DIRECT CONFIRMATION OF TWO PATTERN SPEEDS IN THE DOUBLE-BARRED GALAXY NGC 2950

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ABSTRACT

We present the surface photometry and stellar kinematics of NGC 2950, which is a nearby and undisturbed SB0 galaxy hosting two nested stellar bars. We use the Tremaine-Weinberg method to measure the pattern speed of the primary bar. This also permits us to establish directly and for the first time that the two nested bars are rotates with different pattern speeds and, in particular, that the rotation frequency of the secondary bar is higher than that of the primary one.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 2950) — galaxies: kinematics and dynamics — galaxies: photometry — galaxies: structure

1. INTRODUCTION

Large-scale bars are present in some two-thirds of all disk galaxies (Knapen, Shlosman, & Peletier 2000; Eskridge et al. 2000). Secondary stellar bars within large-scale bars are also common, occurring in about one-third of the barred galaxies (Laine et al. 2002; Erwin & Sparke 2002). Interest in secondary stellar bars is motivated by the hypothesis that they are a mechanism for driving gas to small radii to feed the supermassive black holes powering active galactic nuclei (e.g., Regan & Mulchaey 1999). However, the efficiency of such transport is uncertain because of our complete lack of knowledge of the gas and dust content of bars (Mulchaey 1999). However, the efficiency of such transport is uncertain because of our complete lack of knowledge of the gas and dust content of bars. Nonetheless, when the two bars are not likely to rotate rigidly through each other, the presence of nested bars with different pattern speeds has been inferred largely on the basis of their apparently random relative orientations (Buta & Crocker 1993). The possibility that the secondary bar has an intermediate inclination, and both bars have intermediate offsets relative to the major axis are available for a galaxy. The presence of nested bars with different pattern speeds has been inferred largely on the basis of their apparently random relative orientations (Buta & Crocker 1993). The possibility that the secondary bar has an intermediate inclination, and both bars have intermediate offsets relative to the major axis are available for a galaxy.

A model-independent method for measuring pattern speeds in the double-barred galaxy NGC 2950 is classified RSB0(r), and its total absolute magnitude is . The presence of a secondary stellar bar has been discussed in terms of its rotation frequency of the secondary bar is higher than that of the primary one. The presence of a secondary stellar bar has been discussed in terms of its rotation frequency of the secondary bar is higher than that of the primary one.

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3. SURFACE PHOTOMETRY

The photometric observations of NGC 2950 were carried out at the 1 m Jacobus Kapteyn Telescope on 2000 December 27–28. We took multiple exposures in the Harris B (4 × 1200 s), V (3 × 480 s), and I (18 × 150 s) bandpasses using the SITe2 2048 × 2048 CCD. This camera has a scale of 0.33 pixel⁻¹, yielding an unvignetted field of view of ~10' × 10'. The seeing FWHM was ≈1.0'. The data reduction has been carried out using standard IRAF tasks as in Debattista, Corsini, & Aguerri (2002, hereafter DCA02). Images were bias-subtracted, flat-fielded, cleaned of cosmic rays, and corrected for bad pixels. The sky-background level was removed by fitting a second-order polynomial to the regions free of sources. Photometric calibration, using standard stars, included corrections for atmospheric and Galactic extinction and for color as in DCA02.

The radial profiles of surface brightness, ellipticity, and P.A. were obtained by fitting elliptical isophotes with the IRAF task ELLIPSE. We first fitted ellipses, allowing their centers to vary to test for patchy dust obscuration. We found no evidence of a varying center within the errors of the fits and similar P.A. and ellipticity profiles for all bandpasses. Thus, we concluded that there is little or uniform obscuration, as required for the TW method. The ellipse fits were then repeated with the ellipse center fixed; the resulting photometric profiles are plotted in Figure 1. We interpreted the local maximum in ellipticity at r ≈ 3'' and the corresponding twist and stationary value in P.A. as the photometric signatures of the presence of a misaligned secondary bar inside the primary bar. This is confirmed by the analysis of B−I and V−I color maps and the unsharp mask of the original frames; in all, we find no evidence of other small-scale structures such as nuclear rings or disks, spiral arms, star-forming regions, dust lanes, and/or dust patches, in agreement with previous results (Wozniak et al. 1995; Friedli et al. 1996; Erwin & Sparke 2003). In particular, the structural details unveiled by the unsharp mask of the WFPC2/F814W image of the nucleus of NGC 2950 (Erwin & Sparke 2003) are unlike those typical of nuclear stellar disks (Pizzella et al. 2002). The P.A.'s of the primary (P.A.ₚ = 152.6° ± 0.4°) and secondary bar (P.A.ₛ = 91.1° ± 0.3°) were measured in the I-band image at r = 3'' and r = 2.3'', respectively, at the two peaks in the ellipticity profile (Fig. 1). The lengths of the primary (aₚ = 34.3'' ± 2.1'') and secondary bar (aₛ = 4.5'' ± 0.7'') were measured using three independent methods based on Fourier amplitudes (Aguerri et al. 2000), Fourier and ellipse phases (DCA02), and a decomposition of the surface brightness profiles (Prieto et al. 2001). The inclination (i = 45°6 ± 1°) and P.A. of the disk (P.A.ₐ = 116° ± 1°) were determined by averaging the values measured between 65° and 100° in the I-band profile (Fig. 1).

4. LONG-SLIT SPECTROSCOPY

The spectroscopic observations of NGC 2950 were carried out at the 3.6 m Telescopio Nazionale Galileo on 2001 December 18 (run 1), 2002 March 20–22 (run 2), and 2003 March 9–11 (run 3). The Low Resolution Spectrograph is mounted in combination with the HR-V grism No. 6 with 600 grooves mm⁻¹ and a 0.77 × 8.1 slit. The detector was the Loral CCD with 2048 × 2048 pixels of 15 × 15 μm². The wavelength range from 4660 to 6820 Å was covered with a reciprocal dispersion of 1.05 Å pixel⁻¹ and a spatial scale of 0.275 pixel⁻¹. We obtained four spectra with the slit along the disk major axis (runs 2 and 3) and 11 offset spectra with the slit parallel to it (Y = −3', +1.5', +2.8', ±10' in run 1, Y = ±5', +1'3' in run 2, and Y = −2', +3'5 in run 3; Fig. 2). The exposure times were 2 × 60 and 2 × 45 minutes for the major-axis spectra obtained in runs 2 and 3, respectively, and 45 minutes for all the offset spectra. Comparison lamp exposures before and/or after each object integration ensured accurate wavelength calibrations. Spectra of G and K giant stars served as kinematical templates. The seeing FWHM was ≈1.2' in run 1, ≈1'5' in run 2, and ≈0'9' in run 3. Using standard MIDAS routines, all the spectra were bias-subtracted, flat-field–corrected, cleaned of cosmic rays, corrected for bad pixels, and wavelength-calibrated as in DCA02. The accuracy of the wavelength rebinning (≈2 km s⁻¹) was checked by measuring wavelengths of the brightest night-sky emission lines. The instrumental resolution was 3.10 Å (FWHM), corresponding to σ_int ≈ 80 km s⁻¹ at 5170 Å. The major-axis spectra obtained in the same run were co-added using the center of the stellar continuum as reference. In all the spectra, the contribution from the sky was determined by interpolating along the outermost ≈20'' at the edges of the slit and then subtracted.

5. PATTERN SPEEDS OF THE PRIMARY BAR AND SECONDARY BAR

To measure ψ for each slit (Fig. 3a), we first collapsed each two-dimensional spectrum along its spatial direction in the wavelength range between 5060 and 5490 Å, obtaining a one-dimensional spectrum. The value of ψ was then derived by fitting the resulting spectrum with the convolution of the spectrum of the K1 III star HR 4699 and a Gaussian line-of-sight velocity profile by means of the Fourier correlation quotient (FCQ) method (Bender 1990) as done in ADC03. We estimated uncertainties by Monte Carlo simulations with photon, readout, and sky noise. To compute X for each slit (Fig. 3b), we extracted the luminosity profiles from the V-band image along the position of the slit after convolving the image to the seeing of the spectrum. The V-band profiles match very well the profiles obtained by collapsing the spectra along the wavelength direction, confirming that the slits were placed as intended. We used the V-band profiles to compute X because they are less noisy than those extracted from the spectra, particularly at large
radii. We obtained $\Omega_\ast$ from the values of $X$ and $V$ for the slits at $|Y| \geq 3.1$ and at $Y = 0$ (the latter constrain only the zero point). Since the slits at $|Y| \geq 3.1$ do not cross the secondary bar, we assume $X = X_0$ and $V = V_0$ for them and obtain $\Omega_\ast \sin i$ with a straight-line fit. This gives $\Omega_\ast = 11.2 \pm 2.4$ km s$^{-1}$ arcsec$^{-1}$ (99.2 $\pm$ 21.2 km s$^{-1}$ kpc$^{-1}$; Fig. 3c). The value of $\Omega_\ast$ does not change within errors ($\Omega_\ast = 10.9 \pm 2.4$ km s$^{-1}$ arcsec$^{-1}$) when we exclude the slits at $Y = -3.1$, +3.5, confirming that they are not dominated by the secondary bar (Fig. 2).

We used the FCQ to measure the line-of-sight velocity and the velocity dispersion profiles of the stellar component along the major axis (Fig. 4). All the major-axis spectra were co-added after being convolved to the same seeing. We derived the circular velocity in the disk region, $V_c = 356.6 \pm 1$ km s$^{-1}$, after a standard correction for the asymmetric drift as in ADC03. Thus, the corotation radius of the primary bar is $D_a = V_c/\Omega_\ast = 32.0 \pm 0.6$ kpc, and the ratio $R_{cp} = D_c/D_a$ of the corotation radius to the bar semimajor axis is $R_{cp} = 1.0 \pm 0.1$ (the error intervals on $D_a$ and $R_{cp}$ are at the 68% confidence level and were measured with Monte Carlo simulations as in ADC03). We conclude that, within the errors, the primary bar of NGC 2950 is consistent with all previous measurements of $R_c$ in SB0 galaxies (ADC03), which gives us confidence in our assumption that the signals in the outer slits are generated by the primary bar only.

The photometric and kinematic integrals measured with the innermost slits ($|Y| \leq 2.7$) include a contribution from the secondary bar. In particular, $|V| \gg |V_\nu|$ for the slits at $Y = 0$, and the measured profiles are folded around the center, with the filled circles and asterisks referring to the southeast (receding) and northwest (approaching) sides, respectively.

![Image](image-url)
−2′.5, +2′.8 if we extrapolate \( V_p \) from large \( |Y| \). A straight-line fit to \( X \) and \( V \) for the slits at \( |Y| \leq 2′.8 \) has a slope \((=63.7 \pm 7.1 \text{ km s}^{-1} \text{ arcsec}^{-1}; \text{Fig. 3c})\) that is different at better than the 99% confidence level from the slope \((=8.0 \pm 1.7 \text{ km s}^{-1} \text{ arcsec}^{-1}; \text{Fig. 3c})\) of the straight-line fit for the primary bar. This may be because \( \Omega_1 \neq \Omega_2 \); however, to justify this conclusion, we needed to exclude the possibility of a systematic error due to P.A. errors, which \( X \) and \( V \) are quite sensitive to (Debattista 2003). We tested whether the difference in the slopes of the straight-line fits may only be due to P.A. errors when \( \Omega_1 = \Omega_2 \), by building a model of a S2B galaxy with a single pattern speed from an N-body simulation of an SB0 galaxy described in Debattista (2003). We rotated particles by 90°, rescaled their phase-space coordinates by a factor of 0.2, and added them back to the original galaxy with various primary-to-secondary mass ratios to approximately match NGC 2950. After projecting this system as in NGC 2950, we proceeded to measure \( X \) and \( V \) for slits misaligned with the major axis. Even when P.A. errors reached \( \pm 5° \), we were not able to produce a system that approaches the behavior of our observations. In particular, we were not able to produce a system in which the slopes of the integrals plotted versus \( |Y| \) are larger for \( V \) and smaller for \( X \) in the region of the secondary bar than in the region of the main bar, as we observed in NGC 2950 (Figs. 3a and 3b). We therefore concluded that the signatures we observed could not be an artifact of any P.A. misalignments on two bars rotating with a single pattern speed. Our results, therefore, lead us to conclude, directly and for the first time, that \( \Omega_1 \neq \Omega_2 \).

However, estimating \( \Omega \) is model-dependent; we illustrate this by considering two extreme cases. First, we assumed that the secondary bar dominates at \( |Y| \leq 2′.8 \) and used equation (1) with \( \Omega \) replaced by \( \Omega_2 \) to find \( \Omega_{s,1} = 89.2 \pm 9.9 \text{ km s}^{-1} \text{ arcsec}^{-1} \) (Fig. 3c). In the second case, we rewrote equation (2) as \( X_c(\Omega_1 - \Omega_2) \sin i = V - V_p X \sin i \). The observed quantities are \( X \) and \( V \), while \( \Omega_0 \) was measured above. To obtain \( X_c \), first we derived the values of \( X_c \) in the region of the nuclear bar by fitting a straight line to the values of \( X \) at \( |Y| \geq 0′.1 \) (fits extending to smaller \( |Y| \) give larger \( |\Omega| \)) and obtained \( X_c = X - X_p \). Then plotting \( (V - V_p)X \sin i \) versus \( X_c \), we obtain \( (\Omega_1 - \Omega_2) \sin i \) as the slope of the best-fitting line; the result is \( \Omega_{s,2} = -21.2 \pm 6.2 \text{ km s}^{-1} \text{ arcsec}^{-1} \); i.e., the secondary bar is counterrotating relative to the primary. (Note that the range from \( \Omega_{s,1} \) to \( \Omega_{s,2} \) passes smoothly through \( \pm \infty \), i.e., a vertical line.)

6. Conclusions

We showed that the primary bar in NGC 2950 is rapidly rotating. If this is the norm in S2B galaxies, then it guarantees that primary bars are efficient at funnelling gas down to the radius of influence of secondary bars. In Figure 4, we plot the lines of slope \( \Omega_{s,1} \sin i \) and \( \Omega_{s,2} \sin i \). The range of \( \Omega \) is large enough that it must include the case in which \( R_s \approx 1 \). However, it also includes the case in which \( R_s \approx 2 \), and hydrodynamical simulations find that this leads to inefficient gas transport (Maciejewski et al. 2002).

We suggest two avenues for fruitful future work. First, since the two bars cannot be in exact solid-body rotation (Louis & Gerhard 1988; Maciejewski & Sparke 2000; Rautiainen et al. 2002), a more accurate measurement of \( \Omega \) will require careful modeling and comparison with simulations to account for such effects. Second, it may be that secondary bars oscillate about an orientation perpendicular to the primary bar, possibly accounting for \( \Omega < 0 \). This can be tested by repeating our measurements on a sample of S2B galaxies. Nonetheless, we can confidently conclude that in NGC 2950, the two bars must have different pattern speeds, with the secondary bar having a larger pattern speed.

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