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EVIDENCE FOR UNUSUAL DYNAMICAL EFFECTS IN THE HALO OF NGC 5128 (CENTAURUS A)[1]

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ABSTRACT

New observations bring to 35 the number of spectroscopically confirmed globular clusters in NGC 5128. At radii less than $\sim 11'$ the ensemble-average cluster velocity appears to exceed by $\sim 4\ \sigma$ the systemic velocity of the galaxy, while at larger radii the two values agree. Several sources of possible systematic error are eliminated by the new data, suggesting that this peculiar result is not likely to have arisen from a statistical fluctuation. These inner clusters lie beyond the obvious bulge light but within the faintest outer isophotes, and generally have redder colors than more distant ones. We suggest that whatever phenomenon produced the warped dust lane and/or the faint optical "shells" around NGC 5128 may also be related to the unexpected cluster velocities. If the phenomenon involved a merger, the cluster velocity observations would appear to suggest that the last merger occurred more recently than a dynamical crossing time.
Subject headings: clusters: globular — galaxies: individual — galaxies: internal motions

I. INTRODUCTION

The peculiar optical appearance of NGC 5128 = Centaurus A, first noted by Herschel in 1847, may indicate that it is an anomalous elliptical galaxy and/or, by reason of proximity, merely that it is the best studied of a much larger class of active galaxies (Ebneter and Balick 1983). Until 6 yr ago the lack of a conspicuous globular cluster system (such as seen around other giant ellipticals) was thought to be another anomaly. Following spectroscopic confirmation of the first visually identified globular cluster candidate (Graham and Phillips 1980), star counts and low-resolution spectra of the brightest candidates have revealed a large globular cluster system (van den Bergh, Hesser, and Harris 1981, hereafter Paper I; Hesser *et al.* 1984, hereafter Paper II; G. Harris *et al.* 1984, hereafter Paper III; H. Harris *et al.* 1984, hereafter Paper IV).

Properties inferred to date from our studies include the following:

1. A total population of $1200 < N_t < 1900$ clusters and a specific frequency (i.e., the number of clusters per unit halo light) $3.0 < S < 3.2$; for other ellipticals $4 < S < 10$ (Harris and van den Bergh 1981).
2. A cluster luminosity function whose Gaussian σ determined over the 5 mag range of our data is probably consistent with the 1.2 mag value observed (Harris and Racine 1979, but see also van den Bergh 1985) for the Galaxy and M31, although values as large as 1.4 cannot be excluded. In this respect, Cen A may be like M87 (Kormendy and Lauer 1986; Grillmair, Prichet, and van den Bergh 1986).
3. At radii $> 4'$ the surface density of clusters inferred from star counts can be described by the same $r^{1/4}$ law found for the spheroidal light, while at smaller radii the inferred cluster density falls below that profile.
4. Some NGC 5128 clusters are ~ 0.1 mag redder in $(B-V)_0$, implying greater metallicity, than the reddest Galactic globulars, a result also inferred from infrared photometry (Frogel 1984).
5. From the cluster system properties a distance of ~ 3.3 Mpc and a mass $\sim 10^{12}\ M_\odot$ can be inferred for NGC 5128.

The foregoing characteristics do not greatly distinguish the NGC 5128 cluster system from those surrounding other nearby galaxies. However, the cluster radial velocities reported in Paper II led to the unexpected result that *their ensemble average*, $\langle v_r \rangle = 640 \pm 32$ km s^{-1}, *appeared to differ from* $v_{\rm sys} = 549$ km s^{-1}. New observations nearly doubling the

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sample size confirm the earlier result and also probe possible sources of systematic errors.

II. SPECTROSCOPIC OBSERVATIONS

Twenty clusters having heliocentric radial velocities $340 < v_r < 860$ km s^{-1} were identified in Paper II from 3–4 Å resolution, blue spectra obtained in 1980–1982 with a 16 mm UV SIT (Atwood *et al.* 1979) on the R-C spectrograph of the CTIO 4 m telescope. Observations were obtained in 1983 and 1984 with the identical equipment but using a 40 mm SIT; in spite of considerable interference from clouds, 15 new clusters (Fig. 1 [Pl. L6]) have been spectroscopically confirmed.[3] We have not observed any objects with velocities in the range 120–300 km s^{-1} in which case a decision about membership in NGC 5128 might have been difficult. Therefore, the distribution of cluster velocities probably is not biased by selection effects.

[3]Another goal of the 1983–1984 observations was to correlate our $\langle B \rangle - \langle V \rangle$ photographic colors with metallicity. Those results will be the subject of another paper, though we note here that long exposure spectra for clusters 5, 3, and 23 yield spectral types of $\sim F6$, $\geq G4/5$, and $> G4/5$; the latter two appear to be stronger lined than any Galactic globular studied by Hesser and Shawl (1985). In turn, the bulge light spectrum is stronger lined than the aforementioned NGC 5128 clusters.

Table 1 summarizes the cluster data as follows: (first column) object number (Fig. 1); (second column) radial distance from the nucleus in arcmin (at a distance of 3.3 Mpc, 1 arcmin = 1 kpc); (third and fourth columns) orthogonal distance from the adopted minor and major axes (Fig. 1); (fifth column) $\langle B \rangle$ from improved photographic photometry of CTIO and Las Campanas plates calibrated primarily by a CCD sequence; (sixth column) total exposure time; (seventh column) heliocentric radial velocity; velocity data from different nights have been combined (weighting by exposure time) for clusters 3, 5, 7, 23, and 39.

Errors computed from the line-to-line scatter of individual cluster observations in 1983 and 1984 ranged from 13 to 37 km s^{-1}, and the mean value was 22 km s^{-1}. While other sources contribute to the internal errors (principally flexure and magnetic interference in the spectrograph/SIT), the evidence suggests that the internal precision is generally better than 30 km s^{-1}, i.e., much smaller than the velocity dispersion observed for the cluster system. The systematic errors in our velocities are, to the best of our knowledge, also small. Several tests have been previously described (cf. Paper II; Hesser *et al.* 1985; and references therein), and 1983–1984 observations also probe the accuracy of our velocities. Velocity differences (observed − published) are given in Table 2 for ROA 40 and 65 (ω Cen giants used for monitoring the velocity

TABLE 1

SUMMARY OF CLUSTER PROPERTIES

OBJECT	R (′)	D_{minor} (′)	D_{major} (′)	<B> mag	Exp. min.	$\langle v_{r,\odot} \rangle$ km s^{-1}
6	2.0	2.0	0.1 (E)	17.87	25	780
35=83−26	3.4	3.0 N	1.5 E	19.23	60	477
18	4.7	2.2	3.9 E	18.22	45	520
22	4.8	4.0 N	2.9 E	18.89	30	640
23	4.9	3.8 N	3.1 E	18.19	180	650
24	4.9	4.0 N	3.2 E	19.30	38	...
17	5.2	5.2 N	0.9	18.31	60	860
31=83−41	5.4	3.0	4.3	19.20	60	680
11	5.8	3.5	4.1	18.81	60	800
21	6.5	1.4	6.3 E	18.58	45	490
19	6.9	3.7	5.7 E	18.88	45	760
20	7.2	7.2 N	0.0 ( )	18.63	55	800
3	7.2	1.2 N	6.9	18.51	240	554
25	7.3	6.6 N	3.1 E	19.53	60	660
7	8.1	7.2 N	3.2 E	17.78	154	592
5	8.2	5.3 N	6.0	18.18	225	542
30=83−44	9.4	3.1 N	9.0	18.15	36	750
4	9.5	9.4	0.6 E	18.64	105	660
10	10.0	9.8	2.0	19.28	90	770
33=83−35	10.0	7.3 N	7.0	19.33	60	650
12	10.1	9.9	1.8 E	18.82	60	440
37=83−14	10.4	10.1 N	2.5 E	19.24	60	780
32=83−39	10.8	6.0 N	9.0	19.29	50	680
36=83−19	11.2	11.2 N	1.3 E	19.04	45	790
38=83− 6	12.1	11.1 N	4.7 E	19.00	45	430
2	12.8	12.5	0.5 E	18.31	90	640
26	14.9	14.8 N	0.8 E	19.04	120	340
39=84− 4	15.0	1.7 N	14.8 E	18.22	72	334
14	15.9	11.5 N	11.0	18.62	63	710
28=84−15	17.1	3.0 N	16.7	19.11	60	460
29=84− 1	19.0	18.7	2.0 E	19.04	60	710
27	19.6	19.5 N	2.8 E	19.15	90	500
34=84− 8	20.2	16.0	12.7 E	19.12	60	620
1	21.5	18.5	10.1	18.26	60	690
16	24.5	21.4 N	12.0	19.40	90	490

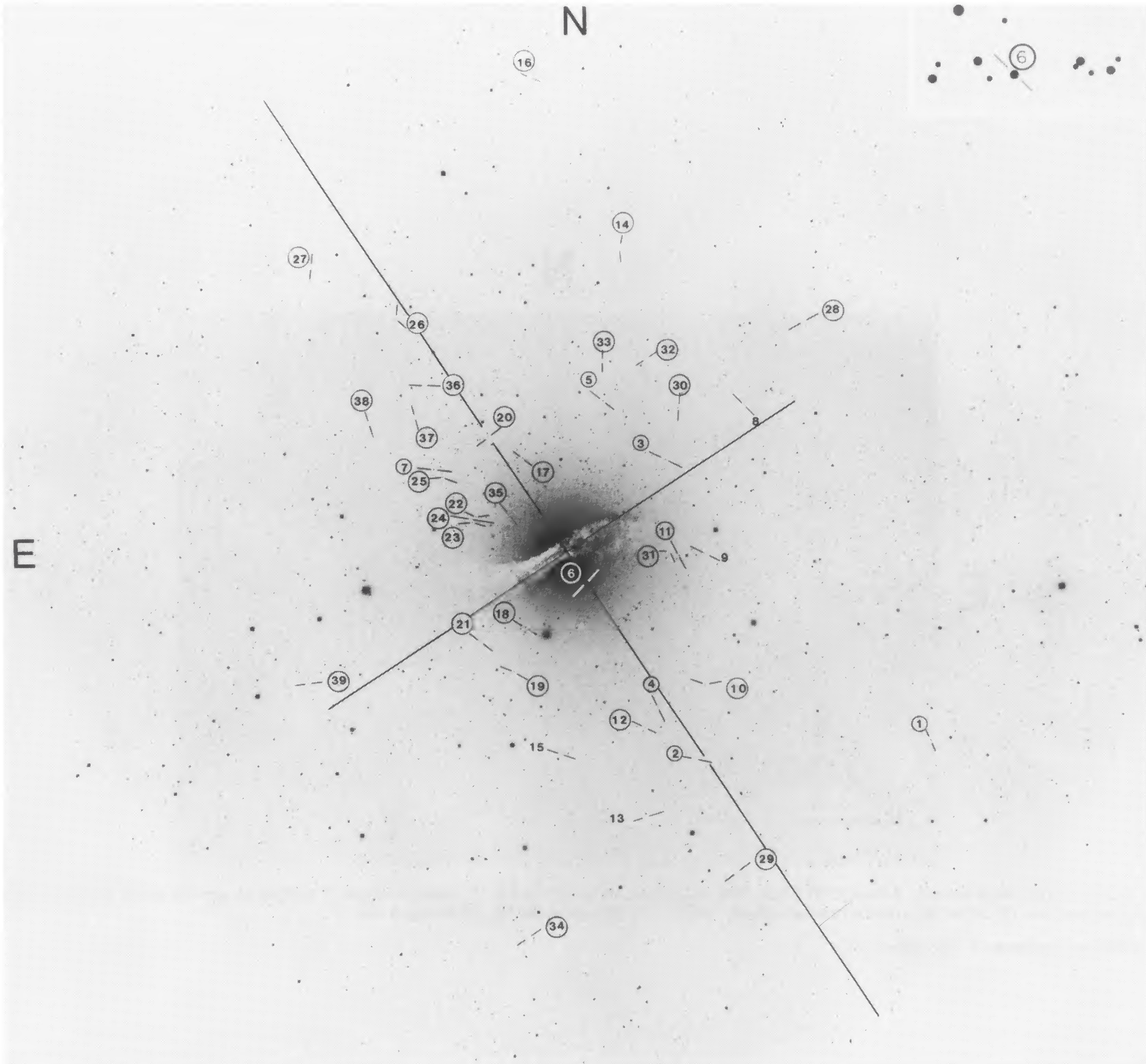

FIG. 1.—Identification of spectroscopically confirmed clusters (*circled numbers*) and cluster candidates (*uncircled*—see Paper II). The axes adopted for measurement of orthogonal distances are shown, where that running NE–SW (roughly parallel to the radio axis) is assumed to be the major axis.

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TABLE 2

VELOCITY COMPARISONS

Object	N	$\langle \Delta v \rangle$ (km s^{-1})
1983		
ROA 40	10	-1 ± 11
ROA 65	10	-9 ± 11
Galactic Globulars	4	4 ± 6
1984		
ROA 40	9	6 ± 7
ROA 65	12	8 ± 7
Galactic Globulars	10	18 ± 6
Ellipticals	4	-1 ± 28

system—cf. Paper II), integrated light of Galactic globular clusters spanning a wide metallicity range, and of elliptical galaxies. Evidently the 1983–1984 observations require no zero-point corrections, and our effective wavelengths (cf. Hesser, Shawl, and Meyer 1986) satisfactorily account for metallicity dependence.

A final external check of our NGC 5128 velocity system was made by measuring a 60 minute 1984 exposure of the absorption spectrum of the bulge light (taken 8".3 N of a star which is 8.5 mm E and somewhat N of H II region 10 in Graham's 1979 Fig. 2). Sky was taken from bracketing 60 minute exposures of clusters outside the bulge. From 24 spectral lines we find $v_{\rm bulge} = 480 \pm 13$ km s^{-1} at this position, which agrees very well with values reported by Bertola, Galletta, and Zeilinger (1985) and by Wilkinson *et al.* (1985).

III. DISCUSSION

With the new evidence that the accuracy of our velocities is $\sim$ 25–30 km s^{-1}, and with the sample of clusters almost double that in Paper II, we now ask if the difference between $v_{\rm sys}$ and $\langle v_r \rangle$ persists. For the 34 clusters with velocity determinations we find $\langle v_r \rangle = 625 \pm 24$ km s^{-1}, a value $\sim$ 76 km s^{-1} (or $\sim 3\ \sigma$) larger than $v_{\rm sys}$ (cf. Paper II). Clusters beyond $r \approx 11'$ average to $v_{\rm sys}$, while ones nearer the galaxy rise above it (Fig. 2). For the 22 clusters having $r < 11'$, $\langle v_r \rangle = 661 \pm 25$ km s^{-1}, which is $\sim 4.5\ \sigma$ larger than $v_{\rm sys}$. On the other hand, for the 12 clusters having $r > 11'$, $\langle v_r \rangle = 560 \pm 44$ km s^{-1}, which is indistinguishable from $v_{\rm sys}$. Within the errors the velocity dispersion is invariant, but when calculated with respect to $v_{\rm sys}$ it appears to rise as r decreases (cf. Table 3). With a dispersion $\sim 150/\sqrt{n}$ km s^{-1}, the probability that randomly selected clusters would average to either 625 or 661 km s^{-1} is $\sim$ 0.3 and 0.006%, respectively, making it unlikely that the velocity difference arose in that manner. (Paper IV provides evidence that our clusters rather thoroughly sample the bright end of the cluster luminosity function, although a luminosity bias to the velocities seems improbable.) The inner, "perturbed" clusters basically lie beyond the normal bulge light (Fig. 1) but within the faintest outer isophotes (Malin, Quinn, and Graham 1983) and contribute substantially to the visual impression (Paper II and Figs. 1, 2) that the spatial distribution of confirmed clusters is

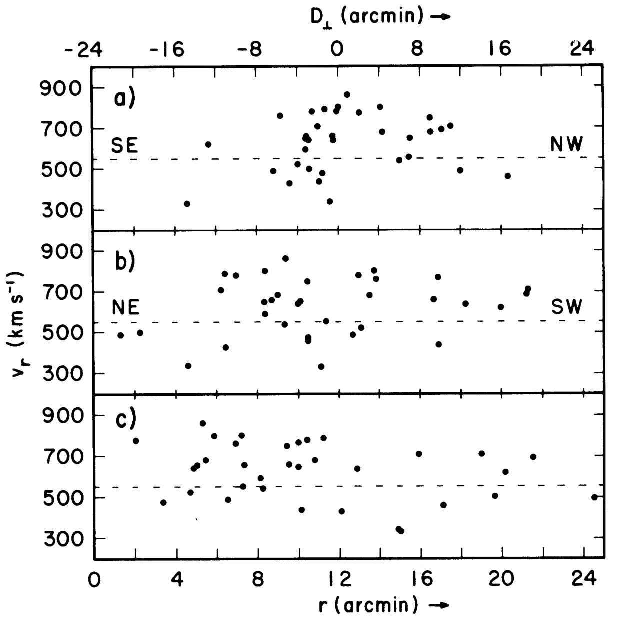

FIG. 2.—The orthogonal distances to the presumed major and minor axes ([a] and [b], respectively—upper scale), and the radial distance ([c]-lower scale) vs. v_r. The dashed line in each panel represents $v_{\rm sys}$, taken to be 549 km s^{-1} (cf. Paper II).

TABLE 3

NGC 5128 CLUSTER VELOCITIES

PARAMETER	RADIAL BIN 2.0–7.2	7.2–10.8	11.2–24.5	All
$\langle r \rangle$ (arcmin)	5.2 ± 0.5	9.2 ± 0.4	17.0 ± 1.2	10.6 ± 1.0
$\langle v_r \rangle$ (km s^{-1})	678 ± 41	643 ± 32	560 ± 44	625 ± 24
N	11	11	12	34
$\sigma_{\rm sys}$ (km s^{-1})	191	144	154	159
$\sigma_{\rm bin}$ (km s^{-1})	135	105	154	139

flattened towards the major axis. It is unclear from our data if the cluster system as a whole is rotating, although we suspect it may weakly be (NE approaching, SW receding about the minor axis and/or SE approaching, NW receding about the major axis—cf. Fig. 2).

Providing our ensemble average velocities are not vitiated by undetected errors, we are left with the rather puzzling situation that the bulk of the NGC 5128 *globular clusters differ kinematically from the prominent bulge light.* We are, frankly, at a loss to explain how the clusters (which by virtue of their high luminosity must be reasonably massive) could have been accelerated in the manner observed. It seems possible, but by no means certain, that the peculiar velocity distribution is associated with some of the phenomena which gave rise to NGC 5128's warped dust band and/or its faint optical shells (cf. Malin, Quinn, and Graham 1983; Haynes, Cannon, and Ekers 1983). Various models invoking processes occurring in an isolated galaxy, as well as merger processes, have recently been explored.

Williams and Christiansen (1985) have proposed that early in the history of ellipticals a blast wave could sweep the initial interstellar medium out of the galaxy into an expanding shell. A brief epoch of star formation leads to stars in highly radial, bound orbits moving in phase preferentially near apogalacteum. As Athanassoula and Bosma (1985) note, this model for the sharp shells requires the stars to remain in phase for > 20 crossing times. Van Albada, Kotanyi, and Schwarzschild (1982) propose a model of stable orbits in a triaxial potential. They envision that the gas rotates about the radio (major) axis, while the stellar system rotates about the dust band (minor axis). A slow rotation of the stellar component perpendicular to the NGC 5128 dust lane—*but contrary to the sense they predicted*—has been observed spectroscopically by Bertola, Galleta, and Zeilinger (1985) and by Wilkinson *et al.* (1985), thereby leading them to favor the alternative, merger class of models.

Following Graham's (1979) suggestion that perhaps the NGC 5128 warped dust lane was produced by a merger with a gaseous cloud, Tubbs (1980) developed an interaction model involving a nonrotating prolate spheroid. Subsequently others have explored various configurations. In particular, Malin, Quinn, and Graham (1983) argue that the faint optical shells could have been produced by phase wrapping of a tidally disrupted small disk galaxy settling to the preferred plane of the potential of the more massive elliptical. With time the number of shells would grow in reflection of the original spread of orbital periods of the stars in the disk. After careful review of the available models and data, Wilkinson *et al.* (1985) favor a merger picture involving either an effectively stationary oblate triaxial ellipsoid or prolate spheroid, depending upon whether or not the radio jet lies along a principal axis. Finally, Bland (1985) finds that the very complicated warp does not seem to conform to any of the stable configurations yet proposed.

If the globular clusters have somehow been tidally affected by a merger process, their systematically high velocities imply that the perturbation occurred more recently than a dynamical time scale ($< 3x10^8$ yr?). It also seems likely that the outer shells must have been produced by an earlier merger event than the one which produced (is producing?) the inner shell and dust band; otherwise phase wrapping would have occurred, and no inner shell would be visible. The fact that the innermost globulars are on average redder (more metal-rich) suggests they originated with the more massive elliptical galaxy. The nearly circular isophotes and lack of significant disklike rotation in the inner bulge also seem to rule out the presence of a substantial contribution of bulge stars from the victim which we would expect to see were the globulars from it. It is possible that perhaps formation of some clusters was stimulated by the merger process, such that they are only $\sim 10^9$ yr old but very metal-rich (D. Burstein, private communication). This intriguing suggestion recognizes the existence of younger, globular-like star clusters in the Magellanic Clouds but requires arguing that the failure to detect carbon stars in the IR photometry of 12 NGC 5128 clusters (Frogel 1984) is insufficient to eliminate the possibility of (relative) youth. However, aside from possibly very important uncertainties in the evolution of young, very metal-rich stars, an analysis similar to that of Bothun *et al.* (1984) suggests that Frogel's interpretation is correct and that the inner clusters are not preferentially younger than the outer ones. We also note that $\langle v_r \rangle$ for the bluer and redder inner clusters are the same. For a shock phenomenon associated with the victim to have stimulated cluster, as well as shell, formation simultaneously over the face of NGC 5128 would require the existence of dense clumps of material in the outer regions of NGC 5128 and the existence of an intrinsically elliptical distribution of material (with major axis along the NE–SW direction).

Regardless of our inability to propose a plausible explanation, the apparent extension of the already complex dynamical picture of NGC 5128 to objects far beyond the obvious warped dust band offers the promise of a new class of constraints on the history of this fascinating object. If velocities could be measured in the bulge and shell light at radii > 5′ we suggest that they might show similar peculiar effects.

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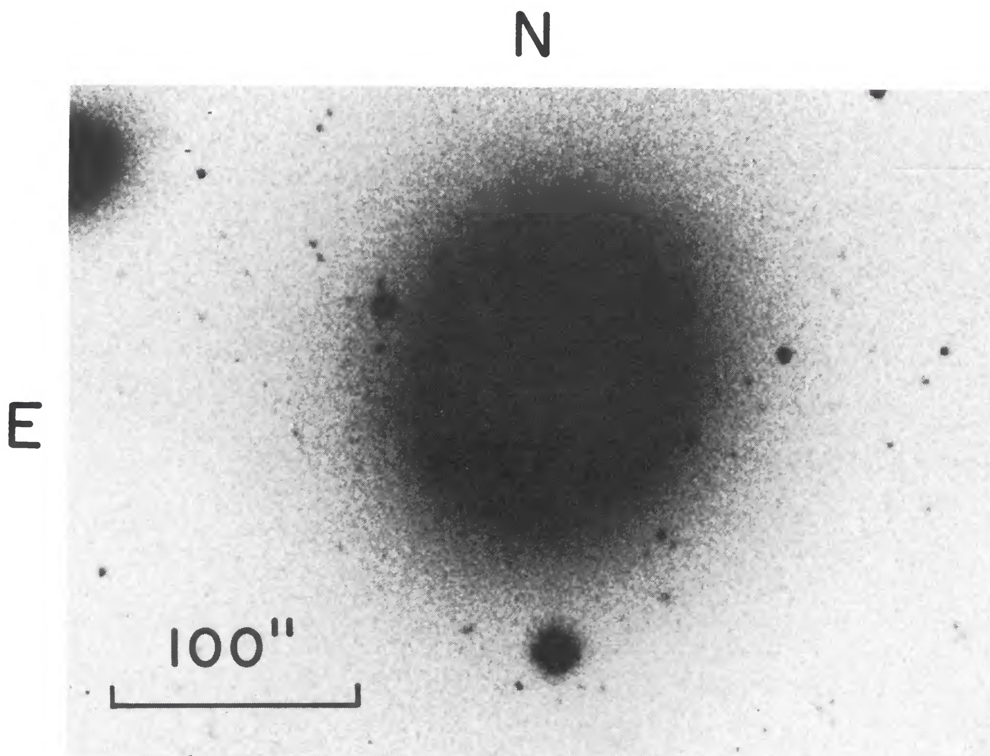

FIG. 3.—NGC 4261 from an *R* band CCD frame. The object lying about 70″ in PA 71° from the center of NGC 4261 appears on the PA 71° slit and confirms that this slit shows the greatest rotation velocity. NGC 4264 appears to the far NE of this frame.

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