

The Peculiar Rotation Curve of NGC 404

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Abstract. The S0 galaxy NGC 404 was mapped with the VLA in the 21 cm HI line at a spatial resolution of $15.2'' \times 14.4''$ and at a velocity resolution of 2.6 km s^{-1} . The HI distribution is in the form of a doughnut, seen almost face-on, extending from a radius of $R = 90''$ to $400''$. A faint outer ring can be seen at $R > 400''$, which is somewhat more inclined to the line of sight, $i = 20^\circ$ rather than $i = 10^\circ$ as for the doughnut. We modeled the velocity field in annuli and found that the plane of the galaxy is warped, the position angle of the kinematical major axis varying with radius by $\sim 40^\circ$. Our fits favour a rotation curve which declines like a Keplerian. Assuming a distance of 2.4 Mpc for NGC 404, we derive a total HI mass of $\sim 8.0 \times 10^7 M_\odot$. The distance-independent $M_{\text{HI}}/L_{\text{B}}$ ratio is found to be 0.18 in solar units. Adopting the falling rotation curve we determine a total mass of $\sim 1.2 \times 10^{10} M_\odot$, which corresponds to a global M/L_{B} ratio of ~ 27 in solar units, which is high. It should be noted, however, that due to the almost face-on orientation of the galaxy the inclination and rotational velocity are strongly coupled. We therefore also explored alternatives, such as a flat rotation curve.

1. Introduction

NGC 404 is a good example of an early-type galaxy which shows more activity than expected from such systems. This is evidenced by various bright UV point sources (Maoz et al. 1998). Barbon et al. (1982) showed that the object consists of a bulge, lens, and exponential disc, as is characteristic of a lenticular galaxy. At the same time they mention the presence of a prominent, semicircular dust lane encircling the nucleus. In addition NGC 404 contains an appreciable amount of atomic (Baars & Wendker 1976) and molecular gas (Wiklind & Henkel 1990).

Studies of NGC 404 suffer from one major drawback which is that its distance is highly uncertain. With a radial velocity of -55.4 km s^{-1} it has to be nearby. Tully (1988) derived a distance of 2.4 Mpc and a linear diameter of

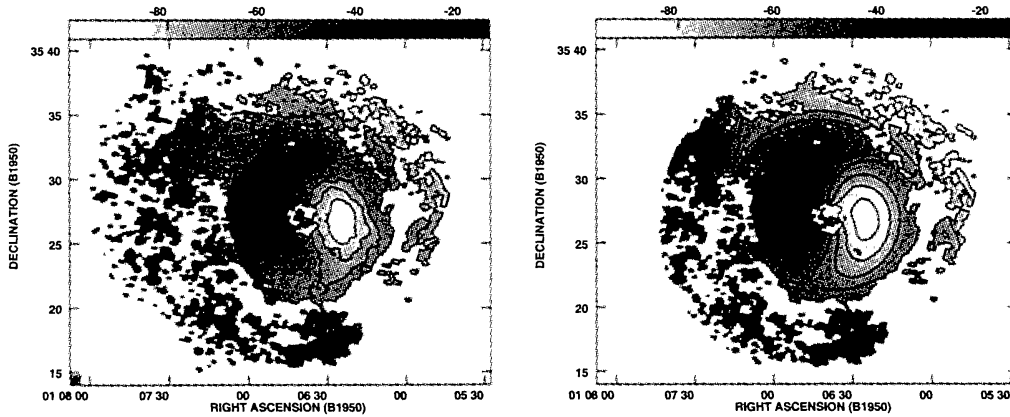


Figure 1. Observed velocity field (left) and model (right) based on the rotation curve fit as described in the text. Contours are drawn at velocities ranging from -90 to -20 km s^{-1} at intervals of 10 km s^{-1} .

4.2 kpc for an optical diameter of $D_{\text{opt}} \sim 6'$. As S0s are generally larger and more brilliant than dEs, the derived diameter is fairly small for an S0, suggesting that it must be at a larger distance. Not having independent distance estimators, we decided to stick to Tully's value for the remainder of this contribution, realizing that it is likely a lower limit to the true distance.

2. HI Results

From the global HI profile we derive a total flux of 59.4 Jy km s^{-1} , a systemic velocity of -55.4 km s^{-1} and an HI profile width at the 20% level of 85 km s^{-1} (not corrected for inclination, nor for instrumental effects). The total flux corresponds to an HI mass of $M_{\text{HI}} = 8.0 \times 10^7 M_{\odot}$. The distance-independent HI mass-to-blue luminosity ratio is $M_{\text{HI}}/L_{\text{B}} = 0.18$, which is fairly typical for S0s.

The HI is distributed as a bright doughnut with an inner diameter of $\simeq 180''$ and an outer diameter of $\simeq 800''$. At considerably lower signal-to-noise an outer ring can be seen. The ellipticity of that ring is higher than that of the disc, suggesting a higher inclination. Our VLA HI data imply a mass of $M_{\text{HI}} \simeq 6 \times 10^7 M_{\odot}$ for the doughnut ($R < 400''$) and $M_{\text{HI}} \simeq 2 \times 10^7 M_{\odot}$ for the outer ring ($R > 400''$). There is considerable fine-scale structure visible, but no large-scale pattern such as spiral arms. The doughnut is very nearly circular, suggesting an almost face-on orientation. This is corroborated by isophotal fits to the optical image and our analysis of the velocity field.

3. Velocity Field and Rotation Curve Fitting

A velocity field was obtained from smoothed ($25'' \times 25''$) channel maps and is presented in Fig. 1. The projected radial velocities range from ~ -100 to ~ -20 km s^{-1} . The isovelocity contours suggest a twist in the line of nodes when

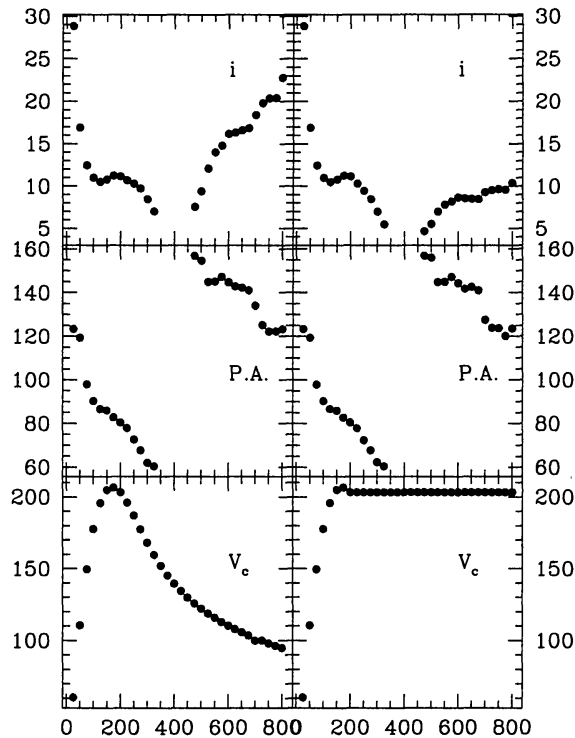


Figure 2. Tilted-ring model fits to the velocity field of NGC 404 showing the Keplerian (left) and Flat (right) rotation curves. The axes are labelled as follows: P.A. and i are in degrees, V_c is in km s^{-1} , and the radial distance from the centre is in arcsec.

going to increasing radii. The velocities of the outer ring fall within the same range as those of the main body, but the position angle shows a discontinuity. What is especially striking in the left-hand panel of Fig. 1 is that the isovelocity curves form closed loops, clearly seen on both sides of the galaxy, implying a declining rotation curve. As shown in del Río et al. (1999), this decline is close to Keplerian. Rotation curves are generally flat and if NGC 404 were to have an intrinsically flat rotation curve, this would require a conspiracy in the form of a warp with just the right amount of twist, turning the galaxy virtually face-on at large radii, so as to mimic a Keplerian decline.

The velocity field in the inner region ($R < 400''$) is sufficiently regular to fit a tilted-ring model (Begeman 1989). The results are plotted in Fig. 2. In this figure points are omitted for P.A. and i in the transition region between the doughnut and the annulus around $400''$. We find a systemic velocity of -55.4 km s^{-1} , a kinematic centre in B1950.0 coordinates of $\alpha = 01^{\text{h}} 06^{\text{m}} 39.4^{\text{s}}$ and $\delta = 35^{\circ} 27' 5''$ and a position angle (P.A.) which varies smoothly from $\sim 120^{\circ}$ at $R = 25''$ to $\sim 60^{\circ}$ at $R = 350''$. It should be noted that at low inclinations (or for those galaxies where the velocity field shows solid body rotation) the solution for the circular rotational velocities and the inclination are strongly coupled. Based mainly on “circumstantial evidence” we deduce an inclination of around 10° . The right-hand panel of Fig. 1 shows the model based on the rotation curve fit we derived. The agreement between the model fits and the observations is excellent.

Our fitting process seems to favour a solution of a falling rotation curve, close to Keplerian (see Fig. 2)! If this result could be strengthened, NGC 404 would be the first galaxy for which such a decline has been measured. However, as mentioned above, the inclination and rotational velocity are not independent parameters. To explore the parameter space, we produced fits during which the rotation curve was forced to remain flat. This resulted in residual maps which are indistinguishable from those for which the shape of the curve was left as a free parameter. As can be seen in Fig. 2, to compensate for the flatness of the rotation curve the inclination has to gradually decrease as a function of radius. If furthermore we insist that the annulus shares the same flat rotation curve, its inclination should approach $i = 10^\circ$. This is in disagreement with the observed ellipticity of the annulus. Because of this, it is tempting to discard the flat rotation curve. Besides it requires a conspiracy between the rotational velocities and the inclination in order to mimic an almost perfect Keplerian decline. Unfortunately, a definite statement cannot be made yet.

4. Summary

Our HI observations of NGC 404 have produced the following results:

1.- The HI is distributed in a doughnut shape with inner and outer radii of $R = 90''$ and $R = 400''$, respectively. At radii beyond $400''$ a dynamically distinct, and somewhat more inclined annulus is found.

2.- We derive an HI mass of $8 \times 10^7 M_\odot$. The distance-independent ratio between HI mass and blue luminosity is 0.18, which is a fairly typical value for S0 galaxies.

3.- The total (dynamical) mass of NGC 404 calculated by performing a rotation curve analysis and assuming Keplerian behaviour beyond $R = 200''$, is $1.2 \times 10^{10} M_\odot$.

4.- In the inner part of the galaxy ($R < 400''$) it is not possible to choose between a Keplerian or a flat rotation curve, although there are more arguments in favour of the former.

5.- We confirm that the galaxy is almost face-on at an average inclination of $i = 10^\circ$ and shows a warp in position angle of up to 40° .

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