THE ASTROPHYSICAL JOURNAL, 394:L9–L12, 1992 July 20

COSPATIAL COUNTERROTATING STELLAR DISKS IN THE VIRGO E7/S0 GALAXY NGC 4550

VERA C. RUBIN[1,2,3] AND J. A. GRAHAM[1,2]
Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015
AND
JEFFREY D. P. KENNEY
Astronomy Department, Yale University, Box 6666, New Haven, CT 06511
Received 1992 March 24; accepted 1992 May 7

ABSTRACT

We have discovered two cospatial stellar disks, one orbiting prograde, one orbiting retrograde, in NGC 4550, an E7/S0 galaxy in the core of the Virgo Cluster. One of the stellar disks is coincident with a gas disk. Absorption and emission-line velocities for the two counterrotating components have been measured over about one-third of the optical diameter (30″). We propose that after the initial stellar disk of NGC 4550 was formed, a substantial amount of counterrotating gas was acquired $\geq 10^9$ yr ago. It then settled to the plane via dissipation; the bulk of the counterrotating stars most likely formed after the gas settled to the plane.

Subject headings: galaxies: clustering — galaxies: elliptical and lenticular, cD — galaxies: kinematics and dynamics

1. INTRODUCTION

NGC 4550 is an E7/S0 (Sandage & Tammann 1987; SB0 uncertain, de Vaucouleurs et al. 1991, hereafter RC3) galaxy (Fig. 1 [Pl. L2]) located in the core of the Virgo Cluster only 1°2 E of M87. We have discovered a unique pattern of stellar and gas kinematics over the inner 30% of the optical galaxy. One *stellar* disk is rotating such that the north is receding and the south is approaching. Over the same radial distances, a *gas* disk is counterrotating with respect to the stars, such that the north is approaching, the south is receding. Small counterrotating circumnuclear gas disks have been previously observed in E and S0 galaxies (Bender 1990; Bertola et al. 1990), and galaxies with outer retrograde gas rings have been found (Schweizer, van Gorkom, & Seitzer 1989). However, NGC 4550 is spectacular since it is the first system known in which there is a second *stellar* population orbiting along with the counterrotating gas. Thus, the inner one-third of the galaxy has complex kinematics; a disk of stars orbits prograde and coexists with a disk of stars and gas which orbits retrograde. Because these two cospatial counterrotating disks extend over a sizable portion of the galaxy, we may be detecting a phenomenon different from that observed in elliptical galaxies with counterrotating or skew small nuclear disks. Our observations illuminate yet another example of the complexity which exists within some elliptical galaxies.

2. THE OBSERVATIONS AND REDUCTIONS

For about 100 galaxies in the Virgo Cluster, spectra at high velocity resolution and high spatial scale have been obtained with the Palomar 200 inch (5 m) and 60 inch (1.5 m) telescopes and the Kitt Peak 4 m telescope (V. Rubin and J. D. P. Kenney, in preparation). NGC 4550 exhibits one of the most unusual spectra of this set. We show in Table 1 the journal of observations. Each detector is a TI CCD, and normal procedures of bias subtraction and flat-fielding were followed. The slit width was 2″ for all spectra.

Velocities were measured by Rubin at DTM, using a method described by Rubin, Hunter, & Ford (1991). Night-sky OH lines are used for the two-dimensional wavelength calibration, except for the Kitt Peak 1990 spectrum at 0.33 Å pixel^{-1}. Because this frame shows few sky lines, a calibration thorium-argon frame taken immediately after the galaxy integration is used. Emission-line velocities come principally from [N II], [S II], and Hα only where it is clearly distinguished from the Hα absorption. We estimate that the uncertainty of a single emission-line velocity is a few km s^{-1}, and of order 20 km s^{-1} for the absorption lines.

Reproductions of the spectra are in Figure 2 (Plate L3). For all spectra, a mean radial surface brightness has been formed from the emission-free regions of the spectrum and removed. For the red 200 inch spectrum displayed in Figure 2*a*, night sky (at the 85% level) has been subtracted from the frame. For the blue spectrum, a "sky" has been formed (full sky + faint galaxy) and subtracted from the frame.

From the spectra centered at Hα, it is immediately apparent (Figs. 2*a* and 2*b*) that there are two velocity components, one in absorption rotating prograde and one in emission rotating retrograde. Moreover, retrograde absorption at the velocity of the emission-line system can be seen poking out at about 15″ between the north end of the rapidly rotating emission core and the more slowly rotating disk emission (Fig. 2*b*).

From the spectrum centered near 5007 Å (Fig. 2*c*), prominent absorption lines have an X-shaped appearance where they cross the nuclear region. The strongest absorption lines, due to Mg I(5168, 5173, 5184 Å), are complicated by the overlapping of the closer doublet. Nevertheless, they too exhibit two absorption velocity systems, as shown in the spectrum (Fig. 2*d*, reversed so that absorption is dark) and in the trace and accompanying sketch (Fig. 5, below).

[1] Adjunct Staff Member, Observatories of the Carnegie Institution of Washington.

[2] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomical Observatories, which are operated by AURA, Inc. under contract with the National Science Foundation.

[3] Observations at the Palomar Observatory were made as part of a continuing collaborative agreement between the California Institute of Technology and the Carnegie Institution of Washington.

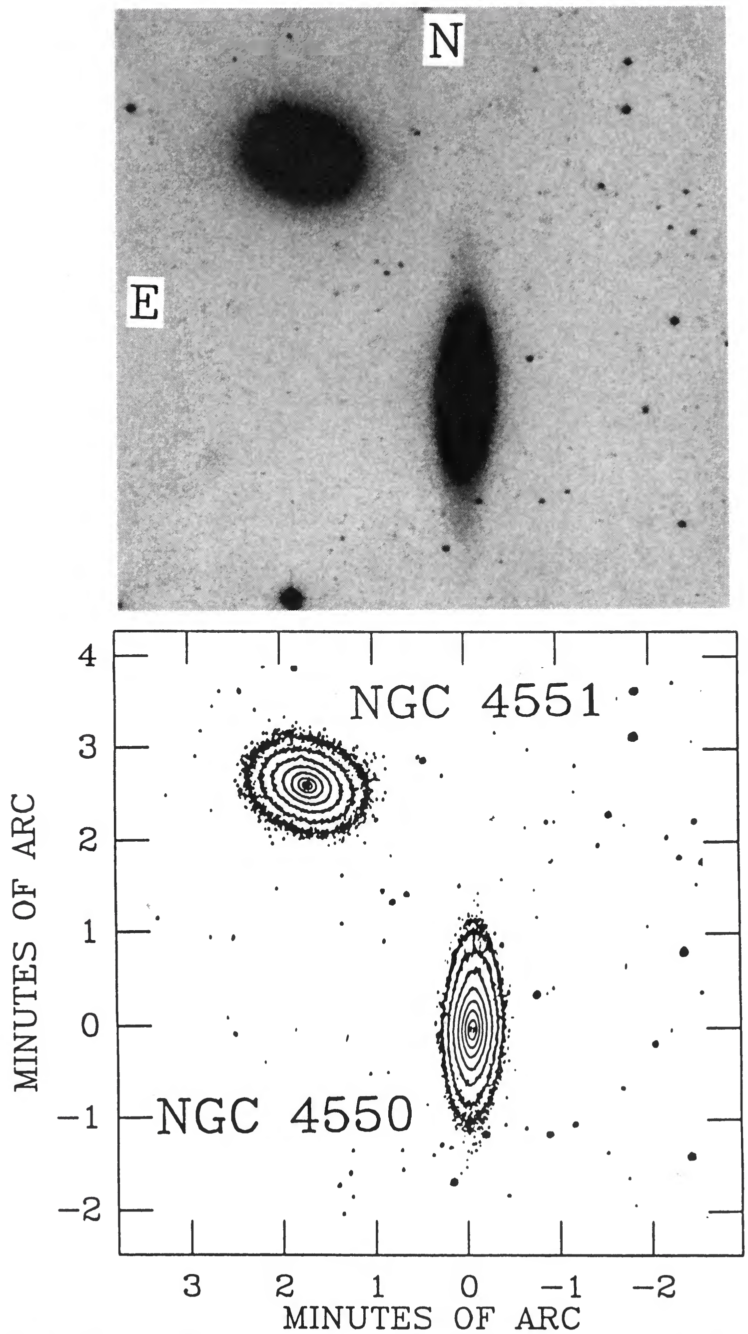

FIG. 1.—*Upper*: *R*-band image showing Virgo galaxies NGC 4550 and 4551, obtained by C. Bailyn and Y.-C. Kim at the CTIO 0.9 m telescope, using a 1024 × 1024 TEK CCD. There is no evidence of morphological peculiarity in either galaxy. NGC 4551 has a radial velocity 700 km s^{-1} higher than NGC 4550, so the galaxies may not be physically associated. *Lower:* Isointensity contours of the *R*-band image.

RUBIN, GRAHAM, & KENNEY (see 394, L9)

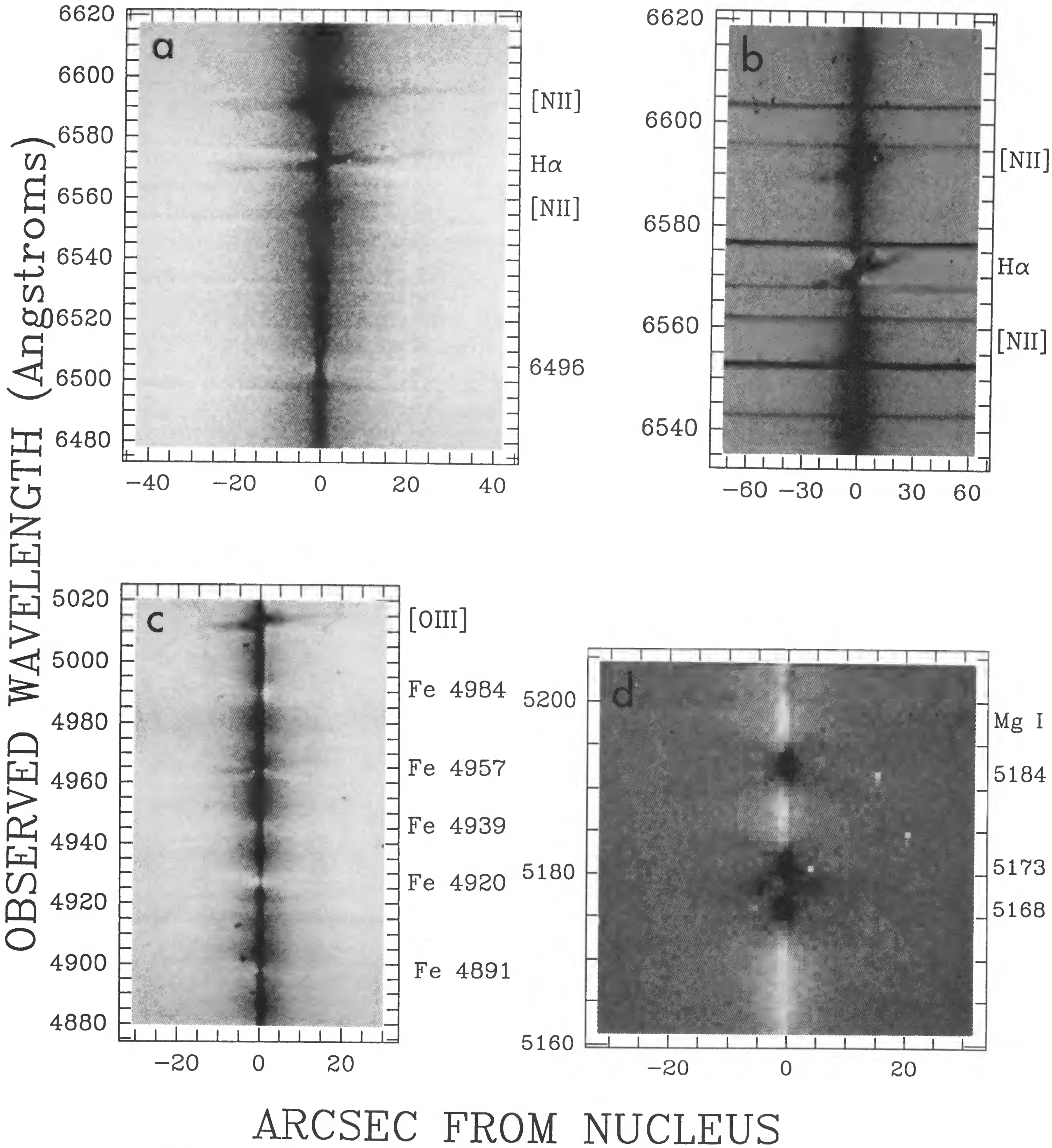

FIG. 2.—(*a*) Hα portion of 200 inch Palomar spectrum of major axis of NGC 4550 showing disk absorption and counterrotating emission. Scale and dispersion 0″.59 pixel^{-1} and 0.82 Å pixel^{-1}; integration 2000 s. The absorption blend at 6496 Å is indicated. On all spectra, red is to the top; emission lines are shown black on (*a*), (*b*), and (*c*). (*b*) Hα portion of 4 m spectrum of major axis of NGC 4550 showing absorption at Hα and counterrotating emission. Note counterrotating absorption ≈15″ north at edge of the Hα emission. Scale and dispersion 0″.91 pixel^{-1} and 0.33 Å pixel^{-1}; integration 6000 s (clouds). (*c*) Portion of 200 inch major axis spectrum showing [O III] emission and several blueward absorption lines, scale and dispersion 0″.82 pixel^{-1} and 0.56 Å pixel^{-1}. Note the X-shaped appearance of the absorption approaching the nucleus, arising from the prograde and retrograde stellar disks. (*d*) The Mg I triplet (5168, 5173, and 5184 Å) from the 200 inch spectrum, here reversed so that absorption lines are black. Note the two clear absorption rotation components at 5184 Å and the complex blending of the 5168 + 5173 Å doublet. Compare with Fig. 5 to identify the separate features.

RUBIN, GRAHAM, & KENNEY (see 394, L9)

TABLE 1

SPECTRAL OBSERVATIONS OF NGC 4550

Date (UT)	Telescope	Dispersion (Å pixel^{-1})	Scale (arcsec pixel^{-1})	Spectral Region	Axis on Galaxy	Integration (s)	Seeing
1989 Apr 10	200 inch (5 m)	0.82	0.59	Hα	Major	2000	1″.8
	200 inch (5 m)	0.56	0.82	[O III]5007	Major	2000	1.8
1990 Feb 17	4 m	0.33	0.91	Hα	Minor	2591	1.5–2
1992 Feb 4	4 m	0.33	0.91	Hα	Major	6000 (clouds)	2

Measured velocities are shown in Figure 3. Each plotted velocity is the mean of all measured emission (or absorption) in that radial bin. The agreement of the velocities from the two different telescopes is excellent. Along the major axis, the steep velocity rise is clearly seen in the measured emission velocities, while absorption velocities can be measured only beyond the nucleus. On the weakly exposed minor axis frame, little stellar continuum is recorded, and emission is almost absent beyond the nucleus; the velocities are constant with only a slight rise in the outermost (5″) emission.

3. DISCUSSION

NGC 4550 is a galaxy of moderate luminosity, with $B_0^t = 12.40$ (RC3). Of 14 galaxies in the Virgo Cluster in which we have detected rapidly rotating emission cores, NGC 4550 is the earliest type and the faintest. On the sky, NGC 4550 forms a pair with NGC 4551 (E3), although their central velocities differ by over 700 km s^{-1}. No evidence of tidal interactions or morphological peculiarities are evident. Optical emission in NGC 4550 has been known since Humason, Mayall, & Sandage (1956) but has not been studied since. (In mistakenly classifying it as a LINER, He & Impey 1986 confuse it with NGC *4450*, based on the coordinates and the velocity they tabulate.) NGC 4550 has been observed between 1.25 and 10 μm by Devereux, Becklin, & Scoville (1987). It is undetected in H I (Roberts et al. 1991), and undetected in X-rays (Forman, Jones, & Tucker 1985). Surface photometry by Bender,

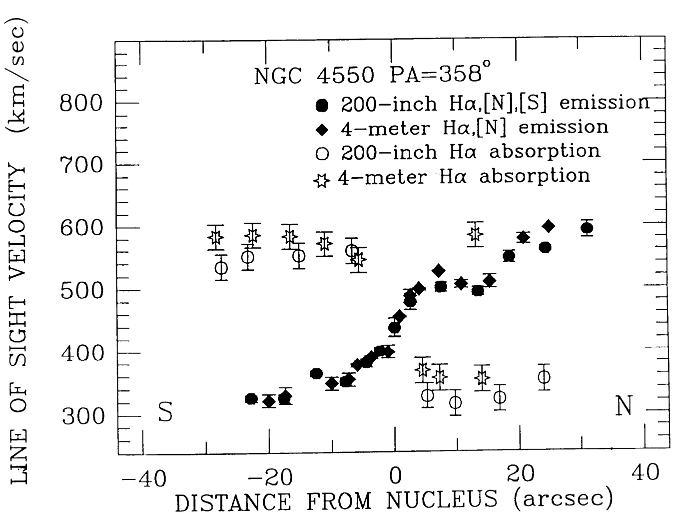

FIG. 3.—NGC 4550 major axis heliocentric velocities, from emission lines (*filled symbols*) and from Hα absorption (*open symbols*), measured on two different CCD frames. Error bars indicate 1 σ variation of all measures within that radial bin, except that for the absorption lines, 1 σ has been adopted as 20 km s^{-1}.

Dobereiner, & Mollenhoff (1988) shows NGC 4550 to be the most disky of all the ellipticals they studied. As befits such morphology, the velocity dispersion in NGC 4550 is extremely low, and it is this fact, coupled with the high-velocity resolution, which permits us to identify the kinematically distinct components within the galaxy.

The presence of two cospatial and counterrotating stellar velocity systems is so bizarre that we have made every effort to establish the reality of the double-valued absorption features. We discuss briefly a few of the questions we have attempted to address.

1. Is the double-valued absorption appearance an artifact of image processing? We have processed over 300 long-slit CCD spectra taken with the telescope+CCD combinations used here, and in no other case have we observed complex absorption lines.

2. Is the appearance of the absorption lines an artifact of the presence of the extended counterrotating emission? We have previously observed one other galaxy, NGC 1216 (Hickson 23C; Rubin et al. 1991) with extended emission counterrotating with respect to a narrow Hα absorption feature. A careful examination of the lines in both the red and the blue spectral regions shows only a single narrow component for all the absorption lines, with no peculiarity whatsoever. Slightly more often we have observed a narrow Hα emission core within a broader but corotating Hα absorption line (e.g., NGC 3189, Hickson 44A; Rubin et al. 1991; Fig. 2*l*). Here too, we see no evidence of peculiarity in the absorption-line properties.

3. Are we observing an extremely broad absorption, somehow giving the appearance of two individual features? According to Tonry & Davis (1981), the central velocity dispersion of NGC 4550 is remarkably small, $\sigma_v = 86 \pm 37$ km s^{-1}; the velocity dispersion is determined with the 3″ × 12″ slit aligned E-W along the minor axis (major axis PA = 358°), so as to exclude the rotation component. For Virgo S0 galaxies NGC 4459 and 4435 which are less than 1 mag brighter than NGC 4550 and for which we also have 200 inch spectra, the Tonry-Davis central velocity dispersions are 160 ± 22 and 174 ± 16 km s^{-1}, respectively. We show in Figure 4 a trace of the central nuclear column at the Mg I triplet spectral region of NGC 4550 and NGC 4435. While the spectrum of NGC 4550 shows partial resolution of the Mg I 5168+5173 doublet, the same feature in the spectrum of NGC 4435 is unresolved. Moreover, a spectrum of an (unidentified) star 10″ W of the nucleus of NGC 4459 exhibits a stellar Mg I absorption, also plotted in Figure 4; the lines in the spectrum of NGC 4550 are only a little broader than those in the star. Thus we are satisfied that in NGC 4550 there are no abnormally broad absorption features which are deceiving us.

4. Can we convincingly display the double-valued absorption? We show in Figure 5 (*upper*) a spectral extraction, 6″ in radial extent, of the region 9″.5 N of the nucleus of NGC 4550.

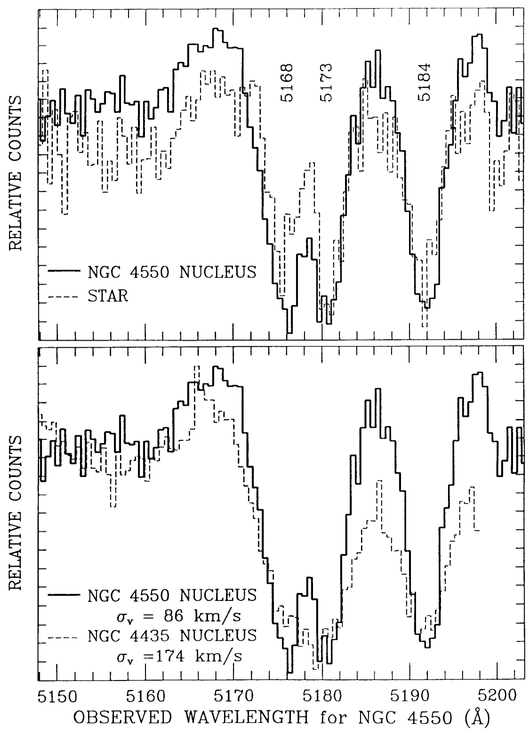

FIG. 4.—*Upper:* Nuclear spectrum of NGC 4550 in the region of the Mg I triplet (*bold line*), showing partial resolution of the close pair, compared with a star of smaller velocity dispersion; the star is shifted in wavelength by +7.5 Å. *Lower:* Nuclear spectrum of NGC 4550, $\sigma_v = 86 \pm 37$ km s^{-1}, compared with that for NGC 4435, $\sigma_v = 174 \pm 16$ km s^{-1}; both dispersions from Tonry & Davis (1981). Note lack of resolution of the Mg doublet in NGC 4435, thus confirming the lower velocity dispersion in NGC 4550.

Below it we picture the pattern of absorption formed by the three Mg I lines. The predicted wavelengths are based on the measured velocities for NGC 4550 (Fig. 3), with both prograde and retrograde orbiting disks; a central velocity of $V = 450$ km s^{-1}, a nuclear gradient of 120 km s^{-1} over 5″, and a constant velocity beyond.

In the extracted spectrum, we expect in general six absorption features, from the three Mg I lines in the two counterrotating disks. In the nucleus, we resolve only three, for the two disks overlap kinematically there. Beyond the nucleus, we resolve five components, since one of the Mg components from one disk is blended with a different Mg component from the other disk. Clearest are the absorption features from the singlet Mg I λ5184 in the two disks, features 1 and 2, which occur in a region free of any possible residual (e.g., after removal of night sky) night-sky contamination. The 5168 and 5173 Å absorption from the two directions of rotation blend to form one double strength dip (feature 4), and two less well-defined single features, 3 and 5. Note that the binary appearance of the Mg I lines in this region 9″.5 north of the nucleus, as predicted by the pattern of rotation from the two disks, is totally different from the form of the lines in the nucleus (Fig. 4, *bold line*). Note also that in the nuclear overlap region, the 5173 and 5168 Å lines in the model reproduce well the curious diamond structure visible in the spectrum (Fig. 2*d*). Extractions at other radial distances, although noisy, confirm these patterns. The separation of features 1 and 2 is 3.5 pixels, even less for the 3, 4 and 4, 5 features. Thus, had we observed at a resolution ≈2–3 times lower (≈3 or 4 Å rather than 1.5), we would have detected not two velocity systems but only a single broad apparently nonrotating absorption line defined by the outer limits of the two velocity components (e.g., features 1 plus 2; Fig. 5 [*lower*]).

4. CONCLUSION

The value of $V/\sigma = 1.4$, coupled with its ellipticity $(1 - b/a = 0.7)$, places NGC 4550 on the Binney (1978) region of rotating oblate spheroids. Hence it is axisymmetric, flattened by rotation, with no morphological or kinematical evidence of triaxiality. From its binary absorption lines, we conclude that prograde and retrograde stellar systems coexist in the disk of NGC 4550. In addition, one of the systems contains an extended gas disk. Although our limited material does not permit a detailed model, absorption-line intensities and measured velocities suggest that the two stellar systems have approximately similar dynamical properties, are approximately coplanar, and absorption-line strengths within the inner few kpc are only slightly stronger in the prograde disk.

There are several possibilities for the origin of the curious kinematics in NGC 4550, virtually all of which require the acquisition of secondary material after the initial stellar disk of NGC 4550 was in place. Variables include the geometry of the encounter, whether prograde or retrograde; the mass of the

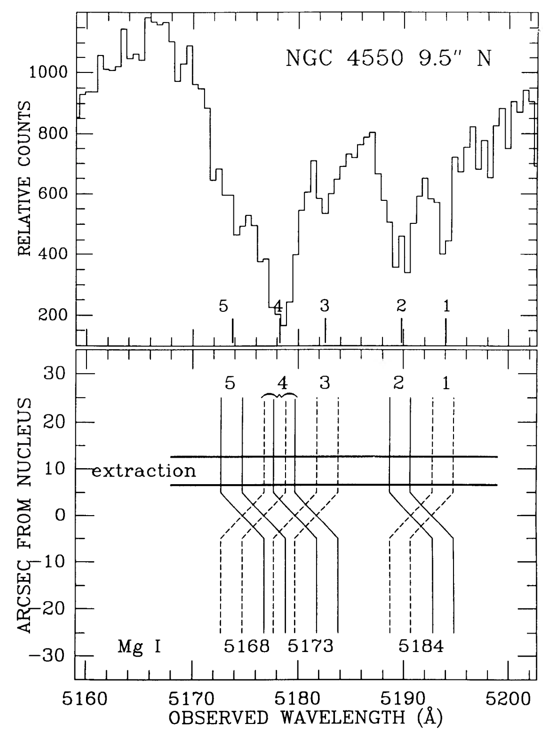

FIG. 5.—*Upper:* Spectrum of NGC 4550 extracted for the region 9″.5 ± 3″ north of the nucleus. Features labeled 1, 2, 3, 4, 5 indicate positions predicted for the prograde and retrograde Mg I absorption lines. *Lower:* Accurate position of the Mg I absorption lines arising from a galaxy with central velocity $V = 450$ km s^{-1}, velocities rising to 120 km s^{-1} at 5″ and constant beyond. Solid lines represent the absorption lines from the stellar (only) disk; dashed lines represent the absorption lines from the stellar counterrotating disk. The width of each line shown is 2 Å = 116 km s^{-1}. Note that the curious diamond appearance where the prograde and retrograde components of the 5168 and 5173 lines cross is a very good approximation to the appearance of the real spectral feature (Fig. 2). Note also the very different appearance of the Mg I lines in the nucleus (Fig. 4, *dark line*) compared with the binary absorption 9″.5 north shown here (an image of the Mg I absorption is shown in Fig. 1*d*).

acquired object relative to the initial mass of NGC 4550; and the form of the matter, whether principally gas or stars. Spectral evolution from integrated populations is complex, with no simple relation between absorption-line strength arising from a merger induced starburst, and the mass of gas and time since the merger (Bica, Alloin, & Schmidt, 1990). Lacking detailed spectral observations, we propose the following likely scenario. A retrograde gas mass, small compared with the mass of NGC 4550, is captured at some angle intermediate between polar and disk, settles to the disk via dissipation caused partly by differential precession (Sparke 1986; de Zeeuw 1990), and forms most stars after the gas has settled to the plane. Such an uncommon system can be understood as a variant of an "equatorial ring" (Schechter 1990), i.e., a disk; an alternative end point to the polar ring sequence. More complicated acquisitions, i.e., more nearly equal masses, or a large fraction of stars rather than gas, will require substantially more restricted orbital geometries, and hence be less likely to occur.

The lack of morphological distortions and the presence of strong metal absorption lines suggest that the time elapsed since the acquisition is at least 10^9 yr, allowing time for the gas to come to equilibrium in the combined gravitational potential, and for the merger population to form and age. An age of 10^9 yr corresponds to about 10 orbital periods at the half-light radius (16″) and to six orbital periods at the limits of our velocity measurements, sufficient time to destroy the morphological evidence of the event.

Discussions of cospatial stellar systems rotating clockwise and counterclockwise exist in the literature (Araki 1987). Lynden-Bell (1960) used a Maxwell demon to reverse the direction (and violate conservation of angular momentum) of one-half the stars in a spherical cluster to form two interpenetrating counterrotating spherical clusters. Toomre (1982) discussed axially symmetric flattened isothermal galaxy models. As nothing in the analysis restricts the disk stars to orbit only prograde, Toomre investigated sets of models in which one-half of the stars rotate prograde, one-half retrograde.

N-body simulations also have produced *small* counterrotating nuclear disks. Barnes & Hernquist (1991; Hernquist & Barnes 1991) show that a prograde merger of two gas-rich stellar disks produces a galaxy photometrically indistinguishable from an elliptical, which contains a kinematically distinct but small ($\approx$800 pc) central gas core. Such cores may be skew or counterrotating, for the tidal trauma has destroyed all knowledge of the previous orientation of the gas. However, the more extended gas, settled in a disk, rotates prograde. This model, so satisfactory in producing the small counterrotating nuclear cores, may not be appropriate to the larger scale phenomenon we observe. Yet gravitational calculations are scale-free, as Binney (1991) reminds us. A more appropriate set of initial conditions may lead to a realistic model for the remarkable NGC 4550. The discovery of galaxies like NGC 4550 confirms yet again the enormous variety within elliptical galaxies; Toomre's (1982) models are no longer just "elegant curiosities."

Although our observations are limited, we hope this publication will encourage others to study this curious nearby galaxy. We thank W. Kent Ford, Jr., for his participation in the initial observations, and the telescope operators for their cheerful, valued assistance. Comments from Penny Sackett, François Schweizer, Alar Toomre, and Scott Tremaine have been of great value and Donald Lynden-Bell's enthusiastic belief was welcome. We acknowledge use of NASA/IPAC Extragalactic Database (NED), operated by the Jet Propulsion Laboratory (Caltech) under contract with NASA.

REFERENCES

Araki, S. 1987, AJ, 94, 99
Barnes, J. E., & Hernquist, L. E. 1991, ApJ, 370, L65
Bender, R. 1990, in Dynamics and Interactions of Galaxies, ed. E. R. Wielen (Heidelberg: Springer-Verlag), 232
Bender, R., Dobereiner, S., & Mollenhoff, C. 1988, A&AS, 74, 385
Bertola, F., Bettoni, D., Buson, L. M., & Zeillinger, W. W. 1990, in Dynamics and Interactions of Galaxies, ed. E. R. Wielen (Heidelberg: Springer-Verlag), 249
Bica, E., Alloin, D., & Schmidt, A. 1989, MNRAS, 242, 241
Binney, J. 1978, MNRAS, 183, 501
———. 1991, Nature, 354, 186
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Buta, R. J., Patural, G., & Fouque, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer-Verlag) (RC3)
Devereux, N. A., Becklin, E. E., & Scoville, N. 1987, ApJ, 312, 529
de Zeeuw, T. 1990, in Dynamics and Interactions of Galaxies, ed. E. R. Wielen (Heidelberg: Springer-Verlag), 263
Forman, W., Jones, C., & Tucker, W. 1985, ApJ, 293, 102
He, X.-T., & Impey, C. D. 1986, MNRAS, 221, 727
Hernquist, L. E., & Barnes, J. E. 1991, Nature, 354, 210
Humason, M. L., Mayall, N. U., & Sandage, A. R. 1956, AJ, 61, 97
Lynden-Bell, D. 1960, MNRAS, 120, 204
Roberts, M. S., Hogg, D. E., Bregman, J. N., Forman, W. R., & Jones, C. 1991, ApJS, 75, 751
Rubin, V. C., Hunter, D. A., & Ford, W. K. 1991, ApJS, 76, 153
Sandage, A. R., & Tammann, G. A. 1987, A Revised Shapley-Ames Catalog (Washington, DC: Carnegie Institution of Washington)
Schechter, P. L. 1990, in Dynamics and Interactions of Galaxies, ed. E. R. Wielen (Heidelberg: Springer-Verlag), 508
Schweizer, F., van Gorkom, G. H., & Seitzer, P. 1989, ApJ, 338, 770
Sparke, L. S. 1986, MNRAS, 219, 657
Tonry, J. L., & Davis, M. 1981, ApJ, 246, 666
Toomre, A. 1982, ApJ, 259, 535