THE ASTROPHYSICAL JOURNAL, **280**:L9–L12, 1984 May 1

3C 324—AN EXTREMELY DISTANT CLUSTER RADIO GALAXY

HYRON SPINRAD[1] AND S. DJORGOVSKI[2]
Department of Astronomy, University of California, Berkeley
Received 1983 November 10; accepted 1984 January 10

ABSTRACT

The strong radio source 3C 324 is identified with a faint cluster galaxy, with $V \approx 22.6$. Our new CCD spectroscopic data yield an emission-line redshift, $z_e = 1.2063$. The emission spectrum is narrow-line and shows a characteristic low-ionization level. The strong [O II] line is both spatially and velocity resolved in 3C 324; a speculative hypothesis on its origin in a rotating and possibly captured gas disk or an infalling galaxy is advanced. The detection of a cluster around 3C 324 is discussed.

Subject headings: galaxies: clustering — galaxies: redshifts — radio sources: galaxies — spectrophotometry

I. INTRODUCTION AND INITIAL OBSERVATIONS

3C 324 is among the more intense radio sources and is identified with a faint galaxy (Kristian, Sandage, and Katem 1978, hereafter KSK; Gunn *et al.* 1981; Laing, Riley, and Longair 1983, hereafter LRL). It has a flux density of 15.8 Jy at 178 MHz (LRL); thus it is a powerful source and was placed on our spectroscopic observing list for that reason. The radio morphology from Jenkins, Pooley, and Riley (1977) is an asymmetric double with 8″ lobe spacing; the KSK and Gunn *et al.* identification is well centered between the radio lobes. The radio spectrum is steep, with $\alpha_{38}^{750} = +0.82$ (Kellerman *et al.* 1969), as is usually the case for powerful radio galaxies.

KSK mention the detection of surrounding galaxies in a probable cluster, near the limit of their V plate with the Hale 5 m reflector; the cluster is not visible on their finding chart, nor is it conspicuous on the Gunn *et al.* (1981) CCD frame illustration. However, our data also do (indirectly) suggest a cluster of galaxies several magnitudes fainter than 3C 324 itself (see § II).

In 1982 May we obtained low-resolution spectra with the Cryogenic Camera (a CCD spectrograph; see DeVeney 1983 for a complete description of the instrument) attached to the Mayall 4 m reflector at Kitt Peak. The typical spectral resolution with the grisms we employed was about 15 Å (FWHM) in the regions where the detector has a good focus.

To obtain the best sky subtraction, a vital link in the procedure needed for an accurate spectral extraction, we utilized a long (4′) slit, with a width of 3″.2 on the sky. This enables reduction with a long, generally smooth run of sky intensity pixels on each side of the object spectrum on the two-dimensional CCD array. The galaxy spectral extractions (after the flat-fielding and frame rectification) used 5 pixels perpendicular to the dispersion (~ 4″ on 3C 324). Full details on our reduction procedure are given by Djorgovski and Spinrad (1983). 3C 324 is optically quite faint, so multiple integrations of 1 hour in each area were obtained—two in the visible (YR grism) and three in the near-infrared.

Figures 1 and 2 show the stacked visual and IR spectrograms respectively. One immediately notes (Fig. 2) the great strength of the emission line at λ8225; its peak intensity with our low resolution exceeds the local continuum by at least a factor of 20. As with other narrow-line radio galaxies, the very strongest line is identified with λ_0 3727 of [O II], and this identification was easily confirmed by the presence of weaker emission features of [Ne III] and possible [Ne V] on the IR grism spectra. In the visible (Fig. 1), we note the broad, partially resolved Mg II doublet (λ2799) and the weaker lines of C II] λ2326 and (Ne IV) λ2424. Table 1 collects the data on the observed emission-line wavelengths and intensities (the latter based upon a conventional flux calibration through observations of standard stars calibrated by Stone (1974, 1977) The mean, unweighted redshift of 3C 324 is $z_e = 1.2062_8$.

II. CLUSTER AROUND 3C 324

KSK, in their initial identification of 3C 324, mentioned a likely cluster ($N \approx 10$) surrounding 3C 324 on their V plate. Our detection of other faint objects near the radio galaxy was atypical; on the sky-subtracted two-dimensional CCD images, several very faint "spectral streaks" appear, on either side of the 3C 324 spectrum. They are especially noticeable on the IR frames (normal fields do not show this great a density of serendipitous objects, presumed galaxies). Of course, these objects, somewhat presumptuously called "companion galaxies," must be spatially along and partly within our spectrograph slit, of 3″.2 full width. We observed in P.A. = 90°. If we imagine a fictitious, uniform density, round, rich cluster with a radius of 0′.5 centered at 3C 324, our slit should include 6% of all cluster candidates; thus if about 4 of the 6 detected spectral images are true companions to 3C 324, the modeled cluster would be very rich indeed, some 50 galaxies above the threshold for detection ($R \approx 25$) if the observations were attempted in a direct mode.

[1]Visiting Astronomer, Kitt Peak National Observatory, which is operated by AURA, Inc., under contract with the National Science Foundation.

[2]Visiting Student, Kitt Peak National Observatory.

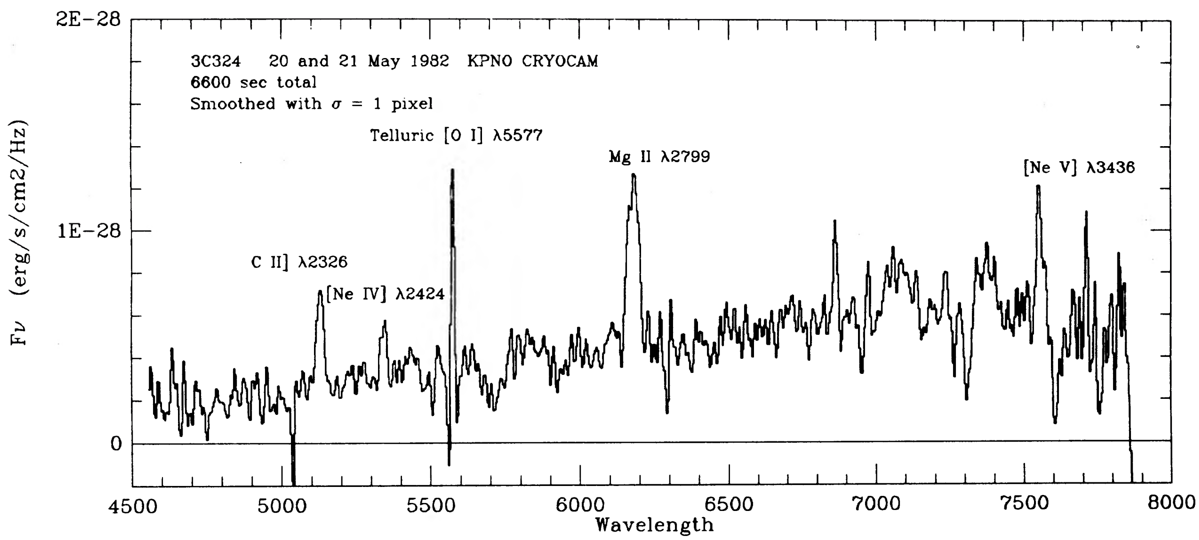

FIG. 1.—Visual spectrum of 3C 324. The features are labeled. The spectrum was smoothed with a Gaussian with $\sigma = 1$ pixel.

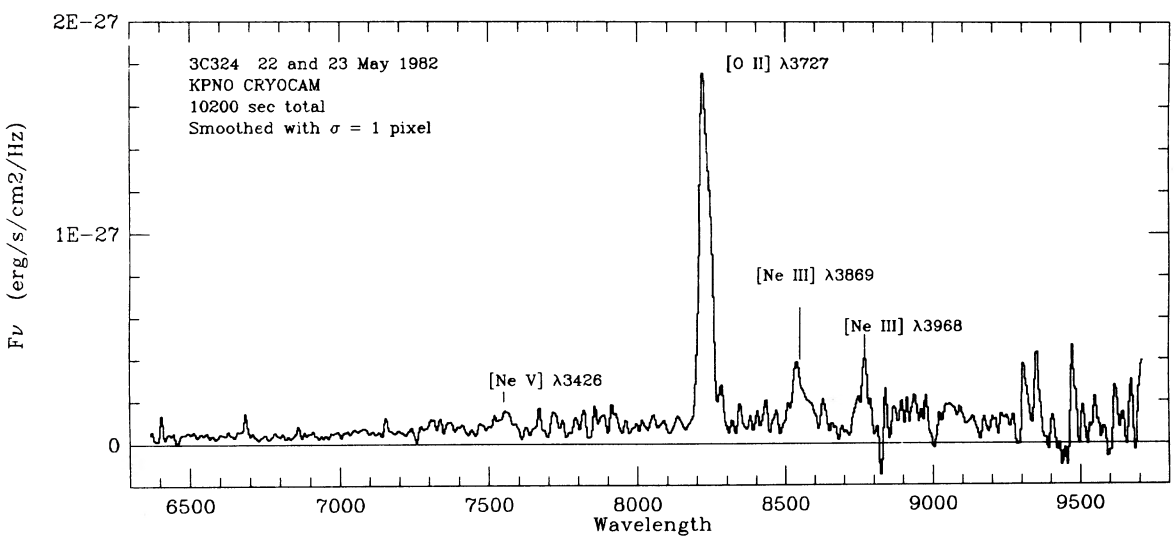

FIG. 2.—Near-IR spectrum of 3C 324, smoothed with Gaussian with $\sigma = 1$ pixel

TABLE 1
EMISSION LINES IN THE 3C 324 SPECTRUM

Ion	λ_0	λ (observed)	z_e[a] (observed)	$W\lambda$ (Å) (observed)	$W\lambda$ (Å) (rest fr.)	Flux (10^{-16} ergs cm^{-2} s^{-1})
C II	2326	5132.5	1.2064	46	21	0.36
[Ne IV] ...	2424	5341.3	1.2034	3:	1.4	0.022
Mg II	2799	6179.1	1.2076	102	46	0.82
[Ne V]	3426	7555:	1.205_2	weak	...	...
[O II]......	3727	8226.0	1.2071	755	342	7.86
[Ne III] ...	3869	8542.8	1.208_0	104	47	1.09

[a] $\langle z_e \rangle = 1.2062_8$.

In fact, we have obtained four fairly deep direct images of the 3C 324 field with the Mayall telescope and Cryocam, used in a direct mode. The images were taken on 1983 May 10 UT, with mediocre seeing.

The exposures were 100 s each, two with the RG 610 filter, and two with the GG 420 filter, in order to extract some minimal color information. The exposures were taken at different telescope pointings, in order to avoid possible CCD artifacts appearing as faint "objects". Photometric calibration was accomplished by obtaining several exposures of the faint photoelectric standards field in M3 (Sandage 1970). The frames were interpolated to twice the sampling (to the pixel size of 0".42), registered, and digitally stacked together. The resulting point-spread function (after the stacking) has a FWHM of approximately 3".5; the limiting magnitude is about 25.

The images ("blue" pair stack, "red" pair stack, and the stack of all four) were processed with the maximum entropy algorithm, and apparent faint objects were checked for repeatability. Some of the more interesting ones are marked in the Figure 3 (Plate L1). Object E coincides with one of the faint spectroscopic streaks and probably shows the oxygen λ_0 3727 line at the same redshift as 3C 324, as can be seen in Figure 4 (Plate L2). This object appears to be a member of an interacting group and has a magnitude of about 23.5. We do not have the redshifts for any of the other objects, and some of them could be foreground or background. The magnitudes and the colors are consistent with their being the fainter cluster members at this redshift.

Thus, the overall evidence is very suggestive of the presence of a cluster around 3C 324. Further photometric and spectroscopic investigations should settle this question. Note that, at the lower redshifts, radio galaxies of this type are often found to be central cluster galaxies.

The presence of a cluster at this redshift (look-back time ≈ 0.6 of the Hubble time) provides a very strong timing constraint on the theories of large-scale structure formation.

III. DISCUSSION OF THE GENERAL SPECTROSCOPIC DATA

There is no doubt that the continuum starlight from 3C 324 is present on the scale of a giant galaxy. With our spectrophotometric (line-free) V-magnitude of 22.6 ± 0.2 mag, we used Bruzual's (1981, 1983) exponential star formation models to compare the intrinsic luminosity of 3C 324 with 3C 295, a somewhat closer ($z = 0.46$), fairly normal radio galaxy identified with a giant E. 3C 295 (Gunn and Oke 1975) is seen to be about the same luminosity as 3C 324.

One of our interests lies in the enormous oxygen line in the spectrum of 3C 324; using the precepts of Spinrad (1982), we find the luminosity in [O II] to be 6.1×10^{42} ergs s^{-1}, among the highest yet measured. A conservative estimate would then place the total line emission near 10^{10} solar luminosities! (This is 3000 times more than the line flux from M87, a nearby, moderately powerful radio galaxy.)

Our spectrophotometric line fluxes in Table 1 can be partially compared to the shock heating models by Shull and McKee (1979) and to dilute photoionization field models (Ferland and Netzer 1983; see Table 2). Both types of models fit the 3C 324 line spectrum moderately well; the UV power-law ionization model, presumably "natural" for most active galactic nuclei (AGNs), predicts [Ne IV] and perhaps [Ne V] too weak compared with [O II], but reducing the dilution to $\log u = -3$ would improve that. As for the straight 100 km s^{-1} shock model, it predicts a C II] λ2326 line somewhat too strong to match 3C 324 but is otherwise almost indistinguishable from the dilute photoionization model. We cannot definitely rule in favor of either; further observations of high-ionization levels, possibly C IV λ1549 will eventually help. The main point we should make is that the spectrum is "soft"; e.g., the low-ionization level indicated by the strength of [O II] and C II] λ2326 is clearly different from the situation observed in most Seyfert galaxy nuclei (cf. Clavel and Joly 1983).

The intrinsic line widths of the 3C 324 emissions are fairly narrow; the Mg II doublet appears slightly resolved near its peak on both YR integrations, and the FWHM of the [O II] line in its rest-frame (approximately corrected by a Gaussian convolution for the instrumental profile) is about 1200 km s^{-1}. However, the next section will show that some of this width is an "organized" velocity field with a large spatial extent. The true nuclear emission-line widths are likely to be consistent with a FWHM of some 500–800 km s^{-1}, similar to other low-ionization radio galaxies studies by Spinrad (1982).

IV. SPATIALLY RESOLVED [O II] LINE IN 3C 324

On our near-infrared spectrograms of 3C 324, the strong [O II] line is noticeably extended and inclined; the best seeing exposure (taken on 1982 May 22 UT through thin cirrus cloud) shows an extended emission structure which projects to

TABLE 2

COMPARISON OF EMISSION LINES IN 3C 324 AND TWO REPRESENTATIVE MODELS

Ion	λ_0 (Å)	3C 324	Model 1	Obs/Model 1	Model 2	Obs/Model 2
Hβ	4861	...	1.00	...	1.00	...
C II]	2326	0.36	1.30	0.3	3.42	0.1
[Ne IV] ...	2424	0.02	0.002	~ 10	0.011	2
Mg II	2799	0.82	1.43	0.6	...	...
[O II]......	3727	7.86	7.74	1.0	7.78	1.0
[Ne III] ...	3869	1.09	0.38	3	0.38	3

NOTE.—Model 1: Ferland and Netzer 1983: dilute UV power law; $\log u = -3.70$. Model 2: Shull and McKee 1979: shock model; $v = 100$ km s^{-1}.

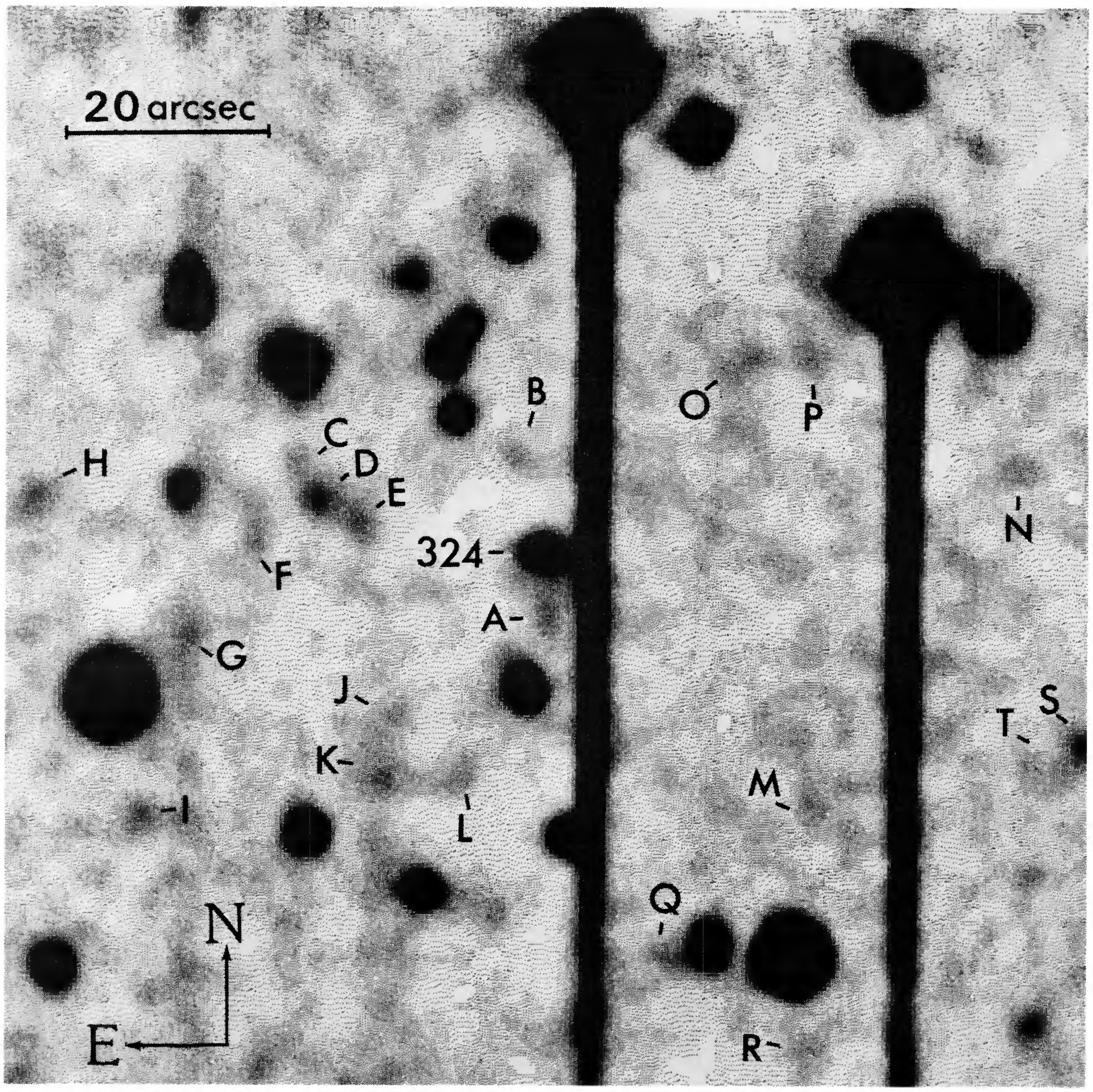

FIG. 3.—A maximum entropy processed stack of four CCD direct frames of the 3C 324 region (400 s total exposure). The limiting magnitude is about 25. Labeled objects are believed to be real and possible cluster members. Object E shows λ3727 emission at the same redshift as 3C 324.

SPINRAD AND DJORGOVSKI (*see* page L11)

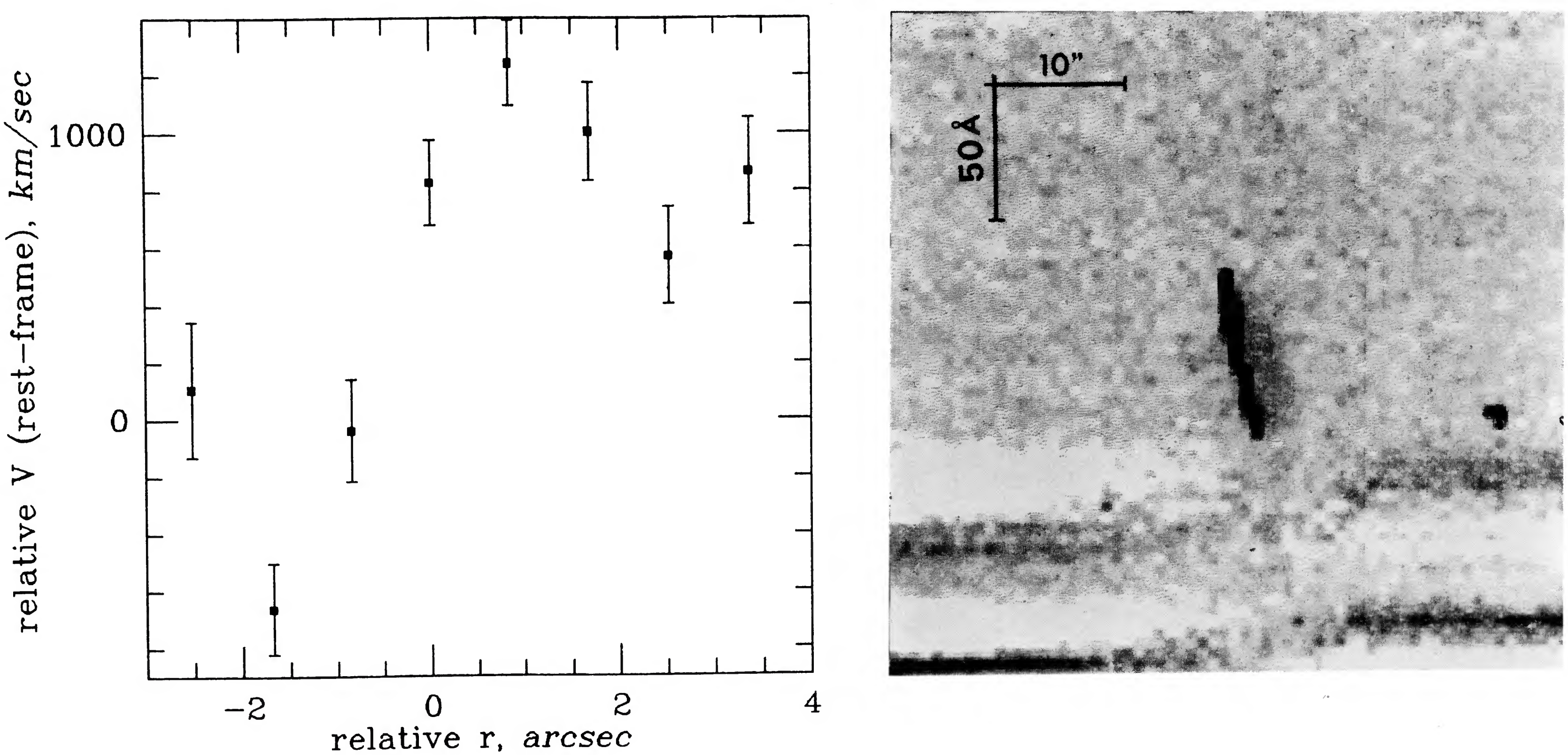

FIG. 4.—Spatial and velocity resolution of the λ3727 line in a good seeing IR frame. East is to the right, and the smaller emission line belongs to the object E (Fig. 3).

SPINRAD AND DJORGOVSKI (*see* page L11)

a large physical dimension at 3C 324. Figure 4 shows an enlargement of the [O II] region on the best-seeing image. Note the greatly tilted [O II] line. It is unclear from the best two exposures as to whether the emission line is centered on the galaxian continuum, but it does seem that at least part of it is located to the west from the continuum center.

The symmetric case may be understood by supposing a large, rotating, ionized gas disk in the presence of the massive spheroidal galaxy. The rest-frame velocity half-amplitude of the 3C 324 [O II] line (Fig. 4) is about 650 ± 100 km s^{-1}. The corresponding radius is about 1ʺ5, which is approximately 15 h_{50}^{-1} kpc at this redshift. A giant spheroid like the M87 corona modeled by the X-ray data of Fabricant and Gorenstein (1983), for example, contains some 2×10^{12} $M_{\odot}$ within only 15 kpc radius. The velocity quoted above would require a minimum mass of the 3C 324 spheroid at that radius to be $M_s \geq 1.5 \times 10^{12}$ $M_{\odot}$, under the usual assumption of circular motion, which is rather plausible. The same semiquantitative reasoning can be used to estimate infall velocity spread, instead of rotational velocity, i.e., a gas-rich galaxy falling in and being tidally distorted in the process (an asymmetric case). We may suppose a gas disk which is tilted and warped, in analogy to the geometry suggested by Fosbury *et al.* (1982) for PKS 2158−380.

Finally, the scenario envisioned here is a tidal encounter and merger of a gas-rich galaxy from the cluster and 3C 324. However, since our strong emission lines require 10^8 $M_{\odot}$ of ionized gas (cf. Spinrad 1982), the accreted system cannot be too small a dwarf. It may also be that the accretion phenomenon is a necessary fueling for the powerful central region of the active nucleus of 3C 324.

If accretion of gas-rich galaxies is a common situation in earlier cosmic epochs ($z > 1$), then a search for H I *absorption* against the two radio lobes of 3C 324 might have a good payoff. Further investigations of this cluster and the stage of its evolution shall be of some interest for the theories of cluster formation.

We would like to thank the staff of Kitt Peak National Observatory for help with our observations, Jon Marr for aid in reductions, P. Monger for valuable and competent help in software development, and Drs. C. McKee and S. Kulkarni for useful discussions. This work was partly supported through NSF grant AST 81-16125 to H. Spinrad, and a University of California Graduate Fellowship to S. Djorgovski.

REFERENCES

Bruzual, G. 1981, Ph.D. thesis, University of California, Berkeley.
______. 1983, *Ap. J.*, **273**, 105.
Clavel, J., and Joly, M. 1983, preprint.
DeVeney, J. 1983, "An Observer's Manual for the Cryogenic Camera," (Tucson: Kitt Peak National Observatory).
Djorgovski, S., and Spinrad, H. 1983, in "AAS/OSA Joint Topical Meeting on Information Processing in Astronomy and Optics," St. Paul, Minnesota (OSA Publication).
Fabricant, D., and Gorenstein, P. 1983, *Ap. J.*, **267**, 535.
Ferland, G., and Netzer, H. 1983, *Ap. J.*, **264**, 105.
Fosbury, R. A. E., *et al.* 1982, *M.N.R.A.S.*, **201**, 991.
Gunn, J. E., Hoessel, J. G., Westphal, J. A., Perryman, M. A. C., and Longair, M. S. 1981, *M.N.R.A.S.*, **194**, 111.
Gunn, J. E., and Oke, J. B. 1975, *Ap. J.*, **195**, 255.
Jenkins, C. J., Pooley, G., and Riley, J. 1977, *M.N.R.A.S.*, **84**, 61.
Kellerman, K., Pauliny-Toth, I. I. K., and Williams, P. J. 1969, *Ap. J.*, **157**, 1.
Kristian, J., Sandage, A. R., and Katem, B. 1978, *Ap. J.*, **219**, 803 (KSK).
Laing, R., Riley, J., and Longair, M. 1983, *M.N.R.A.S.*, **204**, 151 (LRL).
Sandage, A. 1970, *Ap. J.*, **162**, 841.
Shull, M., and McKee, C. F. 1979, *Ap. J.*, **227**, 131.
Spinrad, H. 1982, *Pub. A.S.P.*, **94**, 397.
Stone, R. P. S. 1974, *Ap. J.*, **193**, 135.
______. 1977, *Ap. J.*, **218**, 767.

S. DJORGOVSKI and H. SPINRAD: Astronomy Department, University of California, Berkeley, CA 94720