A COUNTERROTATING CENTRAL COMPONENT IN THE BARRED GALAXY NGC 5728

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1. INTRODUCTION

The discovery of counterrotating cores in elliptical galaxies (Franx & Illingworth 1988; Bender, Saglia, & Gerhard 1994; Rix & White 1992) and the presence of extended retrograde motions in the discs of early type spirals (Rix et al. 1992; Merrifield & Kuijken 1994; Bertola et al. 1996) have been reported in the last few years. This phenomenon is also present in the Sb galaxy NGC 7331, where the bulge rotates opposite to the disc (Prada et al. 1996). The origin of the stellar counterrotation has been extensively studied and generally attributed to the accretion of a small satellite galaxy or gradual infall of gas in a retrograde orbit (e.g., Merrifield & Kuijken 1994; Thakar & Ryden 1996). However, other alternatives are possible in terms of dynamical instabilities (e.g., Wozniak & Pfenniger 1997) that make it still unclear whether the causes of counterrotation are of external or internal origin. Up to now no observational evidence exists of extended stellar counterrotation in barred galaxies; this discovery would represent a challenge to understand the significance of counterrotation throughout the Hubble sequence. Having this in mind, we decided to conduct a photometric and spectroscopic study of the SAB(r)a galaxy NGC 5728 (de Vaucouleurs et al. 1991). As a result of this analysis it will be shown here that extended retrograde motions can also be present in barred systems. In combination with previous observations, our results demonstrate that counterrotation is present all along the Hubble sequence; the study of this phenomenon could thus shed light on understanding the mechanisms and evolution of galaxy formation.

The paper is organized as follows: Section 2 gives details of the observations and data reduction. Section 3 presents a brief description of the structure of the galaxy. Section 4 describes the analysis of the stellar line-of-sight velocity distribution (LOSVD). Section 5 discusses on the nature of the kinematical components present in this galaxy, and finally, § 6 gives the discussions and conclusions of this work.

ABSTRACT

We present a detailed study of the stellar kinematics in the barred galaxy NGC 5728 based on I-band photometry and long-slit spectroscopic observations in the region of the near-IR Ca II triplet. The analysis of the stellar line-of-sight velocity distribution (LOSVD) has revealed, in the central regions of the bar, the presence of a cold ($v/\sigma \approx 2.5$), prograde, $S$-shaped velocity component that coexists in the central 4 kpc, with a fainter and hotter ($v/\sigma \approx 0.5$) counterrotating component. Beyond 4 kpc from the nucleus, the LOSVD shows the stellar bar kinematics. The comparison of the radial surface brightness profile of the velocity components with that obtained from an I-band image shows that the counterrotating core follows a $r^{1/4}$ profile, while the $S$-shaped component does not follow the flat-bar surface brightness profile. Several possible scenarios accounting for such kinematic signatures found in the center of the bar in NGC 5728 are discussed. The data presented in this paper show for the first time the presence of extended retrograde motions in barred systems that, together with previous discoveries, seem to indicate that the stellar counterrotation is a phenomenon present all along the Hubble sequence.

Subject headings: galaxies: formation — galaxies: individual (NGC 5728) — galaxies: kinematics and dynamics — galaxies: structure

2. OBSERVATIONS AND DATA REDUCTION

Long-slit spectroscopic observations of NGC 5728 were performed on several runs with the double-arm ISIS spectrograph on the 4.2 m William Herschel Telescope (WHT) at La Palma. In 1996 July, the slit, 1'3 wide, was placed along p.a. 30°, close to the bar major axis (p.a. 33°; Schommer et al. 1988). We used the red arm of ISIS with a 1200 line mm$^{-1}$ grating centered at 8750 Å, including the near-IR Ca II triplet. The dispersion was 0.38 Å pixel$^{-1}$. Two consecutive 1800 s exposures were recorded. As a velocity template, we observed the K III HR 5826 star. The seeing was 1'4. A similar setup was used in a previous run (1995 February); this time a 1'' wide slit was placed along p.a. 86° and 23°. A 600 line mm$^{-1}$ grating was used, giving a dispersion of 0.79 Å pixel$^{-1}$. Two 1800 s frames were taken centered at 8750 Å for p.a. 86° and one 1800 s exposure for p.a. 23°. The G8 giant HR 7753 star was observed as velocity template in this run. The seeing was 0'9. In both runs the slit length was 4' and centered on the apparent optical nucleus of NGC 5728. The detector was a 1024 x 1024 TEK CCD giving 0.36 pixel$^{-1}$. The debias, flat-fielding, wavelength calibration, and sky subtraction were done in the standard way using the IRAF package.

An I-band CCD image of NGC 5728 was taken with the BroCam CCD camera on the 2.5 m Nordic Optical Telescope (NOT) at La Palma for the analysis of the morphology and comparison with the stellar kinematics. These observations were done in 1996 August with a seeing of 0'7. The camera used a 1024 x 1024 TEK CCD with 0.176 pixel$^{-1}$. In total, we recorded a 40 minute exposure. Figure 1 presents this image; the bar major axis and nuclear features inside the spheroidal component of the galaxy are indicated. Hereafter, we will refer to p.a. 30° as the bar major axis.

3. THE MORPHOLOGY OF NGC 5728

An isophotal analysis of the I-band image of NGC 5728 was done using GALPHOT (Jorgensen, Franx, & Kjærgaard 1992) to determine the surface brightness, ellipticity, position angle, and C4 Fourier coefficient along the semi-
The near-IR Ca II triplet absorption features were used to determine the stellar LOSVD. The analysis was performed by means of the two-dimensional unresolved Gaussian decomposition algorithm described in Prada et al. (1996) and Prada, Gutiérrez, & McKeith (1998). The resolutions used for the observations presented here are 2 and 1.4 pixels in the spectral and spatial axes, respectively, for p.a. 23° and 86° and 3 and 2.2 pixels, respectively, for the bar major-axis spectra. Figure 3 (left) shows the spectra in several positions along the bar major axis in the spectral region analyzed, i.e., 8450–8700 Å, together with the modeled spectra obtained by convolution of the derived LOSVD with the spectrum of the velocity template. The corresponding LOSVD are also plotted on the right side of Figure 3. One sigma error bars for each LOSVD were obtained by Monte Carlo simulations in the following way: first we consider that the difference between the real and the modeled spectra gives an estimation of the error bar in each point of the real spectra. Then we simulate spectra considering that the astronomical signal corresponds to the modeled spectra and the noise follows a Gaussian distribution with the error bar mentioned above. We again run our algorithm for each simulation, obtaining the distribution of the LOSVD and taking the dispersion of this distribution as an estimation of the uncertainty in each velocity bin of the LOSVD. Finally, we average over all velocity bins at each position. These error bars constitute the statistical uncertainty relative to the fit between the original and the recovered spectra and do not...
We have parameterized the LOSVD profiles by fitting one, and, where possible, two Gaussian functions; this is enough to describe the major kinematical features. Figure 5 shows the results of this analysis, plotting the radial velocities as a function of the radius along the bar major axis and at p.a. 23° and 86°. These can be described as an S-shaped velocity profile in the central 20" along the bar major axis with $\sigma \sim 70 \pm 10$ km s$^{-1}$ and a maximum velocity of $\sim 170$ km s$^{-1}$ at $\pm 5^\circ$. Superposed on this cold component is a fainter, counterrotating component that extends from 2" out to 11" at either side of the nucleus along the bar major axis with $\sigma = 95 \pm 10$ km s$^{-1}$ and a slow rotation reaching $\sim 90$ km s$^{-1}$ at $\pm 5^\circ$. In the central 2", a single Gaussian function was fitted to the LOSVD with $\sigma = 165 \pm 15$ km s$^{-1}$. A similar velocity pattern is also present along p.a. 23°. At this position angle we fitted two Gaussian functions to the LOSVD in central 2" (see Fig. 5). Beyond a $\sim 20^\circ$ radius, the velocity linearly rises with radius and the velocity dispersion is $55 \pm 10$ km s$^{-1}$. The kinematics in this region can be attributed to the stellar bar (see next section).

The velocities along p.a. 86° basically describe the overall kinematics seen along the bar major axis, only in the central 4" the LOSVD appears asymmetric. This might suggest the presence of the counterrotating component seen at this position angle, since the fit of a single Gaussian function of $\sigma = 160 \pm 15$ km s$^{-1}$ to the LOSVD agrees with the velocity dispersion of a single Gaussian fit to the LOSVD in the very center along the bar major axis. However, higher spectral resolution data is needed to confirm the presence of the two components along p.a. 86°.

In summary, we have found in the central parts of the 11 kpc (we adopt a scale of 1" = 190 pc for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$) bar of NGC 5728 a cold ($v/\sigma \sim 2.5$), prograde, S-shaped velocity component that coexists in the central 4 kpc with a dynamically hot ($v/\sigma \sim 0.5$) counterrotating component.

5. The nature of the central bar kinematics

A comparison between the photometric and the kinematic components found in the center of the bar in NGC 5728 should shed some light on the nature and dynamics of such structures. For this purpose, we have compared the surface brightness profile for a cut along p.a. 30° obtained from the I-band image with the relative fluxes of the velocity components found in our spectroscopic analysis along this position (see Fig. 6).

On the basis of its kinematical and morphological properties, we propose to fit the surface brightness profiles of the three velocity components inside 70" with three components. First we model the bar by a flat bar profile, $I = I_0/(1 + \exp [(r - b)/a])$, which describes the bar major axis–surface brightness profiles of early type barred galaxies (Elmegreen et al. 1996). The parameters found for NGC 5728 yield a characteristic scale length of $b = 53^\prime$, $a = 4.1^\prime$ for the region between 30° and 60°. For the counterrotating component we propose an $r^{1/4}$ law for the fit, because this is a hot, slowly rotating component and can be associated with the spheroidal component present in the central 20" of the galaxy (see § 3). We get a very good fit with an effective radius of 21′8 for the region between 1° and 9°. Finally, the brighter component in this region, i.e., the S-shaped velocity

![Fig. 2](image-url) - Isophotal analysis of the I-band surface photometry of NGC 5728. From top to bottom: the major axis surface brightness profile, ellipticity profile, position angle profile, and C4 Fourier coefficient profile, plotted against the square root of the radius in arcseconds.
profile, has been fitted by an exponential profile of 4'' scale length. The sum of the three modeled surface brightness profiles agrees very well with the overall radial surface brightness I-band image cut along the bar major axis (see Fig. 6).

The question now is whether the counterrotating core and/or the S-shaped velocity profile represent the kinematics of the bar in the central regions. The S-shaped velocity component has the same $v/\sigma$ as the bar kinematics outside a radius of 20'', but its surface brightness profile does not follow the flat-bar surface brightness profile. The reason for this might be the contamination by the nuclear feature and the star-forming ring inside the 5'' radius. Following the discussion by Wilson et al. (1993), we agree with them that the nuclear feature corresponds to a blue component that dominates the light in the very central regions (see Fig. 5) but does not contribute to the gravitational potential as indicated by its kinematics (see § 4). The reason why we state that the S-shaped component is associated to the barred kinematics is that the gaseous velocity field in NGC 5728 (see Rubin 1980; Schommer et al. 1988) also shows an S-shaped feature and follows the stellar kinematics at radii larger than 20''. The gaseous kinematics has been interpreted by Schommer et al. (1988) in terms of models of gas motions in nonaxisymmetric potentials, and they claim that the star-forming ring and the S-shaped velocity field may be related to an inner Lindblad resonance. The gaseous kinematics also show an expansion of $\sim 400$ km s$^{-1}$ in the central 3'5 but do not show any counterrotating signature.

However, the S-shaped velocity profile can also be interpreted as a very fast rotation due to a heavy mass concentration in the center of the bar in NGC 5728. From the measured velocities in the very center, we can estimate an mass of $\sim 4 \times 10^9 M_\odot$ inside a radius of 300 pc for an inclination of 48'' (Schommer et al. 1988). This mass could be related to its Seyfert nucleus.

6. DISCUSSION AND CONCLUSIONS

Several scenarios have been proposed to explain kinematical structures similar to the ones found in NGC 5728: dynamical instabilities, the accretion of a satellite, or gas
infall with retrograde orbits. In the first case a non-axisymmetric structure such as a bar modifies the stellar orbits, introducing retrograde motions in its center, as shown in numerical simulations by Wozniak & Pfenniger (1997). In their models, the presence of retrograde orbits (almost circular and perpendicular to the major axis of the bar) inside the corotation radius can explain local counterrotation or even could support a counterrotating core. One can expect that if the mass on such orbits increases, a critical mass ratio can be reached beyond which the dynamics of the counterrotating component are decoupled from the direct bar. In this scenario the presence of the counterrotating core in NGC 5728 could be interpreted as a secondary retrograde bar, and its presence could thus be intrinsic to the primary bar. Indeed, n-body simulations by Friedli (1996) have shown that a counterrotating secondary stellar bar can be stable.

However, we cannot rule out an external origin for the presence of retrograde motions in the center of NGC 5728 as shown by the models of Thakar & Ryden (1996). They explain the counterrotation of the disks of spirals by the accretion of small satellites or gas with negative angular momentum.

We conclude that the data presented in this paper reveal for the first time the presence of extended retrograde motions in barred galaxies that, together with previous discoveries in ellipticals, early-type spirals, and Sb galaxies (see Bertola & Corsini 1997 for a review), seem to indicate that counterrotation is a phenomenon present all along the Hubble sequence. The scenarios mentioned above could explain these, or, alternatively, a more general physical mechanism that allows for galaxy transformation processes along the Hubble sequence might be needed. In any case, the relevance of the phenomenon is clear and requires for a deeper understanding, more statistics, and two-dimensional spectroscopy.

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FIG. 5.—Radial velocities determined by fitting two Gaussian functions to the LOSVD along the bar major axis (top), p.a. 23° (middle), and p.a. 86° (bottom). Open and filled squares refer to the fainter and brighter components present in the LOSVD. The triangles refer to a single component in the LOSVD. The open triangles in p.a. 86° refer to the fit of a single Gaussian function to the asymmetric LOSVD in the central 3.5. The dashed line corresponds to the continuum at ~8500 Å obtained from the spectroscopic data along p.a. 86°. The letters ABD indicate the position of the features named by Wilson et al. (1993) in the HST continuum images of NGC 5728.

FIG. 6.—Surface brightness profile of the three velocity components obtained from the LOSVD along the bar major axis, i.e., the counterrotating core (open squares), the cold S-shaped component (filled squares), and the bar (triangles). The open circles represent the sum of the counterrotating and S-shaped surface brightness profiles. Also plotted is the surface brightness cut along the bar major axis obtained from the I-band image (solid line). The dotted lines are the modeled surface brightness profiles for the three velocity components. The dashed line is the sum of these three model components. (see text).
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