THE ORTHOGONAL BULGE–DISC DECOUPLING IN NGC 4698

M. SARZI, F. BERTOLA, M. CAPPELLARI, E.M. CORSINI and J.G. FUNES S.J.
Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy

A. PIZZELLA
European Southern Observatory, Alonso de Cordova 3107, Casilla 19001, Santiago 10, Chile

J.C. VEGA BELTRÁN
Telescopio Nazionale Galileo, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy

Abstract. The *R*-band isophotal map of the Sa galaxy NGC 4698 shows that the inner region of the bulge is elongated perpendicularly to the major axis of the disc. At the same time a central stellar velocity gradient is found along the minor axis of the disc. The same properties have also been recognized in the Sa galaxy NGC 4672. This remarkable geometric and kinematic decoupling is a direct indication that a second event occurred in the history of these galaxies suggesting that acquisition phenomena could play a primary role in the formation of early-type spirals.

1. Introduction

In the course of an investigation of the kinematic properties of early-type spiral galaxies we encountered the peculiar case of the Sa galaxy NGC 4698. In addition to an out-of-the-ordinary geometric decoupling between bulge and disc, whose apparent major axes appear orientated in an orthogonal way on simple visual inspection of the galaxy images (e.g. see Panels 78, 79 and 87 in Sandage and Bedke, 1994), the stellar rotation curve along the major axis exhibits an unusual zero-velocity plateau in the central regions. A subsequent spectrum obtained along the minor axis of the disc shows the presence of a strong stellar velocity gradient. This geometric and kinematic decoupling is a direct indication that a 'second event' occurred in the history of NGC 4698.

NGC 4698 is classified Sa by Sandage and Tammann (1981, RSA) and Sab(s) by de Vaucouleurs *et al.* (1991, RC3). Sandage and Bedke (1994, CAG) in *The Carnegie Atlas of Galaxies* presented NGC 4698 in the Sa section as an example of the early-to-intermediate Sa type as characterized by a large central bulge and tightly wound spiral arms. The E-like bulge appears to be elongated perpendicularly to the disc. In spite of this feature NGC 4698 is not at all morphologically related to the ellipticals with polar ring (e.g. AM 2020-504 in Whitmore *et al.*, 1990).

Astrophysics and Space Science **276:** 467–473, 2001.

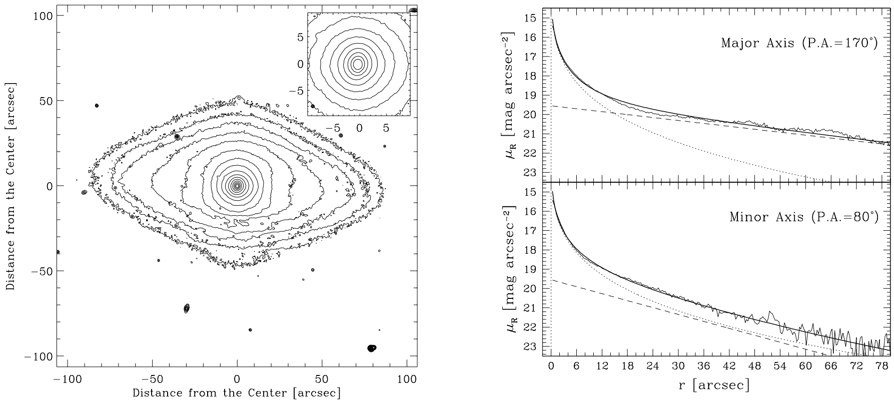

Figure 1. The R-band isophotes (*left panel*) and the surface-brightness profiles along the major (P.A. = 170°) and minor (P.A. = 80°) axes of NGC 4698 (*right panel*). Isophotes are given in steps of 0.4 mag arcsec^{-2} with the outermost one corresponding to 21.8 mag · arcsec^{-2} and the central one to 15.8 mag · arcsec^{-2}. In the *inset* the isophotal map of the inner 10″ is plotted. North is right and east up. The surface-brightness profiles of the $r^{1/4}$ bulge (*dotted line*) and the exponential disk (*dashed line*) derived from the photometric decomposition and their sum (*thick continuous line*) are also plotted.

2. Results

2.1. Photometry

The R-band isophotal map of NGC 4698 is presented in Figure 1. A geometric decoupling (ΔP.A. $\simeq$ 90°) is visible both in the inner isophotes (see inset) and in the outermost one, which is characterized by two 'bumps' orientated perpendicularly to the galaxy major axis. The isophotes between 4″ and 19″ appear round in the plot. However as soon as an exponential disc is subtracted they become elongated perpendicularly to the disc major axis. The overall shape of our R-band isophotes is similar to the one observed in the K-band image by Moriondo, Giovanardi and Hunt (1998). This suggests that it is not an artefact of dust effects.

The analysis of the surface-brightness distribution of NGC 4698 is needed to disentangle the light distribution of bulge and disc in order to understand the observed stellar kinematics. Anyway, it cannot be obtained by means of the elliptically averaged luminosity profiles. In fact it is difficult to model the galaxy isophotes by ellipses at all radii due to the presence of a prominent bulge and to the high inclination of this galaxy (Byun and Freeman, 1995). We therefore performed a two-dimensional photometric decomposition of the NGC 4698 surface-brightness which we assume to be the sum of a $r^{1/4}$ bulge and an exponential disc. We took into account the seeing convolution and masked the dust lanes. The best-fit parameters are $\mu_e = 20.4$ mag arcsec^{-2}, $r_e = 21.0''$ and $q = 1.14$ for the bulge and $\mu_0 = 19.6$ mag arcsec^{-2}, $r_d = 42.9''$, and $i = 65°$ for the disc. The surface-brightness profiles derived along the major and minor axes of NGC 4698 and the corresponding bulge–disk decomposition are presented in Figure 1. The fact that the axial ratio of the bulge is found to be greater than unity confirms the exceptional property of NGC 4698 of having a bulge elongated along the disc minor axis.

An alternative non-parametric decomposition of the NGC 4698 surface-brightness distribution has been recently proposed by Moriondo *et al.* (1998) and produces lower residuals when the modelled surface-brightness is subtracted from the observed one. The isophotes of the resulting bulge (which dominates the galaxy light out to 20″) appear round and the surface-brightness profile of the non-exponential disc flattens toward the centre inside 30″. This removes the excess of light in the parametrically modelled profile between 14″ and 32″ along the galaxy major axis (Figure 1).

2.2. Kinematics

The stellar velocity curve measured along the major axis of NGC 4698 is characterized by a central plateau (Figure 2); indeed the stars have zero rotation for $|r| \leq 8''$. At larger radii the observed stellar rotation increases from zero to an approximately constant value of about 200 km $s^{-1}$for $|r| \gtrsim 50''$ up to the farthest observed radius at about 80″. The stellar velocity dispersion profile has been measured out to 30″. It is peaked in the centre at the value of 185 km s^{-1}. The stellar velocities measured by Corsini *et al.* (1999) agree within the errors with the data of this paper. We measured the minor-axis stellar kinematics out to about 20″ on both sides of the galaxy. In the nucleus the stellar velocity rotation increases to about 30 km s^{-1}at $|r| \simeq 2''$. It decreases to between 2″ and 6″ reaching an almost zero value beyond 6″. The velocity-dispersion profile has a central maximum of 175 km s^{-1}in agreement within the error bars with the corresponding value along the major axis. The velocity curves and the velocity-dispersion radial profiles of the stellar component (out to only 28″ for the spectrum along the major axis) are shown in Figure 2.

The spectral resolution and signal-to-noise ratio of our spectra were not sufficient to perform a two-component kinematic decomposition via a double-Gaussian fit of the line-of-sight velocity distribution (LOSVD) to disentangle the contribution of bulge and disc to the observed major and minor-axis kinematics. Adopting our parametric photometric decomposition, we show that the observed kinematics is consistent with the rotation of the bulge and disc with perpendicular angular momenta by modelling the observed LOSVD in the following way. Along the major axis we assumed for the bulge a constant zero velocity and a constant velocity dispersion of $\sigma_{\rm b} = 180$ km s^{-1}, while for the disc we assumed a linearly rising velocity to match the outer points of the plotted curve (where the light contribution of the bulge is negligible) and a constant velocity dispersion of $\sigma_{\rm d} = 100$ km s^{-1}. The resulting velocity curve obtained by fitting with a Gaussian the sum of the two Gaussian components of bulge and disc weighted according to the photometric decomposition of Figure 1 is shown in Figure 2.

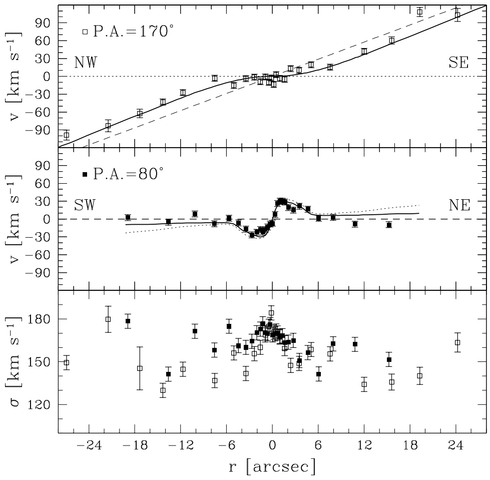

Figure 2. The observed stellar rotation velocity and velocity dispersion as a function of radius along the major (*open squares*) and minor (*filled squares*) axes of NGC 4698 out to 28″ from the centre. The heliocentric system velocity is $V_{\odot} = 992 \pm 10$ km s^{-1}. The *dotted* and *dashed lines* represent the velocity contribution of the bulge and disc components to the total velocity (*thick continuous line*) of our model.

A similar approach has been applied to reproduce the velocity curve along the minor axis. A constant zero velocity and a constant velocity dispersion of $\sigma_{\rm d} = 100$ km s^{-1}have been assumed for the disc, as well as a constant velocity dispersion of $\sigma_{\rm b} = 180$ km s^{-1}for the bulge. At all radii we assumed the bulge velocity to be the maximum value consistent with a resulting rotation curve (represented by the continuous line in the middle panel of Figure 2) within the scatter of the folded data. It reaches a maximum of 30 km s^{-1}in the inner 3″ decreasing to a local minimum of 10 km s^{-1}at $|r| \simeq 6''$ and increasing afterwards.

From the maximum rotation of the modelled bulge, its mean observed velocity dispersion inside $0.5r_{\rm e} = 10.5''$, and the mean ellipticity inside the same radius of the residual surface-brightness distribution obtained after subtracting the 2-D surface-brightness distribution of the exponential disc derived from the photometric decomposition, we evaluated an anisotropy parameter $(v_{\rm max}/\overline{\sigma})^* \approx 0.86$. This lends support to the idea that the rotation curve we found is representative of that of a bulge, assuming that bulges are isotropic rotators (Davies *et al.*, 1983).

3. Discussion and Conclusions

In the previous paragraph we have pointed out that on the sky plane the bulge and disc of the Sa NGC 4698 appear elongated perpendicularly to each other and rotating around two orthogonal axes. Concerning the three-dimensional structure of NGC 4698, if the parametric photometric decomposition is adopted it suggests that the entire bulge is protruding perpendicularly to the disc and that their angular momenta are orthogonal with respect to each other. In fact assuming that the intrinsic shape of bulges is generally triaxial (Bertola, Vietri and Zeilinger, 1991), and that the plane of the disc coincides with the plane perpendicular either to the bulge major or minor axis, we deduce from the observed configuration that the major axis of the bulge is perpendicular to the disc, given that the latter is seen not far from edge on. Morover, the velocity field of the bulge is characterized by a zero velocity along its apparent minor axis (as indicated by the central plateau in the rotation curve along the disc major axis) and by a gradient along its major axis, suggesting that the rotation axis of the bulge lies on the plane of the disc. The case of an end-on bar is ruled out since we measure along the major axis a zero-velocity plateau instead of a velocity gradient similar to those predicted by Merrifield (1996) for end-on bars in edge-on galaxies.

The orthogonal decoupling of the bulge and disc of NGC 4698 indicates that a second event occurred in the formation history of this galaxy. We suggest that the disc formed at a later stage due to the acquisition of material by a triaxial spheroid on the principal plane perpendicular to its major axis. Could the structure of NGC 4698 be an indication that disc galaxies with prominent bulges started as 'undressed spheroids' and their discs accreted gradually over several billion years, as suggested by Binney and May (1986)?

Recently, this kind of processes has been considered within semi-analytical modelling techniques for galaxy formation, where the discs accrete around bare spheroids previously formed either directly from the relaxation of gas in a spherical distribution parallel to that of their surrounding dark haloes (Kauffmann, 1996), or from the merging of disc protogalaxies previously formed (Baugh, Cole and Frenk, 1996). If the disc of NGC 4698 is acquired then polar-ring elliptical galaxies such as AM 2020-504 (Whitmore *et al.*, 1990) and ellipticals with dust lanes along the minor axis (Bertola, 1987) could represent transient stages towards the formation of spiral systems such as NGC 4698.

In order to verify if these acquisition processes are general phenomena in galaxy formation we need to know if objects like NGC 4698 are unique or peculiar. To address this question we began a photometric and spectroscopic survey of early-type spirals with even a slight indication of geometric orthogonal decoupling between bulge and disc. As first result of this survey we present the case of NGC 4672. This is a highly inclined early-type disc galaxy which at long exposures appears as a fairly normal Sa galaxy, but at shorter exposures shows a bulge component slightly elongated perpendicularly to the disc reminiscent of the NGC 4698 structure. We therefore measured both the gaseous and stellar kinematics along the major and minor axes of NGC 4672, as shown in Figure 3.

Whitmore *et al.* (1990) classified NGC 4672 as a possible candidate for a polar-ring galaxy. However the major-axis gas velocity curve we measured shows different gradients in its inner and outer parts, indicating that it contains an edge-on

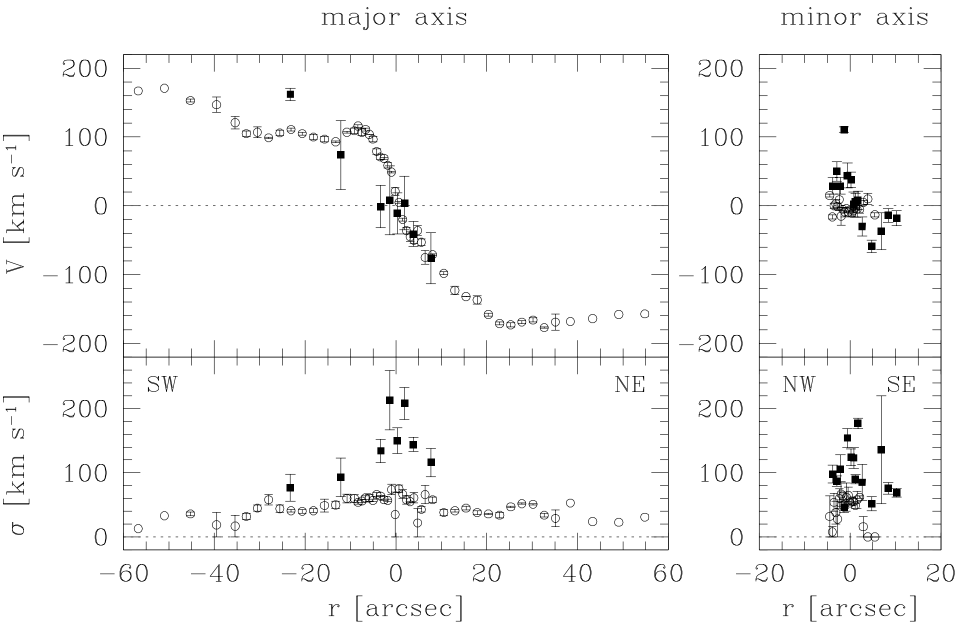

Figure 3. The stellar (*filled squares*) and ionized gas (*open circles*) kinematics measured along the major (P.A. = 46°) and minor (P.A. = 133°) axes of NGC 4672. The heliocentric system velocity is $V_{\odot} = 3275 \pm 20$ km s^{-1}.

gaseous disc instead of a ring (for which a constant-velocity gradient is expected). We observe a stellar velocity gradient along the galaxy minor axis, and if we heed the hint of a zero-velocity plateau along the major axis for $-4'' < r < 2''$, a kinematic decoupling between the inner and outer stellar components of NGC 4672 should be present, as well as in the case NGC 4698.

For NGC 4698, if we adopt the non-parametric photometric decomposition, in order to explain the central plateau along the disc major axis, the velocity gradient within 6″ and the elongation of inner isophotes along the disc minor axis, it is necessary to assume the presence of a third luminous component in the central region of this galaxy, in addition to the round bulge and a the disc with a flattened luminosity profile. Therefore we are led to conceive the presence in the centre of NGC 4698 of a structure similar to the kinematically decoupled cores observed in several ellipticals (see Mehlert *et al.*, 1998, for a list). It should be noted that, according to the statistics by Bertola *et al.* (1991), round bulges, as well as those perpendicular to the disc, are not present. In any case, the main result of this paper, namely the photometric and kinematic orthogonal decoupling between the inner region of the bulge and the whole disc of NGC 4698 (Figure 1), is independent of the type of decomposition, suggesting that this galaxy experienced a ‘second event’ in its history.

References

Baugh, C.M., Cole, S. and Frenk, C.S.: 1996, *Mon. Not. R. Astron. Soc.* **283**, 1361.
Bertola, F.: 1987, in: T. de Zeeuw (ed.), *Structure and Dynamics of Elliptical Galaxies*, Reidel, Dordrecht, p. 135.
Bertola, F., Vietri, M. and Zeilinger, W.W.: 1991, *Astrophys. J. Lett.* **374**, 13.
Binney, J.J. and May, A.: 1986, *Mon. Not. R. Astron. Soc.* **218**, 743.
Byun, Y.I. and Freeman, K.C.: 1995, *Astrophys. J.* **448**, 563.
Corsini, E.M., Pizzella, A., Sarzi, M., Cinzano, P., Vega Beltrán, J.C., Funes, J.G., Bertola, F., Persic, M. and Salucci, P.: 1999, *Astron. Astrophys.* **342**, 671.
Davies, R.L., Efstathiou, G., Fall, S.M., Illingworth, G. and Schechter, P.L.: 1983, *Astrophys. J.* **266**, 41.
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Jr. H.G., Buta, R.J., Paturel, G. and Fouquè, P.: 1991, *Third Reference Catalogue of Bright Galaxies*, Springer, New York. (RC3)
Kauffmann, G.: 1996, *Mon. Not. R. Astron. Soc.* **281**, 487.
Melhert, D., Saglia, R.P., Bender, R. and Wegner, G.: 1998, *Astron. Astrophys.* **332**, 33.
Merrifield, M.R.: 1996, in: R.D. Buta, D.A. Crocker and B.G. Elmegreen (eds.), ASP Conf. Ser., vol. 91, *Barred galaxies*, ASP, San Francisco, p. 176.
Moriondo, G., Giovanardi, C. and Hunt, L.K.: 1998, *Astron. Astrophys. Suppl.* **130**, 81.
Sandage, A. and Bedke, J.: 1994, *The Carnegie Atlas of Galaxies*, Carnagie Institution, Washington DC. (CAG)
Sandage, A. and Tammann, G.A.: 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies*, Carnagie Institution, Washington DC.
Whitmore, B.C., Lucas, R.A., McElroy, D.B., Steiman-Cameron, T.Y., Sackett, P.D. and Olling, R.P.: 1990, *Astron. J.* **100**, 1489.