KINEMATICS OF GAS AND STARS ALONG THE HUBBLE SEQUENCE

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Abstract. We present a comparison between the ionized gas and stellar kinematics for a sample of five early-to-intermediate disc galaxies. We measured the major axis V and σ radial profiles for both gas and stars, and the h_3 and h_4 radial profiles of the stars. We also derived from the R-band surface photometry of each galaxy the light contribution of their bulges and discs. In order to investigate the differences between the velocity fields of the sample galaxies we adopted the self-consistent dynamical model by Pignatelli and Galletta (1999), which takes into account the asymmetric drift effects, the projection effects along the line of sight and the non-Gaussian shape of the line profiles due to the presence of different components with distinct dynamical behaviour. We find for the stellar component a sizeable asymmetric drift effect in the inner regions of all the sample galaxies, as results from comparing their stellar rotation curves with the circular velocity predicted by the models. The galaxy sample is not wide enough to draw general conclusions. However, we have found a possible correlation between the presence of slowly rising gas rotation curves and the ratio of the bulge/disc half-luminosity radii, while there is no obvious correlation with the key parameter represented by the morphological classification, namely the bulge/disc luminosity ratio. Systems with a diffuse, dynamically hot component (bulge or lens) with a scale length comparable to that of the disc are characterized by slowly rising gas rotation curves. On the other hand, in systems with a small bulge the gas follows almost circular motions, regardless of the luminosity of the bulge itself. We noticed a similar behaviour also in the gas and stellar kinematics of the two early-type spiral galaxies modelled by Corsini *et al.* (1998).

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TABLE I

Parameters of the sample galaxies. Col. (3): total observed blue magnitude from RC3 except for NGC 5064 (RSA). Col. (4): inclination from NGB (Tully, 1988) except for NGC 980 and NGC 7782 from RC3 (inferred from R_{25}). Col. (5): systemic velocity derived from the centre of symmetry of the gas rotation curve and corrected for local motion. Col. (6): distance obtained from V_0/H_0 with $H_0 = 75$ km s^{-1} Mpc^{-1}. Col. (8): radius of the 25 B-mag arcsec^{-2} isophote from RC3.

Object [name] (1)	Type [RC3] (2)	B_T [mag] (3)	i [°] (4)	V_0 [km s^{-1}] (5)	D [Mpc] (6)	Scale [pc/″] (7)	R_{25} [″] (8)
NGC 772	.SAS3..	11.09	53	2618	34.7	168	217
NGC 980	.L.....	...	62	5936	79.1	384	51
NGC 3898	.SAS2..	11.60	46	1283	17.1	83	131
NGC 5064	PSA.2*.	12.69	65	2750	36.7	178	74
NGC 7782	.SAS3..	13.08	62	5611	74.8	363	72

1. Introduction

Evidence has been presented (Bertola *et al.*, 1995) that in several S0 galaxies the gas in the inner regions shows broad velocity-dispersion profiles. In addition, in the centres of certain early-type galaxies it was discovered (Fillmore, Boroson and Dressler, 1986; Kent, 1988) that the gas rotation curves fall below the circular velocities predicted by constant M/L models. Both gas phenomena: the 'slowly rising' rotation curve and the high velocity dispersion, can be well interpreted as signs of gas recently expelled by the stars of the bulge but not yet heated to the virial temperature of the galaxy (i.e. *pressure supported*). In the case of the late-type spirals the picture is clearer: both the gas and the stars show essentially circular motions and constant velocity dispersion profiles.

It has been shown for Sa galaxies (Corsini *et al.*, 1998) that the application of dynamical models can tell us a great deal about the structure and the kinematics of galaxies: understanding of the dynamics for the different stellar components, deviation of the gas from circular motions and the presence of dark matter. Here we present a comparison between the gas and stellar kinematics for a sample of five disc galaxies (see Table I) of early and intermediate Hubble types (Sa, Sb).

The study of Sb galaxies allows us to see whether non-circular motions are present in the inner regions for both gas and stars, or if we are dealing with systems with intermediate kinematic properties between early- and late-type objects, as might be inferred from the photometric properties.

2. Observations and Data Reduction

Spectroscopic observations were carried out at ESO 1.52 m Telescope (La Silla, Chile), at the Multiple Mirror Telescope (Mount Hopkins, Arizona) and at the Isaac Newton Telescope operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofíca de Canarias (IAC), Tenerife (Spain).

Photometric observation were carried out on the IAC80 operated on the island of Tenerife by the IAC in the Spanish Observatorio del Teide, the VATT (Mount Graham, Arizona) and the ESO 1.52 m Telescope (La Silla, Chile).

Standard spectral reduction was performed using the ESO MIDAS package. The stellar kinematics were measured from the absorption lines present in each spectrum using the Fourier correlation quotient method (Bender, 1990) as applied by Bender, Saglia and Gerhard (1994). The ionized gas velocities and velocity dispersions were derived by means of the MIDAS package ALICE. The photometric data reduction was carried out using standard IRAF routines.

3. The Model

In order to investigate the different behaviour of the gas and the stellar kinematics a self-consistent dynamical model (Pignatelli and Galletta, 1999; see also Pignatelli and Galletta, elsewhere in this volume) is used to reproduce the data.

The model has $4n + 1$ free parameters, where n is the number of adopted components; namely, the luminosity ($Ł_{\mathrm{tot}}$), scale length (r_e), mass–luminosity ratio (M/L) and flattening (b/a) of each component plus the inclination angle of the galaxy. In principle, all of these parameters can be constrained – within certain confidence limits – by the photometry, with the exception of the M/L ratios, which have to be derived from the kinematics.

In order to compare the observed data with the predictions of the model, we also need to reproduce the deviations of the LOSVD from a pure Gaussian shape. We adopted the usual parameterization in terms of a Gauss–Hermite expansion series (van der Marel and Franx, 1993; Gerhard, 1993).

Once the fit of the stellar kinematics has been performed and the overall potential of the galaxy is known, one can directly derive the circular velocity, V_{c}. By superimposing the V_{c} inferred in this way (corrected for inclination) on to the observed gas rotational velocity, we can immediately notice any deviation from purely circular motions.

4. Results

With limited space, we give in detail the results for only two of the five galaxies studied and briefly summarize the others. We refer to a fuller paper (Vega Beltrán *et al.*, 1999) for details.

NGC 980: The photometric model adopted for this lenticular galaxy is that of an almost edge-on disc component embedded in a lens much more extended than the disc itself, together with a very compact, luminous bulge in the inner 2″ (see Figure 1). The superposition of these three components accounts for the peak in ellipticity at 10″, and the subsequent slow decrease from $\varepsilon = 0.6$ to $\varepsilon = 0.3$.

The most interesting feature of this galaxy is surely the gas–stars kinematic difference. From 3″ to 10″, gas and stars appear to have quite different behaviour, with the gas rising linearly in velocity, while the stars present a plateau. As a consequence, the gas is rotating more rapidly at 3″ than the stars, and *slower* than the stars at 10″. On the other hand, both components are following the same velocity-dispersion curve, marking the likely association of the gas with a hot component. This difference between the gas and stellar rotational velocity is unlikely to be due only to absorption effects and could be due to a misalignment between the gas and the stellar component, suggested also by the slow change of about 10° in the position angle of the *R*-band isophotes.

At 2″ a small peak in the velocity is also visible which is not evident in the gas rotation curve, and we interpret this as the effect of the rotation of a massive central flattened distribution of matter, also responsible for the sharp increase in the velocity dispersion in the inner region. Finally, the presence of a lens is inferred from the slow decrease of the velocity dispersion, much slower than would be expected from a small bulge, as well as from the stellar LOSVD, strongly non-Gaussian at $r = 8''$.

NGC 7782: This Sb galaxy looks like the prototype of a bulge + disc system, with the two components almost decoupled from each other. From both the kinematic and the photometric data we can distinguish two different regions with very different behaviour. In the inner 5″ region, dominated by an almost spherical bulge, the stellar velocity dispersion shows a plateau at ~ 200 km s^{-1} and the rotational velocity is less than half the value expected from the circular velocity, in agreement with the asymmetric drift effect calculated by the model (see Figure 2). On the other hand, the gas shows strictly circular motions with low velocity dispersion. In the outer region, well approximated by an exponential disc, both the gas and the stars appear to rotate close to the circular velocity.

Both an exponential and an $r^{1/4}$ law have been adopted for the potential models of the bulge. While the photometry itself cannot distinguish between the two hypotheses, we found that the exponential bulge gives a better agreement with the kinematic data.

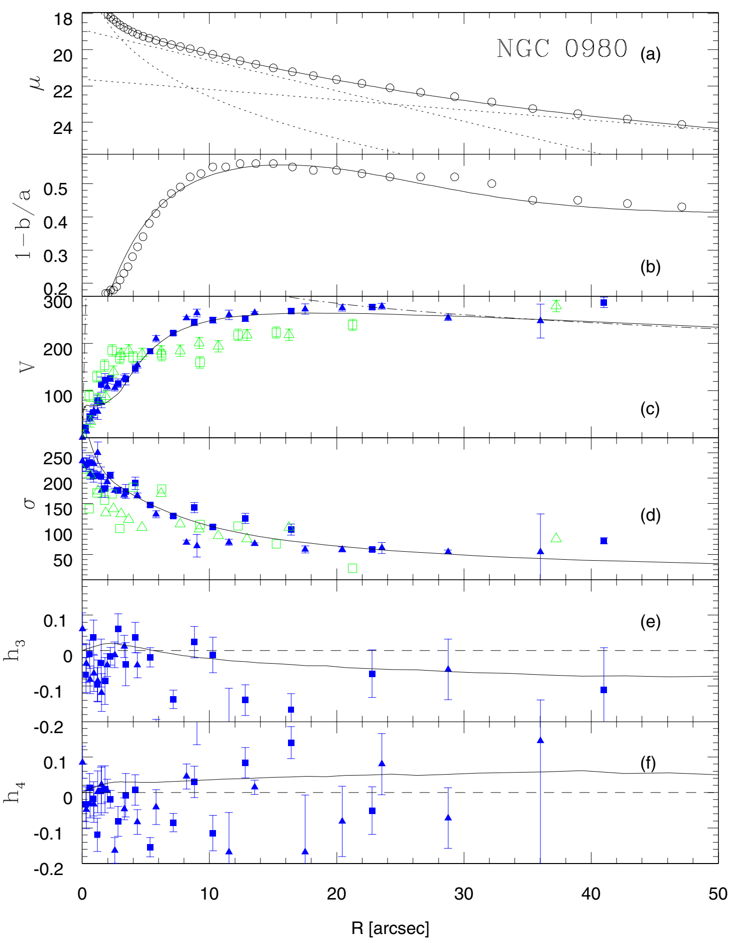

Figure 1. Photometric and dynamical features for NGC 980, with their respective best-fit curves obtained from our models. *(a)*: r-band surface brightness (*open circles*) as a function of radius along the major axis. We also plot the photometric components that we found (*dashed lines*) and the sum of these components (*solid line*). *(b)*: Ellipticity (open circles) associated with the upper r-band surface brightness and the best-fit curve (*solid line*) found. *(c)*: Observed stellar velocity (*filled symbols*) with its associated model (*solid line*), and the H_α observed gas kinematics (*open symbols*). The *dot-dashed* line is the circular velocity inferred from the model. *(d)*: The same as *(c)*, but for the velocity dispersion. *(e)*: The same as *(c)* for the h_3 coefficients of the Gauss–Hermite expansion of the line profile of the stars. *(f)*: The same as *(c)* for the h_4 coefficients of the Gauss–Hermite expansion of the line profile of the stars. In windows *(c)* to *(f)* the squares and the triangles represent data derived for the approaching NE side and for the receding SW side, respectively. In window *(c)*, due to the high values of the predicted circular velocity, its fitting curve is only visible for the outer regions. The plot of the entire curve would only produce a loss of the velocity curve details.

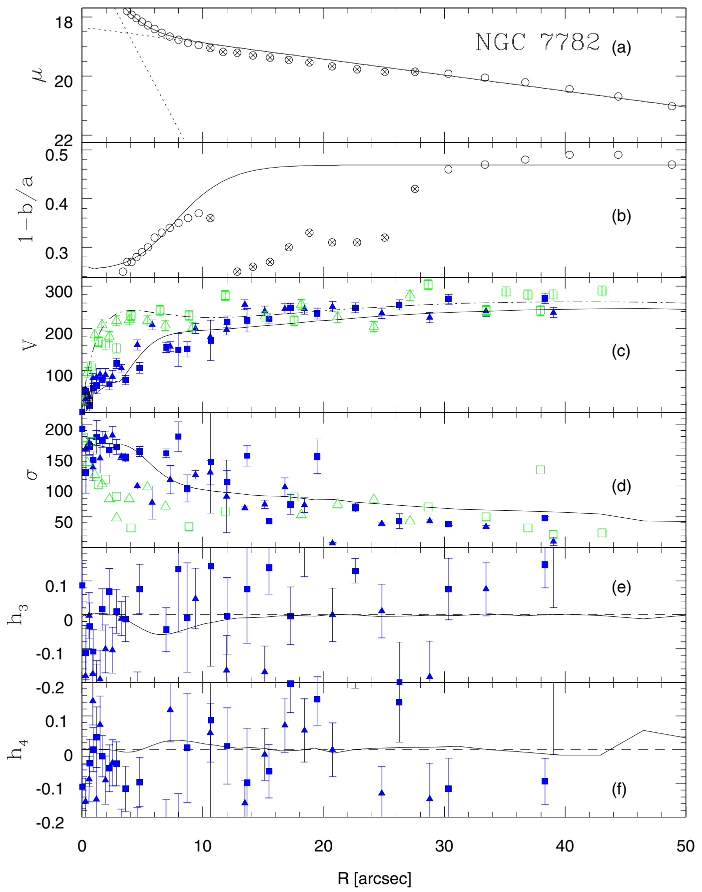

Figure 2. The same as Figure 1 for NGC 7782. In windows *(a)* and *(b)* the circles filled with crosses are not considered to define the best photometric decomposition due to the presence of strong spiral arms. For windows *(c)* to *(f)* the squares and triangles represent data derived for the approaching NW side and for the receding SE side, respectively.

NGC 772: The gas seems to be pressure supported in the inner 6″; after this, the rotational velocity of the gas reaches the expected circular velocity and the velocity dispersion falls to a low constant value ($\sim$ 50 km s^{-1}).

NGC 3898: The stellar kinematics is well fitted by a three-component model, including an inner flat disc coexisting with a spherical bulge of similar scale length. The gas rotational velocity is well approximated by the model circular velocity for $r > 8''$, showing no asymmetric drift effect, and is observed to follow a flat velocity curve out to 100″. In the inner 8″ there is a strong absorption of the H_α line which prevents us from obtaining realistic estimates of the velocity and velocity dispersion.

TABLE II

Parameters from the dynamical models (I). The indices 'b' and 'd' refer, respectively, to the bulge and disk components, and the 'd′' index to the (possible) third component

Object	Scale radius			Axial ratio			Mass [10^{10} $M_\odot$]		
	r_b	r_d	$r_{d'}$	$(b/a)_\mathrm{b}$	$(b/a)_\mathrm{d}$	$(b/a)_{\mathrm{d}'}$	M_b	M_d	$M_{\mathrm{d}'}$
NGC 772	19.″0	20.″0	–	0.80	0.1	–	6.5	9.9	–
NGC 980	2.″1	6.″5	19.″2	0.98	0.2	0.6	24.0	4.9	10.0
NGC 3898	9.″5	6.″6	57.″0	1.00	0.2	0.3	3.7	0.5	3.2
NGC 7782	1.″4	20.″1	–	0.75	0.1	–	6.0	36.0	–

NGC 5064: Apart from a slight oscillation in the ellipticity and the position angle, probably due to the spiral arms, this galaxy does not show evidence for triaxial structures or misalignments in the different stellar components. The position angle is fairly constant and there is no sign of boxy structures. Nevertheless, with the hypothesis of our models, we found that no set of parameters was able to reproduce the data. A possible explanation could be that the observed value of the rotational velocity is the mean of the superposition of different components in the central 20″ region, with different characteristic values of the rotational velocity and/or directions of the angular momentum. This possibility is supported also by the h_3, h_4 profiles, which show a strongly non-Gaussian shape for the line-of-sight velocity profiles in this region. Even inner stellar counter-rotation cannot be ruled out at this moment.

5. Discussion

We have analysed the photometry and kinematics of five disc galaxies (one is classified as lenticular, two as Sa and two as Sb by the RSA catalogue). For four out of five galaxies, we found that an axisymmetric dynamical model can fully account for the observed stellar kinematic features, including the general behaviour of the h_3, h_4 profiles. For the case of NGC 5064, models with decoupled angular momenta may be needed.

In Figures 1–2 we present the photometric and spectroscopic data for two of these galaxies, together with the best-fit models obtained. The parameters obtained from the models are presented in Table II. A sizeable asymmetric drift effect is present in the inner regions of all these galaxies, as we can see by comparing the stellar rotational curves with the circular velocity predicted by the models.

The gas components show a very wide range of kinematic properties. Two of the sample galaxies (NGC 5064 and NGC 7782) show almost circular motions even very near the centre; two present slowly rising rotation curves (NGC 772 and

NGC 3898) and one (NGC 980) even appears to have a gas rotational curve *lower* in velocity than that of the stellar component.

The number of galaxies belonging to the sample is not large enough to draw general conclusions. However, we have found a possible correlation between the presence of slowly rising gas rotation curves and the ratio of the bulge/disc half-luminosity radii, while there is no obvious correlation with the key parameter represented by the morphological classification; namely, the bulge/disc luminosity ratio. Systems with a diffuse dynamically hot component (bulge or lens), with scale length comparable to that of the disc are characterized by slowly rising gas rotation curves. On the other hand, in systems with a small bulge the gas follows almost circular paths, regardless of the luminosity of the bulge itself. We notice similar behaviour also in the gas and stellar kinematics of two Sa galaxies (NGC 2179 and NGC 2775) modelled by Corsini *et al.* (1998). The application of the methods of analysis used in this contribution to a wider sample of galaxies could help us to confirm this picture.

References

Bender, R.: 1990, *Astron. Astrophys.* **229**, 441.

Bender, R., Saglia, R.P. and Gerhard, O.E.: 1994, *Mon. Not R. Astron. Soc.* **269**, 785.

Bertola, F., Cinzano, P., Corsini, E.M., Rix, H.-W. and Zeilinger, W.W.: 1995, *Astrophys. J. Lett.* **448**, L13.

Corsini, E.M., Pizzella, A., Sarzi, M., Cinzano, P., Vega Beltrán, J.C., Funes, J.G., Bertola, F., Persic, M. and Salucci, P.: 1998, *Astron. Astrophys.* **342**, 671.

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G., Jr., Buta, R.J., Paturel, G. and Fouquè, P.: 1991, *Third Reference Catalogue of Bright Galaxies*, Springer.

Fillmore, J.A., Boroson, T.A. and Dressler, A.: 1986, *Astrophys. J.* **302**, 208.

Gerhard, O.E.: 1993, *Mon. Not. R. Astron. Soc.* **265**, 213.

Kent, S.M.: 1988, *Astron. J.* **96**, 514.

Pignatelli, E. and Galletta, G.: 1999, *Astron. Astrophys.* **349**, 369.

Sandage, A. and Tammann, G.A.: 1981, *A Revised Shapley–Ames Catalog of Bright Galaxies,*, Carnegie Institution, Washington DC (RSA).

Tully, R.B.: 1988, *Nearby Galaxies Catalog,* Cambridge University Press, Cambridge.

van der Marel, R.P. and Franx, M.: 1993, *Astrophys. J.* **407**, 525.

Vega Beltrán, J.C., Pignatelli, E., Zeilinger, W.W., Pizzella, A., Corsini, E.M., Bertola, F. and Beckman, J.: 1999, *Astrophys. Space Sci.* **263**, 163.