

## DISCOVERY AND IMPLICATIONS OF A NEW LARGE-SCALE STELLAR BAR IN NGC 5248

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### ABSTRACT

For decades, the grand-design SAB spiral galaxy NGC 5248 has been postulated to host a short bar of semimajor axis  $22''$  (1.6 kpc). From dynamical and morphological arguments, however, we argue that its spiral structure is being driven by a large-scale bar whose corotation radius lies at  $\sim 115''$  (8.6 kpc). Our estimate is based partially on a deep *R*-band image, which reveals that the feature previously thought to be an inclined disk is in fact an extended stellar bar. The bar is embedded within a fainter outer disk visible out to a radius of  $230''$  (17.2 kpc). The bar has a deprojected ellipticity of 0.44 and a semimajor axis of  $95''$  (7.1 kpc). The classical grand-design spirals of NGC 5248, prominent in *B*, *R*, and *K* light, lie on the leading edge of the large-scale stellar bar and are accompanied by concave dust lanes out to at least  $70''$ . The offset between the dust and young stars is consistent with our understanding of gas flows in barred galaxies, where shocks along the leading edges of a moderately strong bar compress the gas to form massive young stars. While in many strongly barred galaxies, optical spiral arms are prominent outside the bar but not within it, NGC 5248 illustrates how intense star formation along a moderately strong bar can lead to conspicuous open spiral arms within the bar itself. NGC 5248 also provides a clear example of how a large-scale stellar bar embedded within a faint outer optical disk can be misidentified as an inclined disk when imaging studies lack the sensitivity to detect the actual outer disk. We discuss the implications for the estimated bar fraction at higher redshifts.

*Subject headings:* galaxies: evolution — galaxies: high-redshift — galaxies: individual (NGC 5248) — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: structure

*On-line material:* color figure

### 1. INTRODUCTION

Grand-design spiral galaxies generally host two long symmetric spiral arms that can be followed over a large azimuthal angle and dominate the optical disk, e.g., NGC 1300 (Sandage 1961), NGC 895, NGC 1566 (Elmegreen & Elmegreen 1995), M51, M100 (Elmegreen, Seiden, & Elmegreen 1989), and NGC 5248 (e.g., Patsis, Grosbol, & Hiotelis 1997). Within the framework of the spiral density wave (SDW) theory (e.g., Lin & Shu 1964), spiral arms in disk galaxies result from a traveling wave pattern that remains quasi-stationary in a frame of reference rotating around the galaxy center at a certain pattern speed. SDWs can be excited by a companion or a bar. The spiral waves can get swing amplified as they are sheared from leading to trailing (e.g., Goldreich & Lynden-Bell 1965) provided the disk is cold enough.

In this Letter we focus on the driving mechanism for an SDW in the nearby ( $D = 15$  Mpc) well-studied grand-design spiral NGC 5248 and discuss the implications of an extended stellar bar in this galaxy. Optical imaging (e.g., Fig. 1) of NGC 5248 reveals two bright, relatively symmetric spiral arms from about

$30''$  (2.2 kpc) to  $80''$  (6.0 kpc). NGC 5248 does not show evidence of any recent or ongoing interaction with its three faint irregular neighbors (UGC 8575, UGC 8614, and UGC 8629; Zaritsky et al. 1997), which have similar redshifts and are located more than  $30'$  (135 kpc) away in projection. It is therefore likely that the grand-design spirals in NGC 5248 are driven by a massive large-scale bar, which is verified in the present work. The circumnuclear ring of H II regions at a radius of  $5''$  (375 pc; e.g., Elmegreen et al. 1997) also suggests the presence of a bar, since rings are commonly associated with the dynamical resonances of a bar (e.g., review by Buta & Combes 1996).

NGC 5248 is classified as SAB(rs)bc (de Vaucouleurs et al. 1991) and has been postulated to have a weak stellar bar with an ellipticity of 0.32 and a semimajor axis of  $22''$  (1.6 kpc) at a position angle (P.A.) of  $110^\circ$  (e.g., Martin 1995). This oval feature is evident in optical images (e.g., Fig. 1). However, the extent and morphology of the grand-design spirals in NGC 5248 strongly suggest that the bar driving these spirals must be significantly longer and more massive than previously assumed. The two bright, inner stellar spiral arms have prominent dust lanes on their *inner (concave) sides* (Fig. 1) out to a radius of  $r \geq 70''$  (5 kpc). Such a dust lane morphology is expected to exist only inside the corotation resonance (CR) of the arms, where young stars that form when gas is compressed by shocks, seen as dust lanes, can overtake the pattern. From this argument alone, we expect that the CR of the spiral pattern in NGC 5248 is beyond  $70''$ . If the bar and spirals in this galaxy have the same pattern speed, the latter must be driven by a stellar bar whose semimajor axis is comparable in size to that of their common CR. Large-scale bars are expected to end at or near CR based on the studies of stellar orbits (Contopoulos & Papayannopoulos 1980) and the analysis of shapes of offset dust lanes within bars (Athanasoula 1992). In order to test the existence of an extended bar in NGC 5248, we obtained a deep *R*-band image with a

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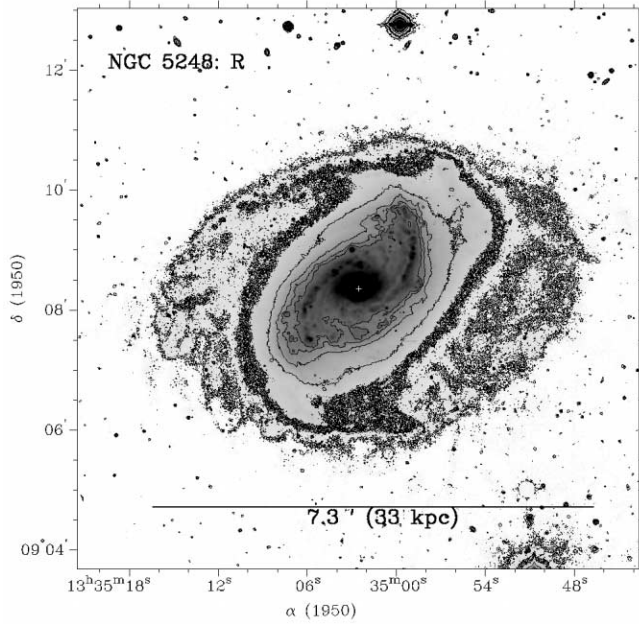


FIG. 1.—*R*-band image, revealing a hitherto unknown prominent stellar bar of size  $95''$ , embedded within a faint, more circular outer disk that is visible out to a radius of  $230''$  ( $17.2$  kpc). The two bright inner spirals between  $30''$  ( $2.2$  kpc) and  $80''$  ( $6.0$  kpc) lie on the leading edge of the bar. [See the electronic edition of the *Journal* for a color version of this figure.]

large field of view (§ 2). While this Letter focuses on the observational aspects of the large-scale bar in NGC 5248 and its consequences for galactic dynamics in nearby and high-redshift galaxies, a subsequent paper (Jogee et al. 2002, hereafter Paper II) addresses gasdynamics in the inner few kiloparsecs of this galaxy, based on multiwavelength observations and modeling.

## 2. OBSERVATIONS AND DATA REDUCTION

NGC 5248 was imaged through the Harris *R*-band filter for a total of 30 minutes using the Wide-Field Camera on the 2.5 m Isaac Newton Telescope (INT) in La Palma in 2001 August. The data frames had a plate scale of  $0''.33$  pixel $^{-1}$ , a field of view of  $11'.3 \times 22'.5$ , and an average seeing of  $1''.8$ . Photometric calibration was performed by comparison with a shorter image of the galaxy in the same band, taken on the same night with the 1 m Jacobus Kapteyn Telescope. The *R*-band surface brightness goes down to  $26.5$  mag arcsec $^{-2}$ . Bias-subtracted and flat-fielded frames were obtained from the INT data reduction pipeline. Sky fringing at the 1% level is present, an effect known for the thinned EEV chip CCD-4. We used the IRAF package for fixing bad pixels, cleaning cosmic rays, and combining frames into a final image. After masking out stars and faint background galaxies, isophotal analysis was performed with the *isophote* package in IRAF. We also refer to a *K'* image obtained in 2000 May using the Isaac Newton Group Red Imaging Device on the 4.2 m William Herschel Telescope. This image, and other data described in this Letter, are fully detailed in Paper II.

## 3. EXTENDED BAR AND FAINT OUTER DISK

The *R*-band image (Fig. 1) reveals a hitherto unknown large-scale stellar bar-like feature embedded within a fainter, more circular outer disk visible out to a radius of  $230''$  ( $17.2$  kpc). Below we describe the morphological, photometric, and dynamical properties of this bar. Earlier optical and near-IR images

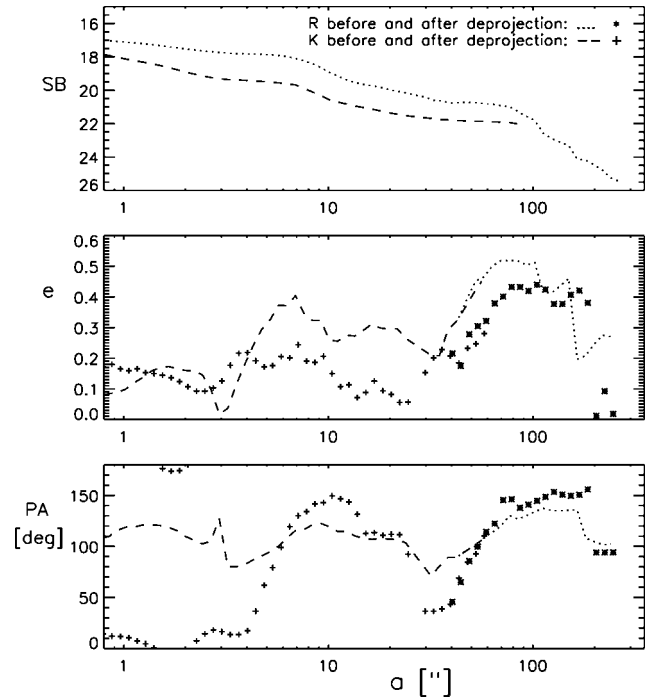


FIG. 2.—Radial profiles of surface brightness, ellipticity, and P.A. of azimuthally averaged *K*-band and *R*-band light are shown. Dotted and dashed lines refer to the values before deprojection. Symbols refer to deprojected values. The *K*-band surface brightness has been scaled by 1.32 so that it can be plotted on the same scale as the *R*-band profile. In deprojected images, we adopt the convention that P.A. values are measured counterclockwise from “north.” The deprojected bar has an ellipticity of 0.44.

lacked the sensitivity and/or field of view to clearly detect the end of the large-scale stellar bar and the faint outer disk. As a result, the bar was misinterpreted as an inclined outer disk. The new *R*-band image (Fig. 1) shows the actual outer disk and the full extent of the bar. In order to quantitatively describe the features in NGC 5248, we performed an isophotal analysis (Fig. 2) of the *R*-band and available *K*-band images. To minimize the effects of extinction, the *K*-band image of  $0''.6$  seeing is used out to a radius of  $50''$ . Beyond this point, its signal-to-noise ratio is low and we use the *R*-band image.

The bright optical stellar spiral arms extend along the leading (§ 4) edge of the bar and cross its major axis (P.A.  $\sim 135^\circ$ ) at around  $95''$  (Fig. 1). This suggests that the bar has a semimajor axis of about  $95''$  ( $7.1$  kpc). Large-scale bars typically tend to end near the ultraharmonic resonance where chaos and orbital instability set in. The ratio of corotation to bar radii ( $R_{CR}/R_{bar}$ ) is expected to lie in the range of  $1.2 \pm 0.2$ , as found empirically by Athanassoula (1992). This corresponds to a CR of  $\sim 115''$  ( $8.6$  kpc) in NGC 5248—a value supported by photometric evidence. As seen in Figure 2, between  $60''$  and  $115''$ , the projected ellipticity  $e$  rises to a maximum of 0.52 and the P.A. settles to a fairly constant value of  $135^\circ$ , after some initial variation between  $120^\circ$  and  $135^\circ$ . This small variation is due to the unusual prominence of the spiral arms within the bar. The peak in  $e$  over a fairly constant P.A., as observed in NGC 5248, is the behavior expected of bars (e.g., Knapen et al. 1995).

Between  $a = 115''$  and  $150''$ , secondary faint spirals that stem off the bar at lower radii become particularly prominent. They dominate the fitted isophotes, which show a varying  $e$  of 0.41–0.46 (Fig. 2). Such features are reminiscent of “plumes,” which are seen in other barred systems such as NGC 1433 and may be secondary compression zones that arise near CR (Buta 1984).

Between  $150''$  and  $230''$ , the isophotes are dominated by the outer disk and very faint spirals that extend away from the bar and cover  $90^\circ$ – $100^\circ$  in azimuth (Fig. 1). This leads to a low but varying  $e$  (Fig. 2). The outer Lindblad resonance (OLR), where arms are expected to end, is probably around  $230''$ . The P.A. of the projected disk is relatively constant at  $105^\circ$ . Assuming the outer disk is intrinsically circular, we derive a P.A. of  $105^\circ \pm 2^\circ$  for the line of nodes and an inclination of  $40^\circ \pm 4^\circ$ . With these parameters, we performed a two-dimensional deprojection of the  $R$ -band and  $K$ -band images. The deprojected disk (Paper II) is circular with  $e$  below 0.02 (Fig. 2), while the deprojected bar is moderately strong with a peak  $e$  of 0.44. We note that the deprojection is somewhat uncertain because the intrinsic shape of the disk between CR and OLR is expected to be slightly elongated along the bar minor axis.

We now turn our attention to the inner regions ( $r \leq 50''$ ) of NGC 5248. A very weak oval feature is present in the inner  $3''$  radius of the  $K$ -band image (Fig. 3) where the deprojected  $e$  varies from 0.18 to 0.10 (Fig. 2). Two  $K$ -band spirals, extending from this oval, are lined with “hot spots” between  $3''$  and  $9''$ . They cross the optically visible starburst ring at  $\sim 5''$ , and between  $5''$  and  $8''$  they delineate the bright super–star clusters seen in *Hubble Space Telescope* (*HST*) images (see Paper II). Near the bar major axis, the spirals fade out, and  $e$  falls from 0.20 to 0.11 between  $10''$  and  $13''$  (Fig. 2). Between  $17''$  and  $26''$ , the stellar distribution looks smoother (Fig. 3), and the  $K$ -band spirals fade as they approach the bar major axis. Farther out, between  $30''$  and  $50''$ , the bright patchy outer  $K$ -band spirals (Fig. 3) dominate, leading to a higher  $e$  (0.15–0.30) and a smoothly varying P.A. The oval-shaped feature of radius  $\sim 22''$  that is visible in the projected images (e.g., Fig. 1) has been interpreted as a primary bar of semimajor axis  $22''$  (1.6 kpc) at a P.A. of  $110^\circ$  in earlier studies (e.g., Martin 1995). However, after deprojection, this feature has a peak  $e$  of only 0.15 (Fig. 2). Therefore, the oval appearance of this feature in the sky plane seems to be largely due to projection effects. The dip in  $e$  at around  $26''$  is due to the  $K$ -band arms joining the oval at its minor axis. Uncertainties in the deprojection are unlikely to change this conclusion; namely, there appear to be no signs of a bar of size  $22''$  in NGC 5248.

#### 4. DISCUSSION: IMPLICATIONS FOR BARRED SPIRALS LOCALLY AND AT HIGH REDSHIFTS

NGC 5248 shows a grand-design spiral morphology in stars, dust, and gas, as traced by  $B$ -band (Paper II),  $R$ -band (Fig. 1),  $K$ -band (Fig. 3),  $B-I$ ,  $H\alpha$ , and CO maps (Paper II). In  $B$ ,  $R$ , and  $K$  light, there are prominent stellar spiral arms between about  $30''$  and  $80''$  (2.2–6.0 kpc) on the leading edge of the large-scale stellar bar. The stellar arms have prominent dust spirals on their inner (concave) sides out to at least  $70''$  (e.g., Fig. 1), as is expected inside the CR. The observed offset between the dust and stellar spirals is consistent with our understanding of gas flows in barred galaxies where offset dust lanes along the leading edges of the bar delineate the shocks that compress the gas, leading to the formation of massive young stars. Within this framework, the bar is rotating clockwise, and the patchy  $B$ ,  $R$ , and  $K$  stellar spiral arms immediately offset from the dust lanes are made of *young* stars. It is particularly noteworthy that the appearance of the  $K$ -band spirals in NGC 5248 is dominated by young stars.  $K$ -band light is generally assumed to trace old stellar populations, but it can be dominated by very young (8–10 Myr) supergiants in starburst regions (e.g., Knapen et al. 1995). Along the  $K$ -band arms in NGC 5248, there is good spatial coincidence

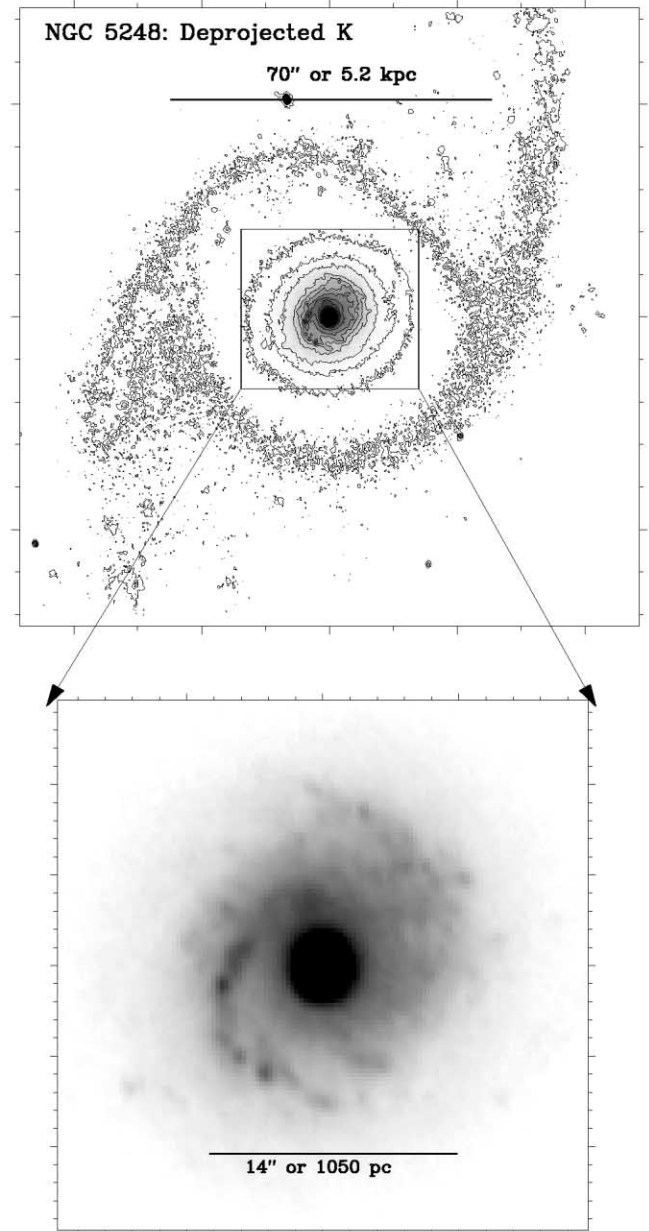


FIG. 3.—*Bottom panel*: Central  $30''$  (2.2 kpc) of the deprojected  $K$ -band image; *top panel*: central  $2.4$  (10.8 kpc) of the deprojected  $K$ -band image. Note the  $K$ -band spirals lined with “hot spots” between  $4''$  and  $9''$ , the relatively axisymmetric distribution between  $17''$  and  $26''$ , and the patchy  $K$ -band spirals beyond  $30''$ .

between peaks in  $K$ -band emission and  $H\ II$  regions as traced by  $H\alpha$  images. The patchy morphology of the  $K$ -band spirals is in stark contrast to the smooth appearance of old stellar arms (e.g., Kennicutt & Edgar 1986). Taken together, these properties suggest that young stars dominate the  $K$ -band spirals.

While grand-design optical spiral arms in many *strongly* barred galaxies stem from the ends of a stellar bar, in NGC 5248 open spiral arms appear conspicuous within the *moderately strong* bar itself, delineating intense star formation. The star formation along the offset bar dust lanes in NGC 5248 is consistent with current understanding of gas flows and star formation in barred galaxies. In strong bars that exhibit almost straight offset dust lanes delineating shocks, little star formation is seen along the bar. Common examples are NGC 1300 and NGC 5383

(Tubbs 1982). Star formation is believed to be inhibited because of the strong shear in the postshock flow (e.g., Athanassoula 1992). In weaker bars, where the offset dust lanes are curved, the weaker shocks and shear can induce star formation rather than inhibit it. For instance, the collapse of gas cores to form stars can be induced by weak shocks with speeds on the order of 20–30 km s<sup>-1</sup> (e.g., Vanhala & Cameron 1998). It is thus common to see star formation along weak bars, e.g., in M100 (Elmegreen et al. 1989), NGC 4254, and NGC 4303 (Koopmann 1997). NGC 5248 falls in this category as its large-scale bar is only moderately strong with curved offset dust lanes (Fig. 1) and a deprojected ellipticity of 0.44.

We note that there exists a class of weakly barred galaxies where bright optical spiral arms appear to emerge from a relatively short oval bar-like feature and extend to twice the radius of this bar (Elmegreen & Elmegreen 1995). We would have put NGC 5248 in this category if we had taken its primary stellar bar to be the oval feature of radius 22", as was long assumed to be the case. However, with our identification of the large-scale bar of radius 95", the bright optical spiral arms with concave dust lanes in NGC 5248 turn out to lie inside the bar. The short oval turns out to be primarily the result of projection effects (§ 3). It is therefore imperative to ask whether galaxies with bright extended optical spiral arms apparently driven by a short oval feature are in fact hiding a more extended large-scale bar. NGC 1566 and ESO 111-110 (Buta 1995) are two such possible candidates.

While the majority of nearby spiral galaxies are barred (e.g., Grosbol 2002), a low fraction of bars (<10%) has been reported in galaxies at redshifts of  $z \sim 0.5-0.8$  (e.g., Abraham et al. 1999). In this latter study, the authors apply the same bar identification method to nearby galaxies and to spirals at  $z \sim 0.5-0.8$ . Images that trace the rest-frame *B*-band light are used. The inclination  $i$  is derived from an outer isophote that corresponds to an arbitrary fraction (1%) of the peak flux. After removing the projected ellipticity corresponding to  $i$ , a bar is identified based on the residual ellipticity in the inner bright regions of the spiral galaxy. The authors find a much lower bar fraction at intermediate redshifts than locally. It has been suggested that this result may be biased owing to the small sample size or that bars are truly deficient at intermediate redshifts because of dynamically hotter disks or an enhanced efficiency in bar destruction (Abraham et al. 1999). Another possibility is that the method used is less efficient in identifying bars at intermediate redshifts than locally. This method relies on the *B*-band surface brightness ratio ( $R_1$ ) between the central regions and the outer disk beyond the bar end. In a barred spiral with a bright central region and a faint outer disk beyond the bar end,  $R_1$  is low, and this method can readily fail: the outer 1% isophote would lie inside the bar

rather than in the faint, more circular outer disk, and consequently, the bar would be misinterpreted as an inclined disk. Bars may be missed more frequently at  $z \sim 0.5-0.8$  than locally with this method because of two factors: evolution and imaging depth. If there is evolution in the surface brightness profiles of spirals with redshift such that  $R_1$  is on average lower at higher redshifts, then bars may be missed more frequently at  $z \sim 0.5-0.8$  than locally. Detailed future studies with large samples are needed to quantify  $R_1$ , but our suggestion is not ruled out by existing data. Spiral galaxies at intermediate redshifts have bright blue central colors indicative of recent starbursts (Ellis, Abraham, & Dickinson 2001), and the outer disk/bar that has presumably formed recently may still be quite faint. Another factor is that images of spirals at  $z \sim 0.5-0.8$  often do not reach the same sensitivity level as images of nearby galaxies.

We also discuss why a higher bar fraction at  $z \sim 0.5-0.8$  is quite likely. It is well known that bars or  $m = 2$  modes can be easily excited in a dynamically cold disk either spontaneously or during tidal interactions and minor mergers. On the other hand, major mergers tend to produce highly disturbed systems that eventually evolve into elliptical-like systems (e.g., Barnes 1992) through violent relaxation. The fraction of spiral galaxies in pairs increases with redshift out to  $z \sim 0.75-1$  (Le Fèvre et al. 2000), suggesting enhanced interaction between spiral galaxies. These interactions do not appear to involve major mergers since *HST* studies hint that sizes of spiral galaxies (e.g., Lilly et al. 1998) and the number counts of spirals with  $I < 22$  mag in *HST* fields (e.g., Glazebrook et al. 1995) do not show much evolution out to  $z \sim 1$ . Taken together, these results suggest that conditions out to  $z \sim 1$  are favorable to the formation of bars in disk galaxies. Furthermore, if the recently discovered massive disk galaxy at  $z = 1.34$  (van Dokkum & Stanford 2001) is representative, it reveals that massive organized disks with ongoing star formation are already in place by  $z = 1$ . The ring of star formation at a  $\sim 10$  kpc radius may be associated with the dynamical resonances of a bar or alternatively could be an out-of-the-plane ring.

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