A COUNTERROTATING BULGE IN THE Sb GALAXY NGC 7331

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ABSTRACT

We have found that the bulge of the large, nearby Sb galaxy NGC 7331 rotates retrograde to its disk. Analysis of spectra in the region of the near-IR Ca II triplet along the major axis shows that, in the radial range between 5″ and ~10″, the line-of-sight velocity distribution of the absorption lines has two distinct peaks and can be decomposed into a fast-rotating component with v/σ > 3, and a slower rotating, retrograde component with v/σ ~ 1–1.5. The radial surface brightness profile of the counterrotating component follows that of the bulge, obtained from a two-dimensional bulge-disk decomposition of a near-infrared K-band image, while the fast-rotating component follows the disk. At the radius at which the disk starts to dominate, the isophotes change from being considerably boxy to being very disky.

Although a number of spiral galaxies have been found that contain cold, counterrotating disks, this is the first galaxy known to have a boxy, probably triaxial, fairly warm, counterrotating component, which is dominating in the central regions. If it is a bar seen end-on, this bar has to be thicker than the disk. We find that NGC 7331, even though it is a fairly early-type spiral, does not have a conventional, corotating bulge. The fact that the inner component is retrograde makes us believe that it was formed from infalling material in either stellar or gaseous form (see, e.g., Balcells & Quinn). Another possibility, however, is that the structure of the galaxy has been there since the formation of the galaxy. In this case, it will be a challenge to explain the large change in orientation of the angular momentum when going outward radially.

Subject headings: galaxies: formation — galaxies: individual (NGC 7331) — galaxies: kinematics and dynamics — galaxies: spiral — galaxies: structure

1. INTRODUCTION

In the last decade, many elliptical galaxies have been found that display complicated multiple-component structure in their kinematics and, in some cases, also in their photometry. This structure has been interpreted as being due to mergers (see, e.g., Balcells & Quinn 1990), as being due to components that were formed later from processed gas (Bender & Surma 1992), or as triaxial systems in projection (Statler 1991). Sometimes, these multiple components give rise to disky isophotes, so that they can be found using photometry. However, in general, they are much better seen in the analysis of the line-of-sight velocity distribution (LOSVD). Examples of galaxies with multiple components can be found in, e.g., Franx & Illingworth (1988), Rix & White (1992), and Bender, Saglia, & Gerhard (1994). Typically, they consist of a bright, pressure-supported body, and a fainter, fast-rotating central disk, although this is not always the case (see, e.g., Balcells & Carter 1993).

The kinematics of stars in spiral galaxies has been much less studied. Bulges are generally thought to be supported by rotation (Kormendy 1993), and no nonrotating bulge has been found up to now, except perhaps for the very small bulge in NGC 4550 (Franx 1993). They rotate in the same direction as the disks, although in general they are also partly pressure supported. Recently, however, a number of cases have been found in which a fraction of the stars in the disk rotate in a retrograde way. These include NGC 4550 (Rubin, Graham, & Kenney 1992; Rix et al. 1992), NGC 7217 (Merrifield & Kuijken 1994), and NGC 3593 (Bertola et al. 1996). These counterrotating disks are thought to have originated from infalling gas, accreted in retrograde orbits in a plane close to the equatorial plane (Merrifield & Kuijken 1994).

In this Letter, we present the discovery of a different type of galaxy: one in which the bulge rotates retrograde to the disk. We have found this by analyzing LOSVDs along the major axis of the large, nearby Sb (Sandage & Tammann 1981) galaxy NGC 7331. Here, two components are seen of which the slow, counterrotating one corresponds to the boxy bulge of this galaxy. Explaining the formation of a system like this will be a challenge to galaxy formation theories. Section 2 of this Letter gives details about the observations. In §§ 3 and 4, we describe our analysis of morphology and the LOSVDs. The discussion and conclusions are given in § 5.

2. OBSERVATIONS AND DATA REDUCTION

We obtained long-slit spectra with the ISIS spectrograph on the 4.2 m William Herschel Telescope (WHT) at La Palma (1992 August) along the major axis (p.a. 167°; Bosma 1981) of NGC 7331. The slit was centered on the apparent optical nucleus, with a projected slit width of 1″, slightly undersampling the 1″ seeing. The spectral dispersion was 2.1 pixels of 25 km s⁻¹ pixel⁻¹. The spectrum, of 1800 s, was taken in the red arm of ISIS, with the wavelength centered at 8700 Å to include the Ca II IR triplet (8494, 8542, 8662 Å). The bias subtraction, flat-fielding, and wavelength calibration of the data were carried out using FIGARO. Sky lines were subtracted using template spectra from the edges of the slit. As a stellar template star, we observed the K0 giant HR 5631. To confirm and strengthen our results, we have also analyzed a spectrum from the La Palma Archive of NGC 7331 along p.a. 172°.
These data were taken with the same instrumental setting and exposure time in 1991 September by D. Carter and M. Balcells. Their seeing FWHM was 1", and their spectral resolution was 2.5 pixels FWHM. From the same observing run, we used the G8 giant HR 7753 as a template.

To study the morphology, we took images in the Cousins I-band and the infrared K-band. The I-band image was taken in 1990 June at the Isaac Newton Telescope (INT) at La Palma with the 2.5 m INT and a 590 × 400 EEV CCD. The pixel size was 0.549", with a seeing of ≈1.2". The K-band data were obtained at UKIRT in 1994 June using IRCAM3 with a 256 × 256 InSb detector. A mosaic was made with a total field of 80" × 80", with pixels of 0.291". The data were taken under photometric conditions with a seeing of ≈0.9". Details of the data reduction can be found for the optical data in Balcells & Peletier (1994) and for the infrared data in Peletier & Balcells (1996).

3. THE STRUCTURE OF NGC 7331

To determine the structure of the central regions of NGC 7331, we fitted ellipses to the images in the K- and I-bands using Galphot (see Jørgensen, Franx, & Kjaergaard 1992). Figure 1 shows the surface brightness profiles in I and K as a function of major axis radius. There are some minor differences in the inner 60" between both profiles, mostly due to extinction by dust. Because of the smaller size of the K-band image, it was not possible to extend the fit as far as in the I-band. Consequently, the slope of the profile in K in its outer parts is much steeper than the slope of the profile in I at large I-band radii. If one tries to decompose the galaxy into an exponential disk and an r^{1/4} bulge based only on the surface brightness profile, one will get a much larger bulge in I than in K (see Fig. 1). In galaxies that are not face-on, however, one can also use the information available in the axis ratio distribution and in this way try to isolate a flat disk and a rounder bulge (Kent 1985). Applying Kent’s decomposition method for this galaxy of inclination 75°, we have obtained in both bands the fit that was obtained in K using the previous method. The reason for this is that the ellipticity in this galaxy changes only up to r = ~10", so that the only possible solution can be a small bulge and a large inclined disk. In Figure 2, we have plotted ellipticity, major axis position angle, and boxiness C_4 as a function of major axis radius.

It seems that the morphology shows three large components: the central bulge, with effective radius of ~10" (K), and then two flat components: an intermediate component with scale length ~25", and from 60" onward the large outer disk. Looking in more detail at the position angle and C_4 major axis profiles, we see in the inner 5" a boxy structure (C_4 = −0.017 at 2.5") and a position angle twist of 10° between 2.5" and 10". This component is entirely part of the bulge. Between 5" and 15", the morphology is suddenly very disky, with C_4 values of ~0.04, which are much larger than the normal values for disky elliptical galaxies (see, e.g., Bender, Dobreiner, & Möllenhof 1988). Beyond 15", C_4 depends on passband and is probably severely affected by extinction. At larger radii, it stabilizes to a value of ~0.02. No major changes of position angle and ellipticity are seen beyond 10".

4. THE LINE-OF-SIGHT VELOCITY DISTRIBUTION IN NGC 7331

To obtain the LOSVD, we compared the shift and Doppler broadening of the Ca ii IR triplet region with a standard reference stellar spectrum (K0 III) recorded the same night and with the same instrumental configuration as for the galaxy. We used an extension of the unresolved Gaussian decomposition technique developed by Kuijken & Merrifield (1993). The basic difference between their and our algorithm is that we perform a two-dimensional fit to the long-slit spectra by using unresolved Gaussian components with dispersion 2 pixels and separation 3 pixels in both spatial and spectral directions. In general, the results of both algorithms are the same, but ours should be more robust to spurious features in regions with low signal-to-noise ratios. A detailed description of the algorithm will be given in a separate paper (Gutiérrez &
Prada 1996). In Figure 3 (Plate L1), a surface plot of the LOSVD along the major axis of NGC 7331 is shown. The LOSVDs in the inner 4" are nearly symmetric (see Fig. 4, top panel). Between 4" and 7", on both sides of the nucleus, a strong asymmetry is evident toward the systemic velocity (see Fig. 4, middle panel) of the galaxy. Between 7" and 15", the LOSVDs show two separate peaks, with the fainter one crossing the systemic velocity (see Fig. 4, bottom panel). Farther out, the fainter peak disappears, and the LOSVDs are again defined by a single component. The archive spectrum was analyzed in the same way, and the same features were found. We have fitted one, and where possible two, Gaussians to the LOSVD and display the kinematic parameters (recession velocity, velocity dispersion, and flux) as a function of major axis radius in Figure 5. Because of the way that our algorithm works, the individual points are slightly correlated; the algorithm effectively smooths the data in this figure in the spatial direction with a Gaussian of FWHM 1.6. We find that between 5" and 15" on both sides of the nucleus, a fraction of the stars rotate slowly and retrograde to the rest of the galaxy. In the inset of Figure 1 we have plotted the relative intensity of both components, obtained from the LOSVDs. The profile of the fainter component agrees well with that of the bulge, as obtained from the photometric decomposition in K. In the inner 5", since an unambiguous decomposition of the LOSVDs was not possible because of the lack of resolution, we have fixed the velocity of the bulge component to the velocity of the dashed line in Figure 5, as well as the intensity ratio of both components, which we assumed to be the ratio of the components from the photometric decomposition. It was possible to obtain reasonable decompositions only if the dispersion of the low-velocity component was taken to be 110 km s$^{-1}$ or larger. For that reason, its dispersion was fixed at 110 km s$^{-1}$. The velocities obtained for the disk are plotted in the upper panel of Figure 5 as filled circles.

5. DISCUSSION AND CONCLUSIONS

To summarize the observations: the inner parts of the galaxy consist of a boxy component, dominating the inner 5". It shows position angle twisting, rotates retrograde to the rest of the galaxy, and is rounder. Outside 5", the disk dominates. This component is much colder, is probably flat, and is responsible for the strong asymmetry. The velocities obtained for the disk are plotted in the upper panel of Figure 5 as filled circles.
for the disky isophotes. At approximately $r = 100''$, the surface brightness profile becomes shallower.

The boxiness and position angle twist make it very likely that we are seeing a triaxial object counterrotating to the main body of the galaxy. It could be that we have a configuration like that in NGC 4736 (Möllenhoff, Matthias, & Gerhard 1995), where the bar is oriented end-on toward us, or alternatively, that the galaxy has no bar, and that we are seeing a triaxial bulge. The steep rise in the surface brightness profile and the low ellipticity show that it cannot be a classical, flat bar with a Freeman-type profile (Freeman 1966). From these data, we cannot distinguish between these two alternatives any further. Whatever the case, the galaxy does not contain a large, corotating bulge; if it has a bar, a small bulge, as in NGC 4736, can be hidden.

It is likely that the origin of the central component is external. Evidence for this would be the fact that it is retrograde and perhaps the fact of its boxiness. Simulations for elliptical galaxies have shown that it is possible to create a central, counterrotating body as a result of a stellar merger (Balcells & Quinn 1990). Another possibility is that the central component is formed as a result of an instability in the disk of counterrotating stars, like that of NGC 7217 (Merrifield & Kuijken 1994). In that case, however, the counterrotating disk must have accreted from outside first. A third possibility might be that the counterrotating stars were formed at the formation epoch together with the rest of the galaxy. Up to now, no models have been proposed in which two counterrotating components were formed from one protogalactic cloud and in which the angular momentum changes so drastically as a function of radius. We might observe something similar to a counterrotating bar within a bar, which Friedli (1996) has shown to be very long lived.

Further evidence for a triaxial potential in the center of this galaxy comes from the $H\alpha$ velocity field by Marcelin et al. (1994). They find the typical $Z$ shape in the isovelocity contours, characteristic of noncircular potentials. The galaxy shows some low-level activity ($H\alpha$, Filippenko, & Sargent 1995). On larger scales, the motion of the gas is quite regular (von Linden et al. 1996; Begeman 1987).

We now ask ourselves how unique this galaxy is. Studies using, e.g., the Fourier quotient method (Tonry & Davis 1979) generally find that the bulge is dynamically supported by rotation and rotates in the same direction as the disk (Kormendy 1993). If, however, the bulge-to-disk ratio diminishes, it becomes difficult to find any slow-rotating component in this way. To show this, we give the $h_3$ and $h_4$ components, as defined by van der Marel & Franx (1993), for NGC 7331 in Figure 4. They are similar to $h_3$ and $h_4$ profiles of many elliptical galaxies (see, e.g., Bender et al. 1994). Since, however, a somewhat fainter, corotating component could give the same $h_3$ and $h_4$ values as we are seeing here, we need to investigate the line profiles in more detail. By now, there are several spiral galaxies and S0’s for which the line profiles have been studied. There are many cases with a hot bulge and a cold disk rotating in the same direction (e.g., NGC 3115 [van der Marel et al. 1994], NGC 4736 [Möllenhoff et al. 1995], and NGC 4594 [Wagner, Bender, & Dettmar 1989]). But as far as we know, no galaxy has been found in which the central and outer components rotate opposite to each other. We conclude that NGC 7331 is special in this respect.

We would like to conclude by advancing some speculations. First, we find here a very boxy, slowly rotating inner component, and a large, fast-rotating disk. Many giant elliptical galaxies, on the other hand, have a boxy, even slower rotating, main body, and a small, rotating disk. Apart from the relative scales, the similarity of both systems is striking and has to imply that the formation scenario of spirals like NGC 7331 and ellipticals cannot be too different. Second, we see a discontinuity in the slope of the surface brightness profile at $r = 100''$. Since this galaxy is of type Sb, it is rather peculiar that it does not have a larger, corotating bulge. Could it be that the component that dominates the light between $5''$ and $100''$ was the previous bulge? However, it is flat, rotates fast, and is disky, but according to Kormendy (1993), many late-type spirals have “bulges” that look like this. This question obviously is still open and needs much more investigation.

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Fig. 3.—Gray-scale plot of the stellar line-of-sight velocity distribution along the major axis of NGC 7331, where for presentation purposes, the data in the spatial direction have been smoothed with a Gaussian of FWHM 4".

Prada et al. (see 463, L11)