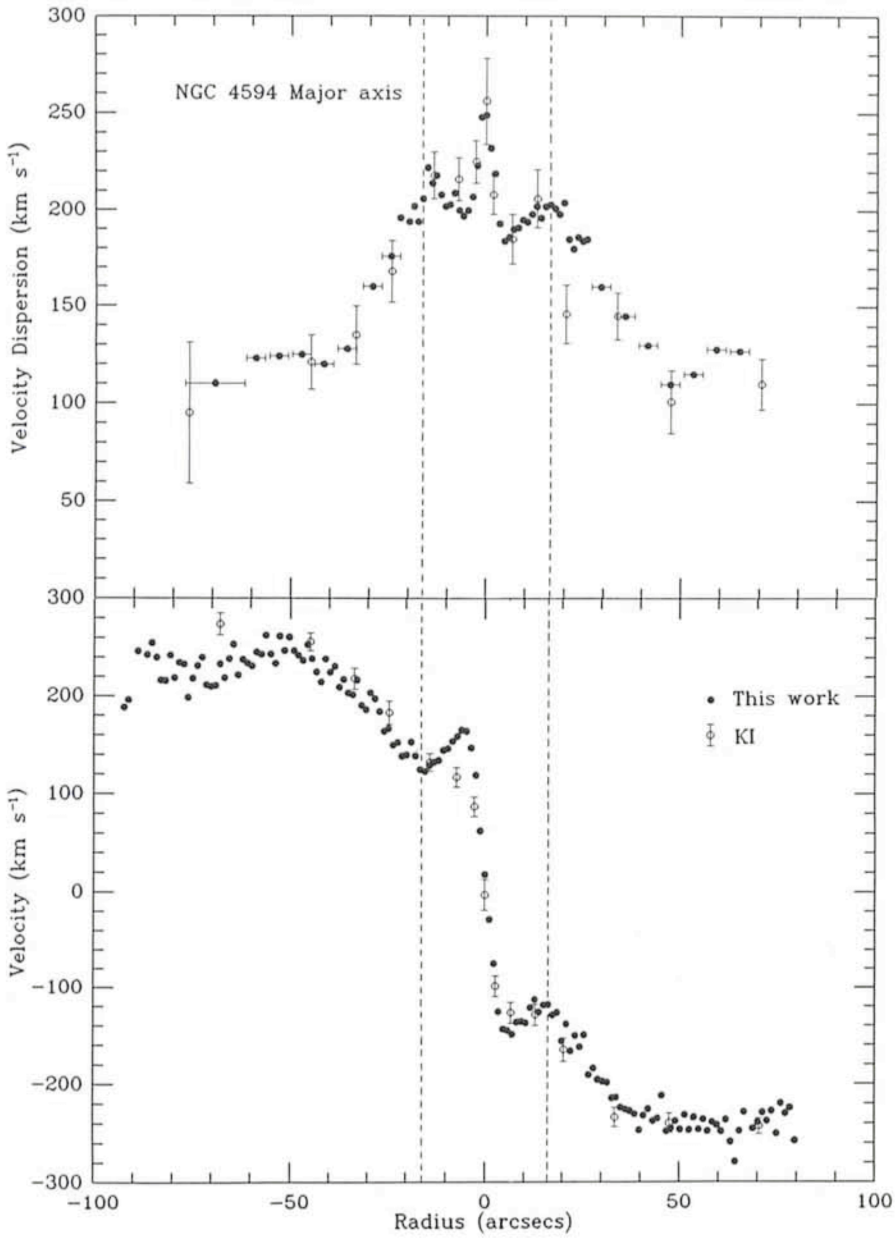

Figure 2: *Major axis rotation (lower panel) and velocity dispersion (upper panel) profiles for NGC 4594. Negative radii denote points east of the nucleus. Units of velocity and velocity dispersion are km s^{-1}. The horizontal bars in the dispersion profile show the extents of averaging adjacent rows to increase the signal-to-noise ratio. Overplotted as open points are the data from Kormendy and Illingworth (1982) for comparison.*

The dispersion rises by at least 65 km s^{-1} on the west side of the nucleus and 52 km s^{-1} on the east over a distance of about 4″.5, much wider than the seeing point-spread-function (PSF). Again, these are probably lower limits due to the finite seeing PSF and the fairly large slit width used. This rapid increase in dispersion is similar to what has been observed in M31 and M32 by Kormendy (1988), Dressler and Richstone (1988) and others. They concluded that the sharp increase in velocity dispersion and the large velocity gradient indicated a significant increase in M/L above that of the surrounding bulge. Moreover, for M31, Kormendy concluded that a central black hole as large as 10^7-10^8 $M_\odot$ was the most likely alternative although a very massive star cluster could not be completely ruled out. Little or no conclusive evidence exists for a corresponding sharp increase in the observed nuclear luminosity of NGC 4594. However, Burkhead (1986) visually observed a bright compact nucleus but this requires quantifying by observation in good seeing.

Unfortunately, a full and complete analysis of the data is hampered by the lack of a good measurement of the seeing during our observation, since there were no observable stars near the slit. However, we estimate that the seeing was between 1″.2 and 1″.5 based on reports from other telescopes on La Silla observing at the same time. Some simple experiments involving the convolution of infinitely sharp jumps in simulated rotation profiles with the seeing PSF showed that the observed velocity gradient is not significantly affected by the seeing but more likely due to the low spatial resolution of the instrument (1″.17 pixel^{-1}) and the relatively large slit-width. Again, we stress that no attempt was made to optimize the instrumental setup for high spatial resolution observations.

An estimate of the total mass inside a radius r can be calculated from the Vlasov equation,

$$M(r) = \frac{V^2 r}{G} - \frac{r^2}{\varrho G} \frac{d}{dr} (\varrho \sigma^2)$$

where ϱ is the stellar volume density, V is the rotation velocity, σ is the radial component of the velocity dispersion and G is the gravitational constant. If we assume that the mass distribution is spherical, the mean rotation is circular and the stellar motions are isothermally distributed, then this equation yields a total mass of about 1.3×10^9 $M_\odot$ within r = 3″.5 of the centre for an assumed distance of 18.2 Mpc (Schweizer, 1978). This mass is at least an order of magnitude greater than that observed in M31 (Kormendy, 1988).

What is the true nature of the central mass concentration? A detailed discussion of this is beyond the scope of this note. The two most likely candidates are a massive black hole or massive star-cluster like object. A mass of 1.3×10^9 $M_\odot$ contained within 3″.5 of the centre of NGC 4594 implies an average density of only 10 $M_\odot$ pc^{-3} at a distance of 18.2 Mpc. Such densities are still consistent with globular cluster like systems. A massive star cluster may be revealed through a colour change or an observable change in the line strength in the nuclear spectrum. A small colour change has already been observed (Burkhead, 1986) but the true magnitude of which must wait for higher resolution data. However, the formation processes of such systems with the required mass remain uncertain. Secondly, if the stars in this cluster are akin to those in globular clusters of our own galaxy, we would expect to see a significant light cusp at the centre of NGC 4594. If future high resolution surface photometry does not reveal such an increase, then this mass must reside within objects of high M/L. A system of degenerate stellar remnants or a black hole would therefore be the most likely candidates. Further constraints on the true nature of the central mass concentration in NGC 4594 must await the availability of more suitable high resolution photometric and kinematic data.

4. Conclusions

The major new finding of this study is the discovery of a large mass concentration at the centre of NGC 4594. Our strongest evidence is the detection of a sharp rise in the observed velocity dispersion of at least 59 km s^{-1} within the central 3″.5, although this is probably a lower limit. Under the assumption of spherical symmetry and an isotropic velocity distribution, the mass contained within r = 3″.5 of the centre of NGC 4594 is $M \simeq 1.3 \times 10^9 M_\odot$. Higher spatial resolution kinematic and surface photometry of the nuclear region of NGC 4594 in good seeing are urgently needed to put new constraints on this problem.

Acknowledgements

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Physical Studies of Asteroids

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Introduction

Photometric and spectroscopic observations of asteroids give important information on the physical properties of these bodies and increase our understanding of the origin and evolution of the asteroids. The 50-cm, 1-m and 1.5-m telescopes and the Schmidt telescope at ESO, Chile, have for almost ten years been used by us for such observations. These observations have so far resulted in more than 20 scientific papers. References to these may be found in (1). Here only a short summary of these results will be given.

Spin Properties of Asteroids

The ESO 50-cm telescope has been used for UBV and UBVRI photometry of asteroids with the intention of deriving lightcurves and broadband colours. These lightcurves give information about spin rates, and the lightcurve amplitudes give a hint of the asteroidal shapes. The study of colours and magnitudes as a function of solar phase angle (phase curve) give important constraints to the light scattering properties of the surface material. One night or a few consecutive nights of observations usually give a full coverage over all rotational phases and enable an unambigous construction of a composite lightcurve. The amplitude of this curve, which can amount to several tenths of a magnitude, gives important statistical information on asteroid shapes and albedo variegation (1, 4). Scenarios for the collisional evolution of the asteroid belt in general, and asteroid dynamical families and other subclasses in particular, may be tested against the wealth of spin rates that have been obtained from photometry. If observations of an object are carried out at several oppositions, the differing viewing geometry gives three-dimensional information which enables us to derive the axis and sense of rotation (6). Such pole information is of importance in the interpretation of most physical observations of asteroids (e.g. radar, infrared, etc.) as soon as the "spherical-featureless-nonrotating-model" is abandoned. One goal with these observations is to obtain an inversion of the full photometric information to interpretable constraints on shape and albedo variegation.

The M-type asteroids have attracted special attention from us in Uppsala since they seem to have different rotational properties from asteroids of other types (1, 5). In this report only the variation of spin rate with the mean distance from the sun will be discussed briefly. Figure 1 shows this variation for asteroids of type S and C. We use only data for asteroids smaller than 140 km in diameter since larger objects show a

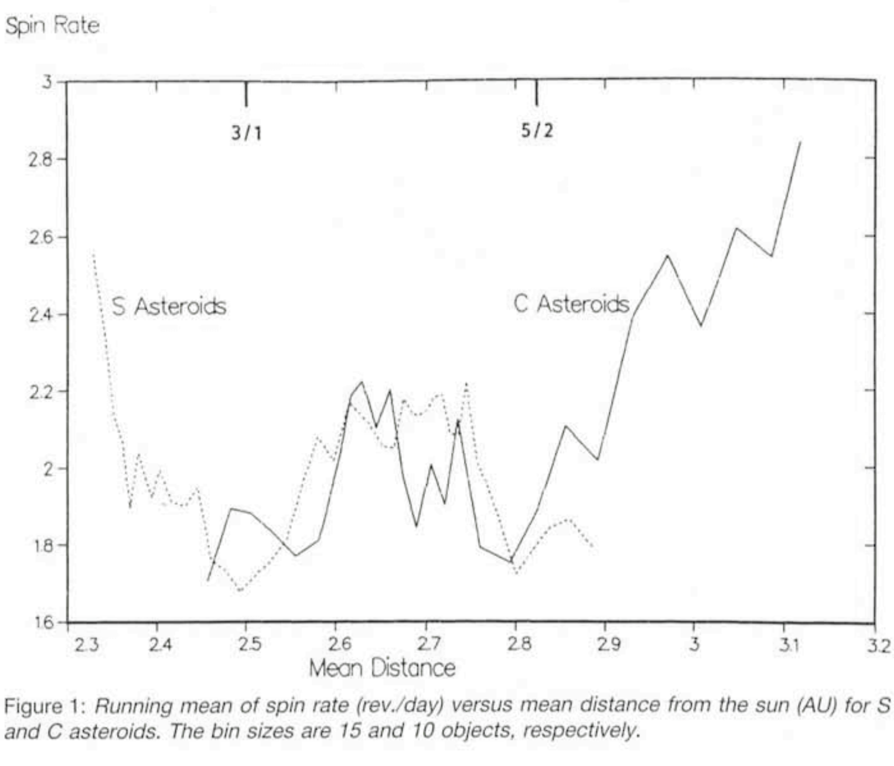

Figure 1: *Running mean of spin rate (rev./day) versus mean distance from the sun (AU) for S and C asteroids. The bin sizes are 15 and 10 objects, respectively.*