Star Formation in Early-Type Galaxies
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HI Observations of Early–Type Galaxies

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Abstract. We present high resolution (15″) HI observations of the S0 galaxy NGC 404. We derive an HI mass of $M_{H_I} = 6.7 \times 10^7 M_\odot$, in good agreement with previous measurements. The HI is distributed in a broad annulus (a doughnut) and extends out to a diameter of 9′, well beyond the optical diameter of 6′. The velocity field is regular and shows, surprisingly, a declining rotation curve. This decline is purely Keplerian, strongly suggesting that all the mass is contained within the inner 200″.

1. Introduction

Traditionally, S0 galaxies were thought to represent a transition between elliptical (E) and spiral (S) galaxies. They share with the latter a central bulge and an exponential disk, and with the former the lack of spiral structure or arms. They are considered inert objects with very little gas, composed almost exclusively of Population II type stars, and virtually a total absence of on–going star formation. This picture has changed considerably over the past 20 years thanks mainly to tremendous progress in observational techniques which are now routinely delivering high quality data over a wide range of wavelengths.

The interstellar medium of early–type galaxies, and especially that of S0s, has attracted a great deal of interest ever since Faber & Gallagher (1976) showed that a considerable amount of mass ejected by evolved stars could pile up over the lifetime of the galaxy ($10^8 - 10^9 M_\odot$). Surprisingly, though, high resolution and sensitive HI observations demonstrated that in general much less gas is detected and that most of it seems to have been accreted (van Gorkom et al. 1986; Wiklind & Henkel 1990). The scarcity of material detected at HI, H_α, CO, and FIR wavelengths and the origin of that material form two puzzles of contemporary astronomy.

Faber & Gallagher (1976) discuss several manners in which gas could have been expelled or eliminated from early–type systems. They reach the conclusion that gas will be particularly hard to remove from these systems via star formation. Still, there are indications that star formation is taking place in S0s based on IRAS observations (Jura 1986, Knapp et al. 1989) and CO observations (Wiklind & Henkel 1989, Sage 1990) who showed that some S0s rival spirals in their CO content, but that the molecular gas is concentrated within 1–2 kpc from the center.

Our project consists of a multi–frequency study of a small sample of early–type galaxies aimed at determining the distribution and the morphology of the atomic, molecular and ionized gas, as well as that of the stellar distribution. We are interested to try to determine if the ionized gas in the centers is due to recent, massive star formation or if it has a different origin. And if it is due to star formation, how and when was this process triggered in the absence of spiral density waves.

The first galaxy in our sample is NGC 404, an isolated early-type galaxy, for which we thusfar have obtained HI observations (this paper), CO data (Cepa et al., this conference), narrow-band H_α, and near–infrared images. NGC 404 is a typical example of an early–type galaxy which shows more activity than expected from such systems. It contains an appreciable amount of atomic (Baars & Wendker 1976) and molecular gas (Wiklind & Henkel 1990), a prominent, semicircular dust lane encircling the nucleus (Barbon et al. 1982) and various bright UV point sources (Maoz et al. 1995). It was classified a LINER by Schmidt et al. (1990). Morgan (1958) classified this galaxy as E_{pec}, because of the dust lane. Humason et al. (1956) and Sandage (1961) classified it as an $S0_3$. Based on photographic surface photometry, Barbon et al. (1982) show that the object consists of bulge, lens, and exponential disk components, characteristic of a lenticular galaxy. This easily rules out a classification as (dwarf) elliptical.

NGC 404 has one major drawback which is that its distance is highly uncertain. With a radial velocity of $-56\,\mathrm{km\,s^{-1}}$ the only statement which can be made with any certainty is that it must be nearby. Naively correcting its radial velocity to galactocentric and using a Hubble constant of $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ would place this object at 2 Mpc, in the outer reaches of the Local Group with a linear diameter of 3.5 kpc, which would turn it into a dwarf galaxy. Tully (1988) derives a distance of $1.8h^{-1}$ Mpc, corresponding to 2.4 Mpc and a linear diameter of 4.2 kpc for an optical diameter of $D_{opt} \sim 6'$. This is still small for an S0, but as we will see below, this is not the only peculiarity of this object. Given that S0 galaxies in general are larger and more brilliant than dEs, this suggests a larger distance. Without independent distance estimators, it will be difficult to give a more reliable value. We therefore adopt Tully's value for the remainder of the paper, realizing that it is likely a lower limit to the true distance.

2. HI Morphology

In this contribution we will concentrate on the HI data. They were obtained with the NRAO[1] Very Large Array (VLA) in its C and D–array configurations. The maps have an angular resolution of 15″ and velocity resolution of 2.5 $\mathrm{km\,s^{-1}}$. Due to its large angular size, of over 10′ in HI, it is possible that we miss some of the most extended emission. Our HI masses are therefore lower limits.

[1]The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation (NSF).

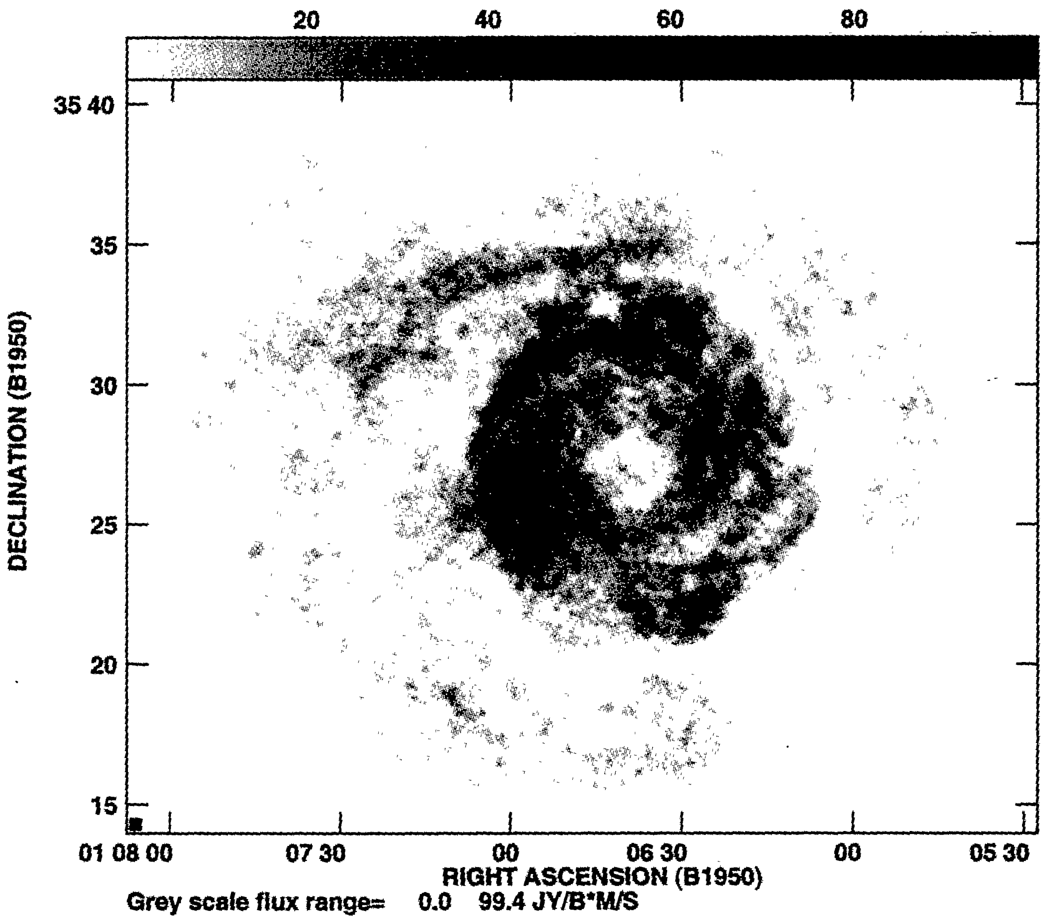

Figure 1. Integrated neutral hydrogen map. Intensities range from 0 to 300 $\mathrm{K\,km\,s^{-1}}$ or $5.5 \times 10^{20}\,\mathrm{at\,cm^{-2}}$.

According to Baars & Wendker (1976), NGC 404 has an unusually high M_{HI}/L_B ratio, $M_{HI}/L_B \approx 0.2 M_\odot/L_\odot$, a value that is more typical of late type spirals than S0s (note that this ratio is independent of distance). Such a high value seems common among early–type galaxies with nuclear activity (Eskridge & Pogge 1991). Based on a distance of 2.4 Mpc, single dish observations by Baars & Wendker (1976) lead to an HI mass of $M_{H_I} = 5.7 \times 10^7 M_\odot$. Observations by Bottinelli et al. (1990) are in reasonable agreement, giving $M_{H_I} = 6.07 \times 10^7 M_\odot$.

The HI is distributed as a bright doughnut with an inner diameter of $\simeq 3'$ and an outer diameter of $\simeq 9'$. At considerably lower signal–to–noise an outer ring can be discerned. Our VLA HI data imply a mass of $M_{H_I} = 6.7 \times 10^7 M_\odot$ in the "galaxy" and $M_{H_I} = 1.7 \times 10^7 M_\odot$ in the "annulus", that is, roughly a distribution of 4/5 of the total mass in the galaxy and 1/5 in the outer ring. 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. Barbon et al. (1982) derive values for the inclination and position angle as a function of radius. Wiklind & Henkel (1990) use a constant value of $i = 16°$

and a position angle, PA = 100°. Because optical data are contaminated by the bright star β And we used our HI images to derive a possible range in values for the inclination of between $i = 5°$ and $i = 16°$ with a slight preference for the lower range. We expect, in the near future, to be able to restrict this range by fitting a differentially rotating disk model to the velocity field.

3. HI Kinematics

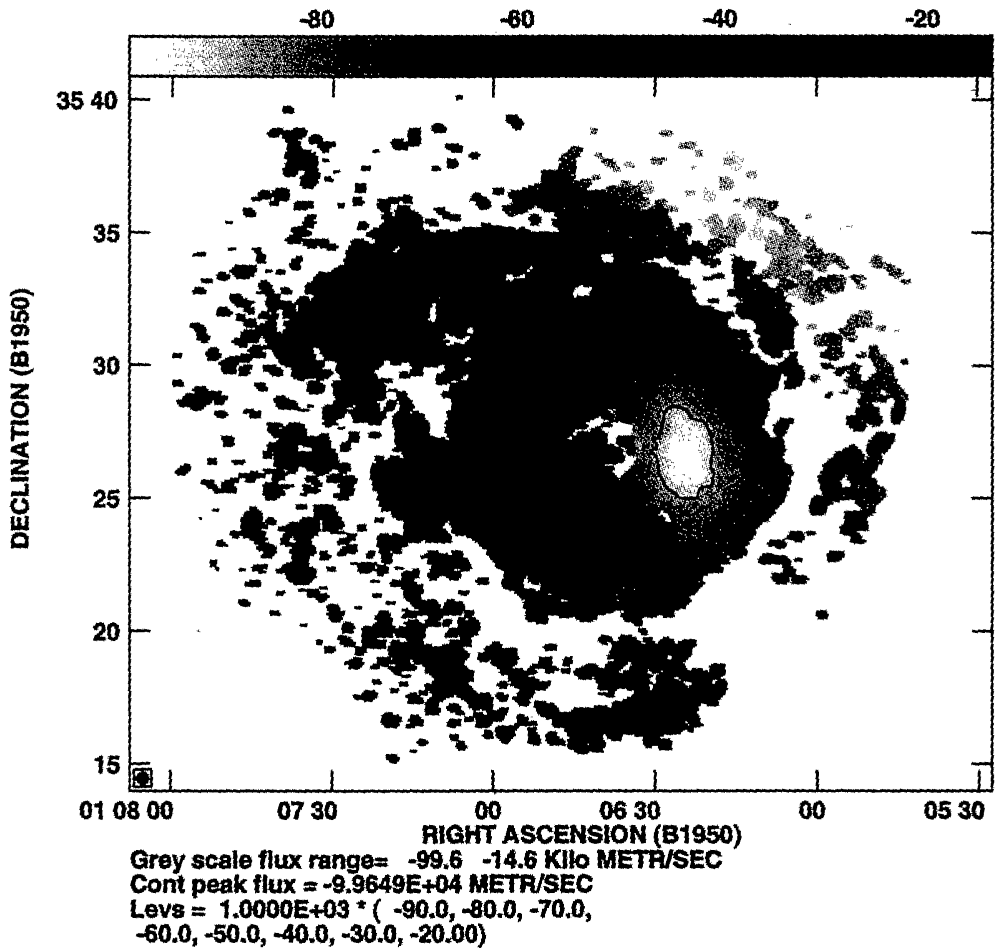

Figure 2. Velocity map. The observed radial velocities range from -100 to -20 km s^{-1}, the eastern half being the receding side.

Figure 2 shows the velocity field based on our HI observations. The projected radial velocities range from -100 to $-20\,\mathrm{km\,s^{-1}}$. The systemic velocity we find is close to the value of $-56\,\mathrm{km\,s^{-1}}$ quoted by Wiklind & Henkel (1990). We find a position angle of $\sim 70°$ NE. The isovelocity contours suggest a slight twist when going to larger radii. The velocities of the outer ring fall within the same range as those of the annulus, but the position angle is distinctly different, at $\sim 55°$ NE.

What is especially striking in figure 2 is that the isovelocity curves form closed loops, implying a declining rotation curve. In figure 3 we show a cut along the kinematic major axis. We decided to plot the observed radial velocities rather than the true rotational velocities because of the uncertainty in the rather large (due to the low inclination) correction. The gap near the center is due to an absence of HI within the inner 3′. The rotation curve rises rapidly to an observed maximum of 40 km s^{-1} at a radius of 200″, after which it turns over and declines! As is illustrated in fig. 3, the decline is very close to pure Keplerian. Fitting a Keplerian decline to the observed curve results in a correlation coefficient of better than 0.9. NGC 404 is the first and hitherto only galaxy to our knowledge which shows a purely Keplerian decline, implying that all the mass is concentrated within a 200″ radius and that no dark matter is required to explain the observed rotation.

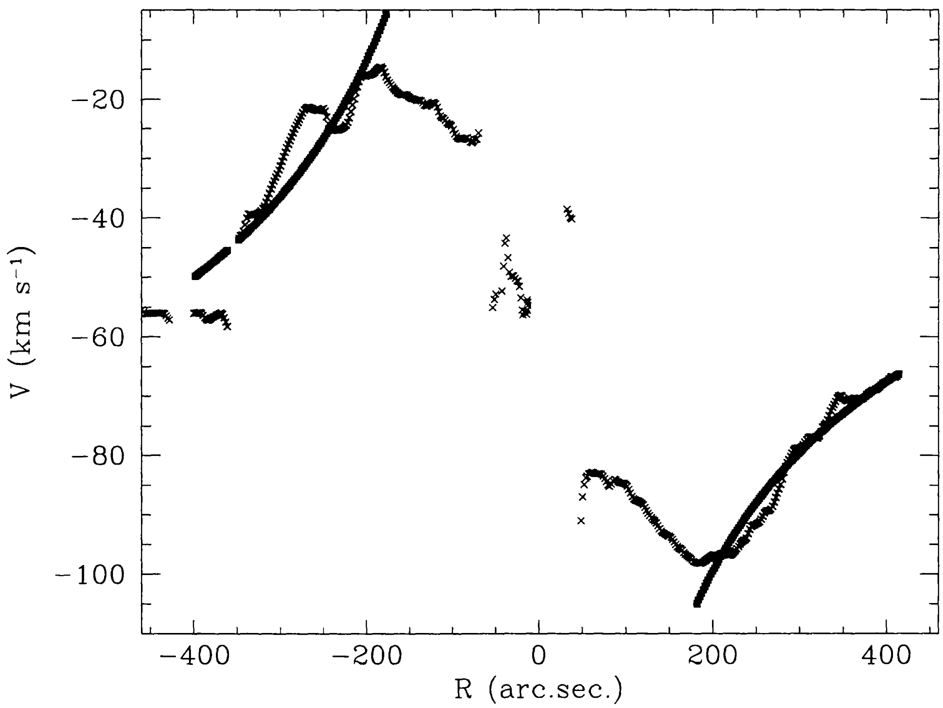

Figure 3. Observed rotation curve, uncorrected for inclination; crosses: observations, solid squares: Keplerian decline

Assuming that this mass resides in a disk–like distribution, we find for the total mass of the system a range of values of:

$$2.7 \times 10^9 \mathrm{M}_\odot \lesssim \mathrm{M_k} \lesssim 8.5 \times 10^9 \mathrm{M}_\odot$$

The lower limit corresponds to an inclination of 16°, the larger one to 5°. The results are compatible with those of Wiklind & Henkel (1990) ($\mathrm{M_T} \sim 3.7 \times 10^9\,\mathrm{M}_\odot$). Taking the total luminosity B from Tully (1988) we derive a range in mass–to–light ratio of:

$$\mathrm{M_T}/\mathrm{L_B} \sim 6\,(i = 16°) - 19\,(i = 5°)$$

These values fall within the range typical for S0s, although the larger value is pushing the limit. But then, Morganti et al. (this conference) also prefer values which are higher than those in use before.

4. Conclusions

NGC 404 is a unique object, showing a large HI content for an early–type galaxy. This HI is distributed in a doughnut–shaped ring. A faint outer ring, apparently at a different orientation, is visible as well. The HI mass which we derive of $M_{H_I} = 6.7 \times 10^7 M_\odot$ is in good agreement with single dish observations. We find an HI mass–to–blue light ratio which is relatively high ($M_{HI}/L_B \sim 0.2$). The HI kinematics show, surprisingly, a rotation curve which shows a purely Keplerian fall-off, suggesting that all the mass is contained within a 200″ radius. There doesn't seem to be a need for dark matter.

Discussion

M. Pahre: Is it possible that the outer disk has a warp in the plane of the sky that could cause the apparently Keplerian rotation at large radii?

S. del Río: Although we cannot, at present, exclude such a contrived geometry, it would be highly unlikely. In fact, Nature would be really perverse if the Keplerian decline which so perfectly explains the rotation curve, would be due to projection effects.

V. Avila-Reese: Are there other galaxies with a rotation curve like the galaxy you have presented?

S. del Río: No, this is the first galaxy, to our knowledge, which shows such a perfect Keplerian decline. Declining rotation curves in other systems are far more gradual and imply huge amounts of Dark Matter.

V. Avila-Reese: Which is the environment of the S0 galaxy?

S. del Río: This is difficult to answer as we have no idea about the distance to this object. It is likely at the edge of the Local Group, but it could be more distant.

H.M. Hernández Toledo: Why is it so difficult to determine the distance to this object?

S. del Río: Basically, it is too nearby to apply Hubble flow. Moreover, there are no data on secondary distance indicators.

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