1. INTRODUCTION

Although polar ring galaxies constitute only a small fraction of the galaxy population, these objects are interesting because they offer a unique insight into the formation and evolution of galaxies. For example, understanding the kinematics of polar rings could ultimately reveal the three-dimensional shape of their dark matter halos (Whitmore, McElroy, & Schweizer 1987; Sackett et al. 1994; Combes & Arnaboldi 1996). They may also provide information on mergers of galaxies. The conventional model for polar ring formation (Schweizer, Whitmore, & Rubin 1983; Schechter, Boksenberg, & Ulrich 1984) attributes ring formation to gas capture after the central galaxy has formed. Bekki (1998) has suggested a different model in which a polar ring galaxy is formed in a dissipative polar merger of two comparable mass disk galaxies with small relative velocity.

Recently, Tremaine & Yu (2000) have offered an alternative model for polar ring formation that requires no accretion or merger. If a galaxy lies in a symmetry plane of a triaxial dark halo with an initially retrograde pattern speed that slowly tends to zero (e.g., as the halo acquires dark matter by infall), disk stars are trapped at a resonance when the rate of precession of a slightly tilted orbit matches the pattern speed of the triaxial halo. As the resonance slowly sweeps outward past the stars, they are levitated into polar orbits. The model predicts that a polar ring formed in this way will contain two equal-mass, counterrotating disk streams. Note that if the halo pattern speed were to increase through zero to prograde, the stellar orbits could become retrograde in the disk and form a counterrotating disk stream. Thus, the Tremaine & Yu (2000) model provides an interesting mechanism that can explain both polar ring and counterrotating disk galaxies without a merger (see also Evans & Collett 1994). Because, in the resonance levitation model, the polar ring contains counterrotating stellar populations, whereas in merger models, the ring stars would most likely be rotating in one direction, the stellar kinematics of a polar ring provides a means to discriminate between these formation scenarios.

A prime candidate for the measurement of the stellar velocities in a polar ring is NGC 4650A. It consists of a central S0 galaxy, surrounded by a prominent polar ring. With an adopted Local Group centric velocity of \( V_L = 2635 \) km s\(^{-1}\) and a Hubble constant of 70 km s\(^{-1}\) Mpc\(^{-1}\), NGC 4650A is at a distance of 38 Mpc. At this distance, 1" = 184 pc. Because of its relative proximity, NGC 4650A has been extensively studied (see, e.g., Gallagher et al. 2002 and references therein). Observations at 21 cm (Arnaboldi et al. 1997) revealed a spatially extended H\textsc{i} disk coincident with the ring, leading these authors to suggest that NGC 4650A is more appropriately called a polar disk galaxy (see also Wakamatsu 1993). Recent observations taken with the Hubble Space Telescope as part of the Heritage project reveal a complex, warped structure of the polar disk (Gallagher et al. 2002; Iodice et al. 2002).

In this Letter, we report stellar and gas velocities in both the S0 galaxy and the ring of NGC 4650A. We believe that these are the first measurements of stellar velocities in a polar ring. Our observations support the identification of the ring as a disk, but we continue to call it a ring, to avoid confusion with the S0 disk.

2. OBSERVATIONS AND DATA REDUCTION

We have obtained spectra of the S0 galaxy and of the ring of NGC 4650A with the Boller & Chivens spectrograph and the Marconi CCD at the Las Campanas Baade (6.5 m) telescope. For all observations, the slit width was 1", and the slit length 72". To increase the signal-to-noise ratio, the data were binned on-chip by four 0.25 pixels in the spatial direction. The spectral coverage was 1600 Å, with an FWHM resolution of 135 km s\(^{-1}\) (0.78 Å pixel\(^{-1}\)). Observational details are provided in Table 1. After each science exposure, an argon wavelength calibration and an offset sky exposure were taken. At the beginning and end of each night, template stars with spectral types in the range of G8 III–K4 III were observed.

The choice of slit position merits special mention. Because of the warp of the ring, a single slit position cannot cover both the center of the S0 galaxy and the brightest regions of the northern (N) and southern (S) parts of the ring. To maximize the signal from the polar ring, we chose to align the slits along...
the brightest parts of the ring. As a result, the ring slit positions are each displaced about 4" from the nucleus of the S0 galaxy. For the major axis spectrum of the S0 galaxy, a position angle (P.A.) of 63° was adopted (Whitmore et al. 1990). The positions and orientations of the slit for each of these pointings are indicated in Figure 1.

During an earlier observing run with the Baade 6.5 m telescope, we obtained Hα emission-line spectra of the N and S parts of the ring (Table 1). The slit positions for these spectra were close to those for the 2002 observations indicated in Figure 1.

The frames were bias-subtracted, flat-fielded, cleaned of cosmic-ray events, wavelength-calibrated, and combined in IRAF. Sky subtraction was done by combining all offset sky images for the appropriate slit position and subtracting it, after scaling, from the corresponding science frame.

2.1. Derivation of the Velocities

To determine the stellar kinematics, the underlying stellar continuum emission was first subtracted from both the galaxy and the template star frames. Next, these continuum-subtracted frames were cross-correlated by R. A. S. to obtain the stellar line-of-sight (LOS) velocities. The absorption velocities were determined by fitting Gaussian profiles to the cross-correlation peaks (CCPs), every 1" where the signal was strong (along almost the entire length of the S0 major-axis slit position and within 10" of the S0 major axis for the ring slit positions). At other locations, the data were binned in 4" intervals. The calculated errors of the derived velocities are the quadratic sum of the formal errors of the cross-correlation and the dispersion resulting from using different template stars. Example CCPs are shown in Figures 2a–2d. The width of the CCPs is about 230 km s\(^{-1}\). The reduction process was not optimized to measure the stellar dispersions.

The wavelength range of these observations also contains the [O III] \(\lambda5007\), 4959 and Hβ emission lines. Emission-line velocities were measured by V. C. R. using the customized Department of Terrestrial Magnetism measuring program in the software package VISTA (Rubin, Hunter, & Ford 1990). The argon frames for each slit position were used for wavelength calibration. Only the line [O III] \(\lambda5007\) was measured because the spectrum degraded rapidly toward the blue and because the Hβ emission was located in a fairly deep absorption trough. The 2001 Hα spectra were measured by V. C. R. using the same procedures as for the [O III] line, except that the night-sky emission lines on each frame were used for the wavelength calibration.
3. RESULTS

In Figure 3, we plot the LOS velocities of the polar ring stars as a function of their distances from the major axis of the S0 galaxy, $d_{\text{so}}$. Note that $d_{\text{so}} = 0$ corresponds to the location where the slit crosses the major axis, rather than the distance from the nucleus. With the exception of the region within $|d_{\text{so}}| \sim 10''$ of the S0 major axis, the stellar velocities along the ring resemble those expected for a normal, late-type disk galaxy.

A notable feature in Figure 3 is the apparently double-valued velocities in the central regions. We attribute these to the combination of the strong contribution of light from the S0 galaxy that overwhelms the contribution from the ring stars and the slit positions that are offset by $4''$ from the S0 center. The radial velocities at these positions along the S0 major axis (see Fig. 5 below) are indicated in Figure 3 by the arrows and match well the velocities observed in the ring spectra.

The observations reveal no evidence of equally populated counterrotating stellar streams in the polar ring. With a velocity difference close to 200 km s$^{-1}$ between the approaching and receding sides of the ring, the spectral resolution is sufficient to detect two equal-mass components. This can be seen in Figure 2e, which shows the CCP for a model equal-mass, counterrotating stream, constructed by co-adding the N and S spectra. This model CCP, with its width of 350 km s$^{-1}$, is significantly wider than the observed CCPs. Note also that the model CCP peaks near the systemic velocity, as expected for two equal counterrotating streams. Thus, merely the fact that we observe significant rotation in the ring rules against the existence of two equal-mass counterrotating streams. However, we cannot rule out the existence of a weaker counterrotating component, whose absorption features would be lost in our instrumental resolution and sensitivity. From analysis of models constructed by adding the N spectrum to a scaled down S spectrum, we estimate that at most about 15% of the stars can be in counterrotation.

A comparison of the measured LOS stellar and [O iii] ionized gas velocities in the ring shows that the velocities of the stars and the gas in the polar ring agree closely (see Fig. 4). Note how well the gas velocities bisect the double-valued stellar velocities, indicating that the emission-line gas is associated with the ring and not with the S0 galaxy. We attribute the double-valued gas velocities, $8'' < r < 15''$, to the different regions sampled by the N and S ring spectra in the region north of the S0 major axis (Fig. 1). The measured H$\alpha$ velocities are virtually indistinguishable from the [O iii] velocities (Fig. 4); differences are probably due to minor differences in the slit positions.

Calculating the stellar and emission-line rotation curves from the observed radial velocities requires corrections for inclination, slit position, asymmetric drift, and LOS integration effects. The inclination correction is complex because of the warped nature of the ring (Arnaboldi et al. 1997; Gallagher et al. 2002). However, outside of $|d_{\text{so}}| \sim 6''$, the main part of the polar ring appears close to edge-on (Gallagher et al. 2002), and there the inclination corrections are negligible. The correction for the off-center position of the slit is 7% at $d_{\text{so}} = 10''$ and less for larger $d_{\text{so}}$. The correction for asymmetric drift depends on the velocity dispersion and the shape of the velocity ellipsoid, and their dependence on radius (Binney & Tremaine 1987, p. 198). In principle, these can be derived from the data presented here, but this is beyond the scope of this Letter. We note that the asymmetric drift correction is largest just outside the galaxy center and gets smaller with radius. A final correction is needed because the spectra are integrated along the LOS, but these corrections are small compared with the corrections for asymmetric drift (Sackett & Sparke 1990). Because the corrections are complex or uncertain, we have not derived the stellar rotation curve for the polar ring. However, given that the corrections are small, or get smaller with larger $d_{\text{so}}$, the flatness of the rotation curve is a secure result.

The agreement between the stellar and emission-line kinematics seems remarkable given that gas and stars are expected to have different corrections for asymmetric drift and LOS integration. However, after convolution with the spectral resolution, any narrow spectral features are washed out, resulting in observed stellar and emission-line profiles that have similar shapes and derived LOS velocities. LOS stellar velocities along the equatorial plane of the S0 galaxy (Fig. 5) show a smooth rotation curve ($r < 20'' = 3.6$ kpc) with LOS velocities approaching 100 km s$^{-1}$. Emission lines of [O iii] and H$\beta$ are observed within $\pm 15''$ of the nucleus.

![Fig. 3.—LOS stellar absorption-line velocities for the N part of the ring (filled circles) and the S part (open circles). Each arrow indicates the stellar velocity in the S0 galaxy (Fig. 5) at the point where the slit crosses the major axis of the S0 galaxy.](image1)

![Fig. 4.—LOS [O iii] emission-line velocities for the N part of the ring (filled circles) and the S part (open circles) overlaid on the absorption-line velocities in gray, with the same coding of the symbols. Velocities of the stars and the gas in the polar ring are strikingly similar, except in the region $8'' < d_{\text{so}} < 15''$, where the two slits sample different regions in the ring (see Fig. 1). The inset shows a comparison between the H$\alpha$ (filled circles) and the [O iii] (open circles) velocities.](image2)
Their LOS velocities, close to the NGC 4650A systemic velocity, independent of radius, suggest that we are probably observing the ionized gas component of the polar ring.

4. DISCUSSION AND CONCLUSIONS

In this Letter, we report the first detection of stellar velocities in the ring of polar ring galaxy NGC 4650A. To our knowledge, these are the first stellar velocities obtained for a polar ring. The kinematics reveals well-defined rotation, both in gas and in stars. The rotation curve appears to reach a flat part for $|d_{los}| > 15\degr$.

The original impetus for this work was to look for evidence of two equal-mass counterrotating streams to test the intriguing polar ring formation model proposed by Tremaine & Yu (2000). However, the fact that we detect well-defined rotation, and the structure of the CCPs, rules out a polar ring that consists of two equal-mass counterrotating streams. Nonetheless, given the sensitivity and resolution of our observations, we cannot rule out that a small fraction ($\leq 15\%$) of the stars is counterrotating.

Thus, it appears that the Tremaine & Yu (2000) resonance levitation mechanism is not at work in NGC 4650A. However, as Tremaine & Yu (2000) point out, the self-gravity of the ring (likely for NGC 4650A given that its luminous mass is similar to that of the S0 galaxy; Iodice et al. 2002) makes it energetically favorable for all stars to be a single stream rather than two counterrotating streams. Another complication is the uncertain effect of the presence of dust and gas in the polar ring of NGC 4650A on resonance capture. Furthermore, because the resonance levitation model predicts that the polar material does not extend to the galaxy center, the possibility that NGC 4650A has a polar disk that does (Iodice et al. 2002; see also below) makes it less likely the polar disk has formed through resonance levitation. Perhaps galaxies with narrow polar rings that have little or no gas and dust, and disk galaxies with counterrotating streams, are more likely to have formed through resonance levitation.

Absent evidence of a resonance levitation mechanism for the formation of the polar ring in NGC 4650A, we briefly consider the merger or acquisition alternatives. The observed flatness of the rotation velocities in the polar gas and polar stars offers strong kinematic evidence that this feature is a spatially extended disk rather than a narrow ring, as suggested earlier from gas kinematics (Arnaboldi et al. 1997) and from morphology (Gallagher et al. 2002). Insight into the radial extent of the polar ring is offered by the emission-line kinematics along the major axis of the S0 galaxy. These velocities, constant at the systemic velocity, most likely arise from polar ring gas. With the inner ring warped with an inclination of 63$\degr$ (Gallagher et al. 2002), the emission lines seen at the center indicate that ring gas extends into the center. The emission likely arises in the chaotic dust lanes that are oriented at random and extend into the S0 nucleus (Gallagher et al. 2002).

Iodice et al. (2002) argue that the luminous mass in the ring is similar to or even higher than that of the S0 galaxy. Its large luminous mass, combined with its disklike morphology, suggest the polar ring in NGC 4650A is a disk galaxy that is the victim of a dissipational polar merger of disks of approximately similar masses (Bekki 1998). Further support for a merger scenario comes from the location of NGC 4650A in a chain of galaxies in the Centaurus Cluster (Sersic 1968, p. 66). It seems unlikely that a single accretion event could transfer the required large mass or that extended accretion over a period of time could produce sufficient coherence to form a ring.

Although we did not detect counterrotating star streams in the polar ring of NGC 4650A, which would have been more exciting, we are continuing the study of this fascinating object. We postpone a detailed kinematic model until we have more extensive observations.

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