NGC 3521: STELLAR COUNTER-ROTATION INDUCED BY A BAR COMPONENT

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Abstract. The spiral galaxy NGC 3521 exhibits apparently normal kinematic properties of gas and stars along its major axis. However, the analysis of the LOSVD reveals strong asymmetries. A decomposition of the LOSVD data with a two-Gaussian component model shows two counter-rotating stellar components. The observed kinematic decoupling is interpreted as a projection effect induced by the presence of a bar component seen almost end on. The bar produces locally a greater concentration of retrograde stellar orbits but this does not relate to a specific counter-rotating population. The signatures of the bar are identified in the velocity field derived from long-slit spectra obtained along the major, minor and 45° intermediate axes and from R-band surface photometry.

1. Introduction

The physical properties of bar components in spiral galaxies have become one of the key issues in the study of the interrelation of gaseous and stellar kinematics in disc galaxies (e.g. Bosma, 1996). The global gas kinematics of barred spirals are much more complex than that of ordinary spiral galaxies. Understanding the consequences of the presence of a bar is even more important, since about 60% of all spiral galaxies exhibit a bar component. One of the most important features is the presence of non-circular gas motions induced by the bar indicative also of a non-spheroidal structure of the bulge.

Accretion of external gaseous matter is considered as an important mechanism for the replenishment of the gas component in the bulge. It is a very common phenomenon in early-type galaxies (Bertola, Buson and Zeilinger, 1992). One of the most important observational signatures for such an event is that in these objects the kinematics of the gas is decoupled from that of the main body of the galaxy leading to phenomena such as counter-rotation or orthogonal angular momenta of gas and stars. For disc galaxies the picture is more complex since one

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TABLE I

Observations for NGC 3521: instrumental set-up

Parameters	4.5 m MMT + RCS	3.6 m ESO + EFOSC2	
Date	1990 Dec 17	1998 Mar 20–21	
Seeing (FWHM)	$1.0''$–$1.5''$	$1.0''$–$1.5''$	
Slit size	$1.25'' \times 4.0'$	$1.0'' \times 5.7'$	
Scale	0.30 $''$/pixel	0.32 $''$/pixel	
Reciprocal dispersion	0.82 Å/pixel	1.99 Å/pixel	1.77 Å/pixel
Wavelength range	4850–5450 Å	4320–5350 Å	5580–7390 Å
Instrumental resolution	$\sim$ 45 km s^{-1}	$\sim$124 km s^{-1}	$\sim$ 111 km s^{-1}
Slit position angle	163°	163°, 73°	163°, 28°, 73°

has to take into account the pre-existing gaseous and stellar components of bulge and disc. If, however, gaseous material is accreted in a second event, it is expected to remain decoupled from the stars because stellar systems are essentially frictionless. Kinematic decoupling is observed in a number of spiral galaxies supporting this picture: e.g. NGC 3593 (Bertola *et al.*, 1996), NGC 4138 (Jore, Broeils and Haynes, 1996), NGC 4826 (Rix *et al.*, 1995) and NGC 7217 (Merrifield and Kuijken, 1994). There is, however, no conclusive evidence in barred spirals.

NGC 3521 is classified as a normal Sb by Sandage and Tammann (1981) and as an SABbc by de Vaucouleurs *et al.* (1991). Its total B-band magnitude is $B_T = 9.8$ mag (RC3) and we adopt a distance of 8.7 Mpc ($H_0 = 75$ km s^{-1} Mpc^{-1}) which corresponds to a linear scale of 42 pc arcsec^{-1}. As inclination a value of 61° is used (Tully, 1988). From the kinematic point of view, NGC 3521 exhibits apparently normal properties of gas and stars along its major axis.

2. Observations and Data Reduction

Long-slit spectra of NGC 3521 were collected at different position angles with the 4.5 m MMT in Arizona and with the 3.6 m Telescope at ESO La Silla. The instrument set-up is described in Table I. Spectra of late G and early K type giant stars were also obtained to be used as velocity templates. Comparison lamp exposures were obtained before and after each object integration in order to measure and correct instrument flexure effects. The spectra were calibrated using standard procedures in the ESO-MIDAS software package. The night sky contribution was determined from the border regions of the images and then subtracted.

The stellar kinematics (LOSVD) was derived 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 K2 III star HR 3905 and the

K2 III star HR 6415 were used as kinematic templates in the 1990 December an 1998d March runs, respectively.

The kinematics of the ionized gas was derived from the analysis of the [NII] (λ6583.41 Å) emission line using the the MIDAS spectral line analysis package ALICE. The position, the FWHM and the (uncalibrated) line flux were measured by fitting interactively a Gaussian to the emission line after subtracting the continuum contribution by fitting a suitable polynomial to the surrounding spectral region. In order to improve the S/N ratio of the emission line, several adjacent spectral rows were coadded in the outer parts of the galaxy spectrum.

For the analysis of the photometric properties of NGC 3521 we used Cousins *R*-band images from the 2.5 m Isaac Newton Telescope data archive. The images were obtained with the TEK3 1024 × 1024 pixel CCD at the Cassegrain focus with a scale of $0.59''$ pixel^{-1} yielding a field of $10' \times 10'$. The typical seeing was of the order $\simeq 3.4''$ as measured from the FWHM of stellar images in the field. The data reduction was carried out using standard IRAF procedures.

A more detailed description of the data analysis will be given elsewhere (Zeilinger *et al.*, 2001).

3. Discussion and Results

The kinematic results derived for the major axis spectrum are displayed in Figure 1. The minor axis and 45° intermediate-axis data are found to be in agreement with the picture of a ‘normal’ rotating spiral. There are, however, two noticeable features in the global kinematic properties of NGC 3521:

1. Gas and stars exhibit the same amount of rotation having at the same time comparable values of the velocity dispersion.
2. The h_3 profile shows pronounced asymmetries, which are interpreted as typical signatures of more than one kinematic component.

A decomposition of the LOSVD along the optical major axis with a two-Gaussian fit indeed yielded two components in apparent counter-rotation to each other (Figure 2). It is evident that the counter-rotating component presents a lower velocity gradient than the second one which is in co-rotation with the main body of the galaxy as deduced from the gaseous kinematics in the central parts of the galaxy ($r \leq 5''$). However, at larger radii the two components appear to be rotating with the same $|v|$ but with opposite angular momentum vectors.

There are two possible explanations for this:

1. The stellar counter-rotation is due to the acquisition of external material. If this is the case, one has nevertheless still to account for the fact that the gas rotates more slowly than the stars. Assuming that the gaseous disc is misaligned with respect to the stellar body in the central kpc region could solve this problem. This could also explain why the two counter-rotating stellar components are not resolved since gas and stars are moving apparently with equal velocities.

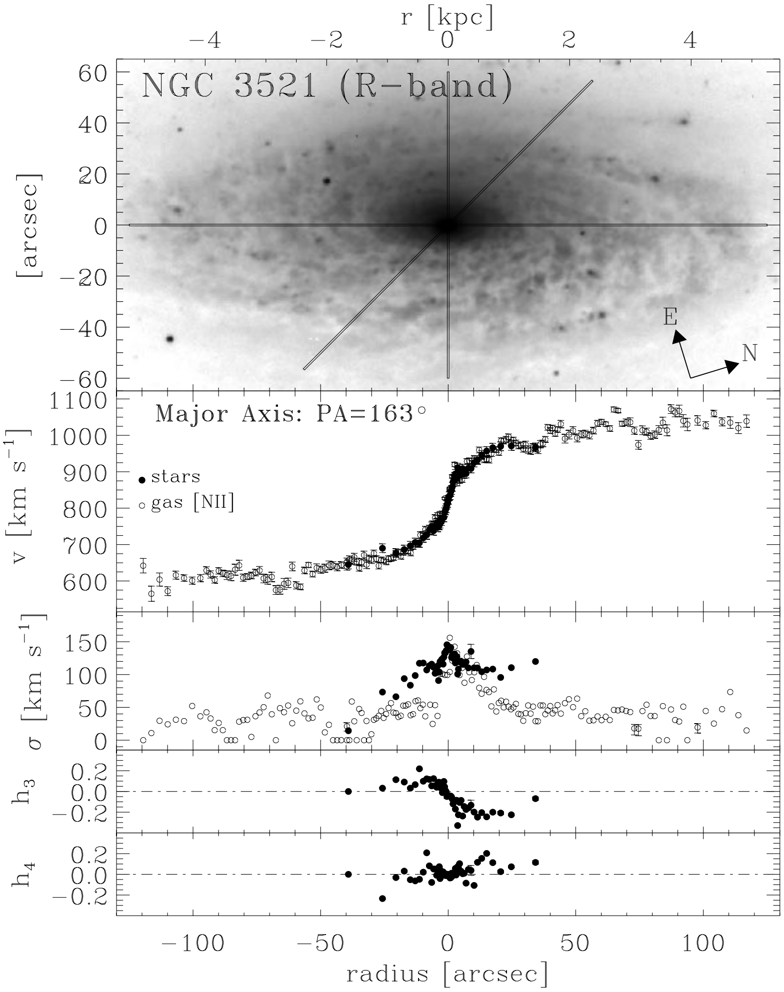

Figure 1. Major-axis kinematics of NGC 3521 together with the scaled ING *R*-band image. The slit positions are indicated in the image.

2. An alternative explanation would be the presence of a bar component.

The surface photometry of the *R*-band image of NGC 3521 helps to disentangle this problem (Figure 3) supporting the morphological classification as barred spiral (SABbc) by de Vaucouleurs *et al.* (1991). The signature of a bar component is evident in the surface brightness and geometric profiles in the region $25'' < r < 45''$.

The velocity curve of gas and stars along the 45° intermediate axis shows a conspicuous ‘wavy pattern’ as described by Bettoni and Galletta (1997) due to

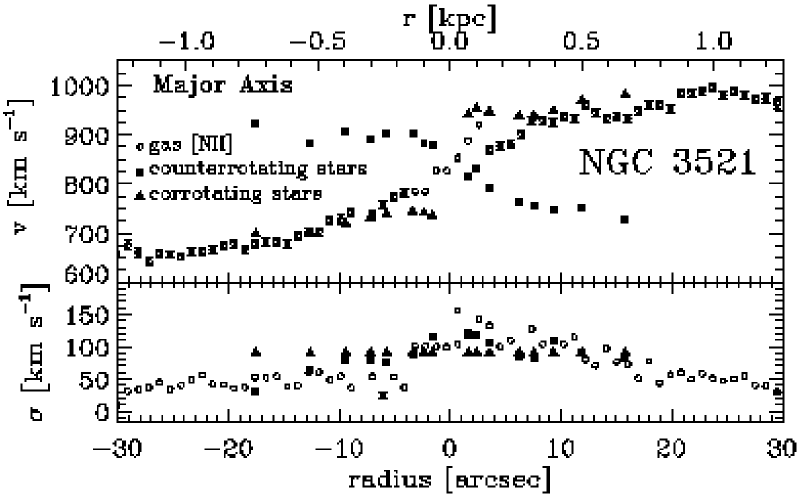

Figure 2. Decomposition in two Gaussians of the LOSVD of the stars in the major axis kinematics of NGC 3521. Solid triangles represent the stars co-rotating with the main body and filled squares the stellar counter-rotating component.

the presence of a bar component. The wavy pattern observed in the line-of-sight velocity curve is a feature appearing along the bar major axis as a consequence of the presence of retrograde orbits trapped around the x_4 family (quasi-circular, retrograde orbits) in the distribution function (Wozniak and Pfenniger, 1997). In this case, the stellar counter-rotation observed is due to a locally greater concentration of these retrograde orbits. The barred galaxy models of Wozniak and Pfenniger predict between 14% and 30% of stellar mass in retrograde orbits inside corotation. The x_4 orbits, perpendicular to the major axis of the bar, can support a counter-rotating secondary (nuclear) stellar and/or gaseous bar.

Figure 4 shows the velocity map of a kinematic model for NGC 3521. The model was obtained by fitting a tilted ring model to the kinematic data. In short, parameters describing the galaxy's velocity field in terms of a set of concentric rings are fitted to the data using a least-squares algorithm. The result agrees well with the presence of a characteristic axisymmetric potential plus that due to a bar. The velocity field shows the classic 'spider' pattern indicating circular motions in a rotating disc and also important deviations from circular velocities. The first deviations from the iso-velocity contours near the edges are produced by streaming motions and the stronger deviations in the velocity field inner part of the disc are due to a bar-induced spiral density wave.

In light of the available photometric and kinematic information, we think that the presence of a bar has been demonstrated and successfully explains the peculiar

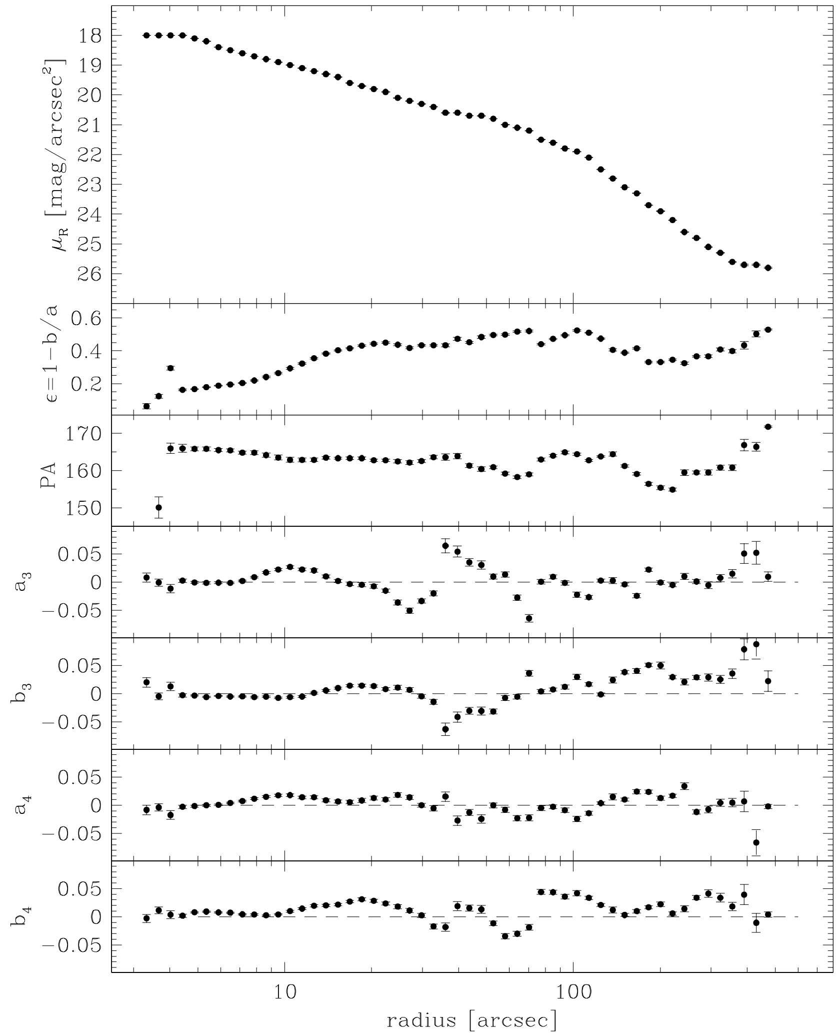

Figure 3. NGC 3521 surface brightness (*upper panel*), ellipticity (*second panel*) and position angle (*third panel*) as a function of radius in the R band. The four windows below this represent the amplitudes (a_3, b_3, a_4, b_4), divided by the semi-major axis length and local intensity gradient, which measure the isophotal deviations from perfect ellipticity.

features observed in the LOSVD of the stars and in the R-band photometry. The bar would be orientated almost end on, and is therefore hard to detect photometrically alone. A similar case is NGC 7331, as reported by Prada *et al.* (1996).

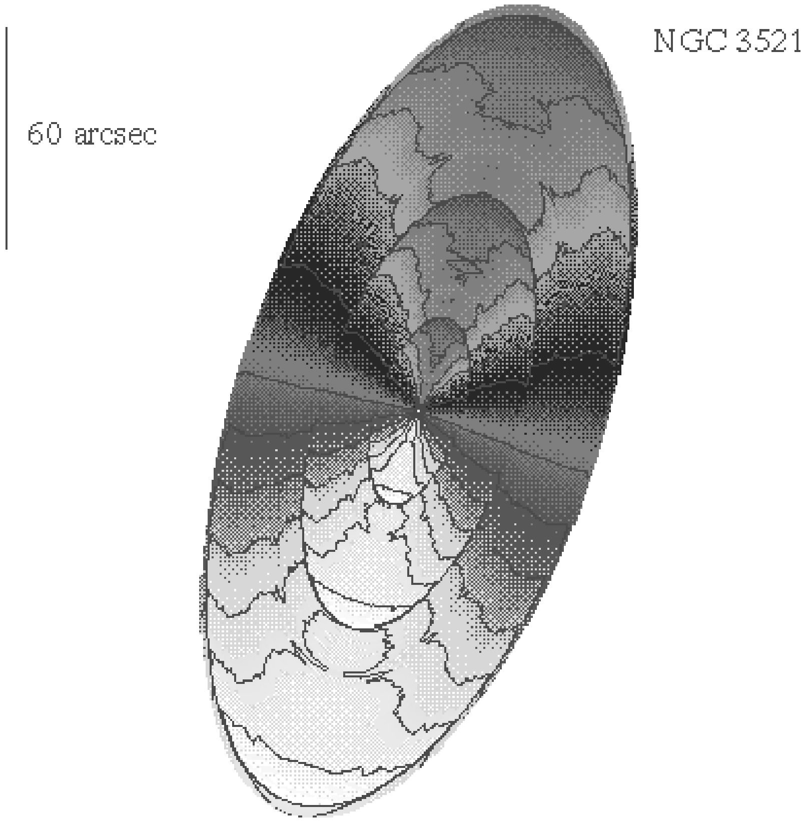

Figure 4. Model velocity map for NGC 3521 calculated by fitting a tilted ring model to the spectroscopic observations. The velocity contours are at intervals 10 km s^{-1}.

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