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Spectrum of the halo of the cD galaxy in Abell 401[a)]

S. M. Faber and D. Burstein
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

A. Dressler
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology, 813 Santa Barbara Street, Pasadena, California 91101

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The spectrum of the cD galaxy in Abell 401 has been obtained both in the nucleus and at a radius of 23 arcsec in the halo (43 kpc for $H_0 = 50$ km sec^{-1} Mpc^{-1}). NaD, MgH, Mg"b," and the *G* band are strongly evident as absorption features in both spectra. The stellar velocity dispersions of the nucleus and the halo have been derived from the line profile of NaD. The value in the nucleus is 480 ± 120 km sec^{-1} and the value in the halo is 470 ± 250 km sec^{-1}. Although this value for the halo is extremely uncertain, it does rule out the hypothesis that the cD galaxy consists *exclusively* of tidal debris stripped from other cluster members, moving with speeds typical of ordinary cluster members. At the very least, the cD must have formed around an already-existing, massive elliptical galaxy. A comparison of the absorption line strengths of the halo with those of normal elliptical galaxies suggests that the mean metal abundance of the halo population is approximately solar at this distance from the nucleus.

INTRODUCTION

At present, there exist two widely discussed interpretations of cD galaxies in clusters. The first of these holds that cD galaxies have attained their present exceedingly high luminosity at the expense of other cluster galaxies, which were either tidally stripped (Gallagher and Ostriker 1972; Richstone 1975, 1976) or consumed outright (Ostriker and Tremaine 1975; Lecar 1975; White 1976). Geller (1974), on the other hand, has argued for a completely opposite interpretation: that the cD is just the bright end of the luminosity function. Since these various viewpoints predict rather different values for the velocity dispersion and metal abundance of the stars in the cD halo, spectroscopic observations of the halo could provide important evidence for testing these hypotheses.

Accordingly, we attempted to obtain spectra of the nuclear region and the outer halo of the cD galaxy in the x-ray cluster A401. The halo spectrum, obtained at a surface brightness in the galaxy of only 24.5 *B* mag arcsec^{-2}, is, unfortunately, too noisy to allow a definitive discrimination between the competing hypotheses. In this sense, our observations are only a qualified success. However, the data contain enough of interest to warrant a brief discussion.

I. OBSERVATIONS

The spectra were obtained with the image-dissector scanner attached to the Cassegrain spectrograph on the 120-in. telescope of Lick Observatory. The dispersion on the first cathode of the intensifier chain was 130 Å/mm. The instrument has two entrance apertures of adjustable length and width and with centers separated by 35 arcsec. The nucleus of the cD galaxy was observed alternately through the right and left apertures and the other aperture monitored the sky. The slit size for the nucleus was 4 × 4 arcsec, which subtends 7.5 kpc at the distance of A401 ($H_0 = 50$ km sec^{-1} Mpc^{-1}). The halo was observed on the major axis of the galaxy at the positions shown in Plate II (p.1043). The center of each aperture was located 23 arcsec (43 kpc) from the nucleus and was 8 × 13 arcsec in size. The telescope was switched alternately between integrations, so that the left channel was located to the northeast of the nucleus and the right channel to the southwest. Sky was observed simultaneously in the indicated sky patches located 58 arcsec from the nucleus. Photographic surface photometry of A401 by Dressler indicates that the contribution of galaxy light in the sky patches is 25% of the signal at 23 arcsec, so that partial cancellation of the signal unfortunately occurred. Unless the properties of the halo change greatly between 23 and 58 arcsec, however, this partial cancellation should not affect any of our conclusions. Dressler's data indicate that the surface brightness in *B* at 23 arcsec is 24.5 mag arcsec^{-2}, a value which was confirmed by comparison of the signal level from the halo with standard stars observed on the same nights.

Wavelength calibrations from a set of standard lamps were obtained at frequent intervals during the night and the wavelength drift of the instrument was continuously monitored by determining the positions of the night-sky

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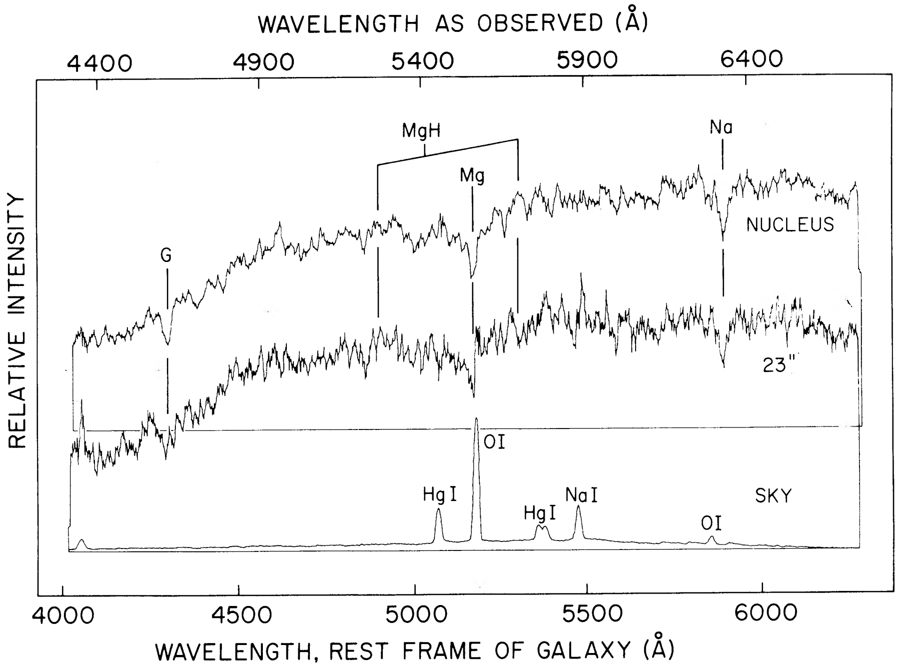

FIG. 1. Spectra of the cD galaxy in the cluster A401. *Top,* nucleus (4 × 4-arcsec aperture). *Middle,* 23 arcsec away from nucleus in halo (8 × 13-arcsec aperture). *Bottom,* sky (8 × 13-arcsec aperture). The three scans are all on a linear intensity scale, but the scale factors are not identical for the three scans. (Taken with the same slit width as the halo spectrum, the sky spectrum provides an indication of the spectral resolution for the halo based on the profiles of the night-sky lines.) The basic similarity between the absorption line strengths in the nucleus and halo indicates that the halo is not extremely metal poor.

lines. The eventual wavelength registration of all the scans should be accurate to 0.5 Å.

The final summed spectra of the nucleus and the halo are shown in Fig. 1. The location of night-sky features are also shown on the figure. Although the spectra were taken on extremely dark nights when the lights of San Jose were obscured by fog, perfect sky cancellation in the emission lines was not achieved. (This failure is understandable in view of the fact that the peak intensity in the 5577-Å line of O I was 170 times the signal from the halo at the same wavelength. The sky subtraction is therefore actually accurate to 0.1%.) The redshift of A401 is such that Mg"b" is located very close to 5577 of O I, for example, and as a result this feature is unusable in the halo spectrum.

II. VELOCITY DISPERSIONS

Because of the sky line contamination, NaD is the only feature in the halo suitable for the measurement of the

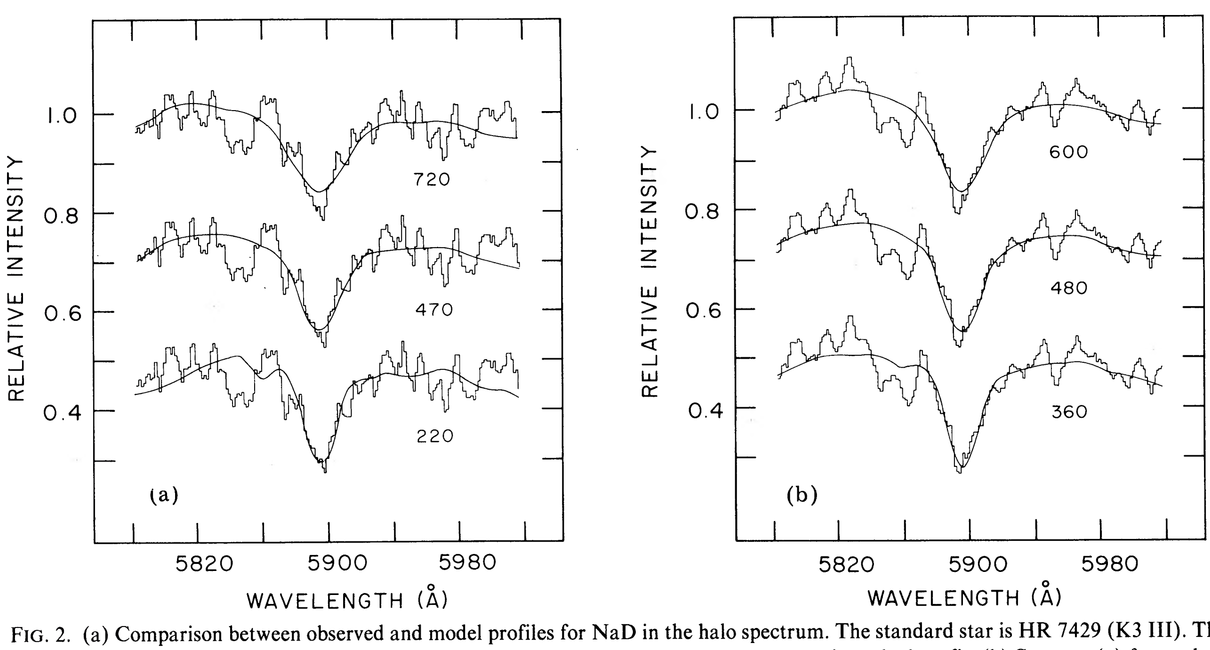

FIG. 2. (a) Comparison between observed and model profiles for NaD in the halo spectrum. The standard star is HR 7429 (K3 III). The equivalent width of NaD in the model profile has been arbitrarily adjusted in each case to produce the best fit. (b) Same as (a) for nuclear spectrum.

TABLE I. Velocity dispersion models for the halo.

Model No.	Description	σ_{low} (km sec^{-1})	% contr.	σ_{high} (km sec^{-1})	% contr.	Σr_i^2	W_{eq} (Å)	Signif. level (%)
		One-component models						
1	Best fit, no restrictions	470	100	...	...	590	3.9	100
2	$W_{eq} \equiv 3.9$ Å; $\sigma \equiv 1390$ km sec^{-1}	1390	100	...	...	3091	3.9	<0.1
3	$\sigma \equiv 1390$ km sec^{-1}	1390	100	...	...	2116	6.4	<0.1
		Two-component models						
4	Best fit, no restrictions	100	30	800	70	530	4.2	100
5	$\sigma_{high} \equiv 1390$ km sec^{-1}, $W_{eq} \equiv 3.9$ Å	200	60	1390	40	747	3.9	30
6		200	50	1390	50	846	3.9	10
7		200	40	1390	60	1089	3.9	2
8	$\sigma_{high} \equiv 1390$ km sec^{-1}, W_{eq} arbitrary	200	30	1390	70	716	5.9	35
9		200	20	1390	80	866	6.0	13
10		200	10	1390	90	1481	6.2	1

velocity dispersion. To determine this dispersion, spectra of standard stars observed with the same slit width on the same nights were converted to a logarithmic wavelength scale, convolved with Gaussian broadening functions and compared with the galaxy spectrum, also on a logarithmic wavelength scale. This comparison was performed in a quantitative manner by calculating the sum of the squared residuals between the observed and model profiles. The equivalent width of the model profile and the width of the Gaussian broadening function were varied. The location of the minimum in the two-parameter fit determined the adopted velocity dispersion and the estimated errors were based on the rate of increase of the residual sum away from the minimum, according to the method described by Cline and Lesser (1970).

The value obtained in this way for the nucleus is 480 $\pm$ 120 km sec^{-1} and that for the halo is 470 $\pm$ 250 km sec^{-1}. Sample profiles are shown in Fig. 2. The evidence from the remainder of the nuclear spectrum aside from NaD favors a somewhat lower velocity dispersion for the nucleus of approximately 350 km sec^{-1}. This value would be more in accord with values of 350–400 km sec^{-1} for luminous cD-like ellipticals determined by Faber and Jackson (1976). As in that paper, the NaD line here yields a larger velocity dispersion, but the discrepancy in this case is not statistically significant.

The error in the dispersion for the halo is very large, partly because the data are noisy and partly because the halo was observed with a wide slit (8 arcsec) in order to increase the count rate. It is obviously not possible to make any statement about the trend in velocity dispersion with radius. However, one fact is clear: The halo does not consist *purely* of stars moving with speeds typical of cluster galaxies. The line-of-sight velocity dispersion of the galaxies in A401 is 1390 km sec^{-1} (Scott and Tarenghi 1976). Such a large value is completely excluded by our data.

To show this quantitatively, we give in Table I the particulars of two models having velocity dispersions of 1390 km sec^{-1}, along with similar data for the best-fit value of 470 km sec^{-1}. These are designated one-component models Nos. 1, 2, and 3. Σr_i^2 denotes the sum of the residuals squared across the line profile (in arbitrary units) and W_{eq} is the equivalent width of the line. With the velocity dispersion σ constrained to be 1390 km sec^{-1}, Σr_i^2 is minimized with W_{eq} equal to 6.4 Å, a very large value which is typical of the innermost nuclei of giant ellipticals and M31. Model 2, with W_{eq} = 3.9 Å, the best-fit value, is also included for illustration. The significance level given in the table is the probability that a residual sum as large, or larger, than that observed for the model could occur by chance. This number was calculated according to the method of Cline and Lesser and depends on the number of free parameters in the model. It is clear from the Table I that even if W_{eq} is allowed to increase arbitrarily, no model consisting purely of stars having a velocity dispersion of 1390 km sec^{-1} can fit the data.

This finding seems at variance with the simplest version of the accretion scheme suggested by Gallagher and Ostriker (1972) and later discussed by Richstone (1976). These authors have suggested that cDs consist largely of debris from galaxy–galaxy collisions, in which case the velocity dispersion of the stars in the cD should be typical of galaxies in the cluster as a whole. This certainty is not the case in A401, nor is it true for the nucleus of NGC 6166, for which Faber and Jackson found a velocity of 350 km sec^{-1}.

However, the discussion does not really end there, for it is possible that cDs form around luminous elliptical galaxies, which then serve as nuclei for the growth by accretion of a very large halo. In this case, we might expect to see a mixture of two structures: the low-velocity underlying elliptical plus a high-velocity halo. Suppose we adopt M87 as typical of such a "seed" object. According to Oemler (1976) and Kormendy (1976), the surface brightness of M87 at 43 kpc (400 arcsec) is 25.6 *B* mag arcsec^{-2}, or roughly 40% of the observed surface brightness of A401 at the same metric radius. Because this simple comparison suggests that the halo might actually consist of roughly equal contributions from a low- and high-velocity component, we have tested whether such a mixed model can adequately fit the observed profile.

In testing these two-component models, we have taken two approaches. In the first case, we have set no arbitrary

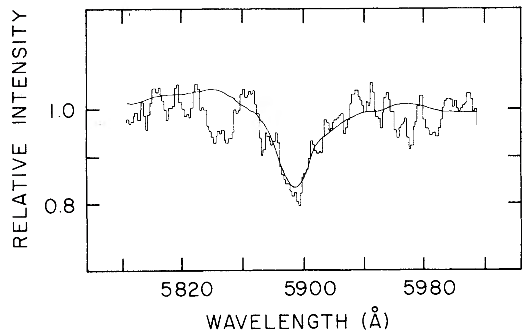

FIG. 3. Two-component model profile based on the standard star HR 7576 (K3 III). Seventy percent of the profile is the standard star broadened by 1390 km sec^{-1}. Thirty percent is the standard star broadened by 200 km sec^{-1}. The equivalent width of NaD in the standard star was artificially increased to 5.9 Å before broadening.

restrictions on the σs of the two components, on their relative contributions, or on the total W_{eq} of the combined profile. The result, model 4, consists of a 30% contribution having a σ of 100 km sec^{-1}, a 70% contribution having a σ of 800 km sec^{-1}, and a total equivalent width of 4.2 Å. The residual sum has declined from 590 to 530, but this decrease is almost exactly what one would have predicted in going from 16 degrees of freedom (model 1) to 14 degrees of freedom (model 4), due to the inclusion of two more adjustable parameters. There is, therefore, no evidence that a two-component model provides a significantly *better* fit.

The second case, however, is more illuminating. In these models we constrained the larger velocity dispersion to be 1390 km sec^{-1} and searched for the maximum allowable contribution from the high-velocity component. In all cases, the best-fitting smaller σ was ~200 km sec^{-1}, but the residual sum was not sensitive to this number. As Table I demonstrates (models 5–10), the allowable contribution from the high-velocity component is quite large, some 60%, even when W_{eq} is forced to be small (3.9 Å). If W_{eq} is also left as a free parameter, the maximum contribution from the high-velocity component is as much as 80%–90%. The profile for model 8 (70% contribution for high-velocity component, W_{eq} = 5.9 Å) is shown for illustration in Fig. 3.

In summary, our data clearly do not rule out a very sizable contribution from a high-velocity halo by an amount comparable to that predicted by the "seed" argument. Indeed, extremely good data will be necessary to exclude small contributions from a high-velocity halo, since the presence of a weak, broad line will always be difficult to rule out. Since our best-fit one-component model does yield a smaller value for the velocity dispersion, however, the data are also consistent with an accretion process of the kind described by Ostriker and Tremain (1975), in which the accreted galaxies are first slowed by dynamical friction, while being tidally stripped. In this picture, the stripped stars should have velocities roughly equal to the circular velocity around the central massive object, a prediction close to our measured dispersion. Finally, the data are also clearly consistent with the interpretation that cDs are simply massive, but normal, ellipticals (Geller 1974).

TABLE II. Wavelengths of absorption line indicators.

	Blue continuum (Å)	Feature (Å)	Red continuum (Å)
MgH_{5104}	4898–4959	5072–5136	5304–5368
MgH_{5178}	4898–4959	5157–5198	5304–5368
NaD	5863–5877	5879–5910	5924–5949

TABLE III. Line strengths in A401 and comparison objects.

Object	Na (Å)		MgH_{5178} (mag)		Aperture (arcsec)	
A401, nucleus	5.0	± 0.3	0.28	± 0.02	4 × 4	
A401, 23 arcsec	3.9	0.6	0.25	0.02[a]	8	13
NGC 1426, nucleus	4.04	0.25	0.26	0.01	2	4
NGC 3379, nucleus	5.08	0.25	0.33	0.01	2	4
NGC 3379, 60 arcsec	2.99	0.30	0.25	0.01	8	13
NGC 3605, nucleus	2.83	0.25	0.23	0.01	2	4
NGC 4472, nucleus	5.55	0.15	0.34	0.01	2	4
NGC 4472, 60 arcsec	3.98	0.30	0.28	0.02	8	13
NGC 4478, nucleus	3.46	0.25	0.27	0.01	2	4
M32, inner 15 arcsec[b]	3.26	0.25	0.21	0.01	...	

[a] Value inferred from MgH_{5104}. For details see text.
[b] Average of six observations within 15 arcsec of nucleus, all taken through 2 × 4-arcsec aperture.

Whatever the case, as long as the halo is in dynamical equilibrium, a measurement of velocity dispersion with radius could in principle yield information on the behavior of mass-to-light ratio as a function of radius. For example, at a distance of 43 kpc, the isothermal sphere model for massive halos (Ostriker, Peebles, and Yahil 1975) predicts very little decline in σ compared to the nuclear value, whereas a King model (Rood *et al.* 1975) predicts a falloff in σ by roughly a factor of 40%. Because of the large errors, our present data are consistent with either possibility, but better observations might resolve this ambiguity.

A word about the rotation of the halo might be included. From comparison of the spectra taken on opposite sides of the nucleus, it was found that the difference in velocity between the two sides is 365 ± 320 km sec^{-1}. Although this value is uncertain, apparently no large rotational motion is present.

III. LINE STRENGTHS

Because of contamination by night-sky lines, the MgH and Mg"b" strengths are difficult to determine in the halo. Nevertheless, even a cursory glance at the observations shows that neither the nucleus nor the halo are extremely metal poor. MgH, Mg"b," NaD, and the *G* band are clearly visible in both spectra.

We have measured the strengths of MgH and NaD by defining a band-absorption indicator for MgH (in magnitudes) and an absorption line equivalent width for NaD (in Å). This system will be described fully in a future paper, but for convenience we include in Table II

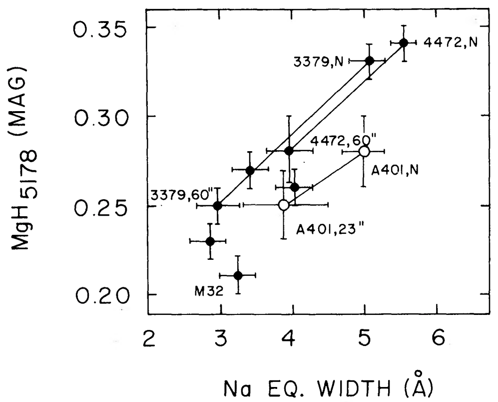

FIG. 4. NaD and Mg"b"—MgH line strengths for the nucleus and halo of A401 plus other comparison objects. The points are labeled as in Table II.

a summary of the locations of the wavelength regions which define the indices (in the rest frame of the galaxy). We use two MgH indices, one (MgH_{5178}) containing the Mg"b" triplet plus MgH and the other (MgH_{5104}) located just to the blue, which monitors MgH alone. For virtually all elliptical and S0 galaxies in our sample, as well as for 100 standard stars, these two MgH indices are closely correlated. MgH_{5178} cannot be determined directly for the halo in A401 because of contamination by O I (5577 Å). However, a value for MgH_{5178} can be inferred from MgH_{5104} based on the well-defined relationship for normal galaxies and stars. This inferred value is used in the following discussion.

Line strengths for A401 plus a few normal elliptical galaxies are given in Table III and plotted in Fig. 4. The weakest-lined object in this collection is M32, which is thought to have approximately solar abundances (Spinrad and Taylor 1969; Faber 1973). The halo of A401 appears to be at least this stronglined. At 43 kpc, the halo definitely does not consist primarily of a globular cluster-like population, a conclusion in agreement with Spinrad and Stone's (1975) measurement of strong CN in the outskirts of at least one normal elliptical.

At first glance, the nucleus of A401 might seem to be surprisingly metal poor for a galaxy of its large luminosity, but this apparent line weakening is probably due to the existence of strong line-strength gradients close to the nucleus, as in other normal ellipticals. To illustrate this point, we include data on regions of NGC 4472 and NGC 3379 taken 60 arcsec away from the nucleus. Both galaxies are much weaker lined at these radii. At the distance of A401, our entrance aperture of 4 × 4 arcsec for the nucleus subtends a region equivalent to 35 arcsec in radius at NGC 4472. Through such a large aperture, NGC 4472 would have line strengths similar to those measured for the nucleus of A401.

These data on line strengths aid us somewhat in discriminating between models for the formation of the halo of A401. Let us assume that the run of line strength with radius in the inner region of A401 is the same as in NGC 4472, an assumption justified by the observations (see above). A study of line strengths in NGC 4472 (to be published) shows that the lines decline more or less exponentially with radius over the entire range of distance observed, out to 10 kpc. If the line strengths continue to fall exponentially, we can predict the strengths expected at 43 kpc in A401. The observed Mg_{5178} index in A401 is in precise agreement with this extrapolation, while Na is slightly too strong, but still well within the errors of observation. Because the errors of observation are significant, however, we cannot rule out the possibility of a leveling out in line strength beyond 10 kpc.

Within the framework of assumptions made above, the halo line strengths in A401 seem to argue for a continuing decline in metal abundance over an extended region of the galaxy. This behavior would be most consistent with Larson's (1974) dissipative collapse models, in particular his models F or G, which show a noticeable gradient far into the halo. The stellar collapse models of Gott (1975) seem less consistent with our results.

Alternatively, accretion theories for the formation of the cD halo predict that the halo abundance should be similar to that of the halos of other cluster galaxies. Since it is presently conceivable that these halos could be moderately metal rich, this prediction is likewise consistent with the observations. Line-strength measures in the halos of the fainter cluster members would, however, aid greatly in testing the accretion hypothesis.

IV. SUMMARY

We have observed the line-of-sight velocity dispersion in the halo of the cD galaxy in A401 and find it to be 470 ± 250 km sec^{-1}. Although the error is large, the measurement is sufficiently precise to exclude a model in which the cD halo is assumed to consist *entirely* of debris stripped from other cluster galaxies moving with speeds typical of cluster members, i.e., 1390 km sec^{-1}. However, the data do not exclude the possibility that a large fraction of the light originates in such a high-velocity component. They are also consistent with the hypothesis that cD galaxies are simply luminous, but normal, ellipticals. The strengths of absorption lines in the spectrum of the halo suggest that the metal abundance of the halo population at a radius of 43 kpc is not extremely metal poor and is probably close to the average of stars in the solar neighborhood.

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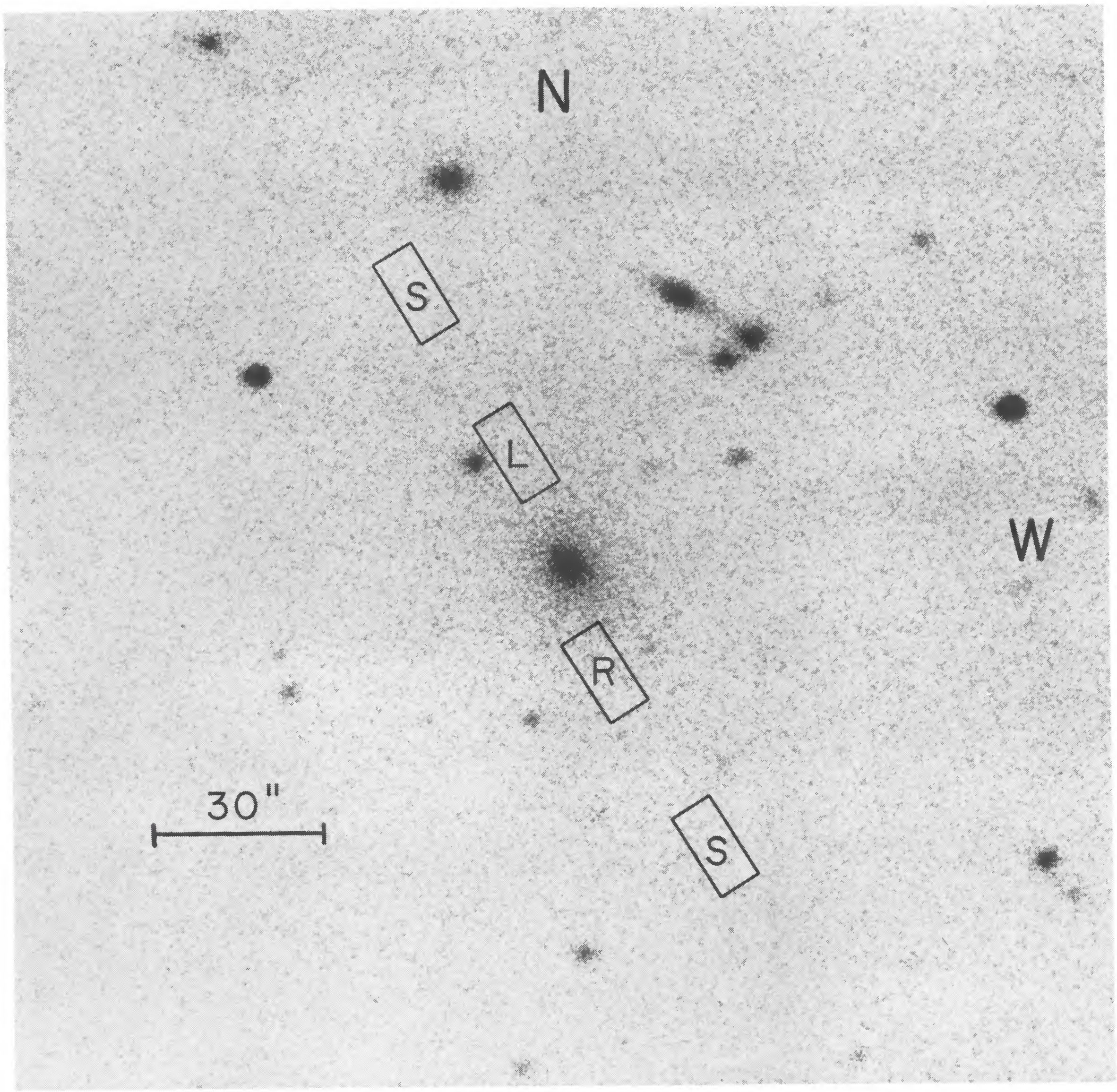

PLATE II (Faber, Burstein, and Dressler, p. 941). The cD galaxy in the cluster A401. Rectangles show locations and size of observing apertures used to obtain the halo spectrum of 23 arcsec from the center of the galaxy. R = right channel, L = left channel, S = sky.