THE ASTROPHYSICAL JOURNAL, 336:1–8, 1989 January 1

LUMINOUS ARCS IN CLUSTERS OF GALAXIES

ROGER LYNDS
Kitt Peak National Observatory, National Optical Astronomy Observatories[1]
AND
VAHÉ PETROSIAN[2]
Center for Space Science and Astrophysics, Stanford University
Received 1988 March 17; accepted 1988 June 20

ABSTRACT

We report observations of what appears to be a new class of spatially coherent extragalactic features having, in the two most compelling known examples, the following joint properties: location in clusters of galaxies, narrow arclike shape, enormous apparent length, and situation of center of curvature toward both a cD galaxy and the apparent center of gravity of the cluster. We present the principal available facts concerning the arcs and briefly discuss a variety of interpretations. The weight of evidence seems to favor the interpretation that these features are images of more distant objects produced by the gravitational field of the intervening clusters.

Subject headings: galaxies: clustering — galaxies: intergalactic medium — gravitational lenses — polarization

I. INTRODUCTION

In the spring of 1976, during test and evaluation of the KPNO (Kitt Peak National Observatory) video camera, an embryonic program was initiated to obtain multicolor pictures of distant clusters of galaxies. Of the 29 clusters observed, one cluster, Abell 2218 (redshift $z = 0.170$), was distinctive in conveying a subjective impression of patterned circularity in the location and orientation of certain elongated blue features within a zone more or less centered on the apparent center of gravity of the cluster.

By the fall of 1976 the general cluster program had been formalized as a collaboration between the present authors and Allan Sandage, with the aim of determining the cosmological evolution of surface brightness of galaxies (Petrosian 1976). Two of the 29 additional clusters observed, Abell 370 (redshift $z = 0.373$) and Cluster 2244−02 (redshift $z = 0.328$, from a special deep survey by Sandage; see Kristian, Sandage, and Westphal 1978 for additional information on all three clusters), revealed continuous arclike features much more clearly delineated than were those in Abell 2218. Although it was clear that these features were not merely conspiratorial arrangements of normal objects, the data were not good enough to permit either photometric measurement or defensible conclusions on points of morphological character such as might, for example, serve to define the arcs either as filaments or as fragments of shells. The data did, however, seem to show that the arcs were distinctly bluer than typical E galaxies in the clusters, especially in the case of Cl 2244−02.

We did not obtain improved pictures of these arcs until 1985, when the clusters were included among fields of opportunity during test and evaluation of the scanning CCD guider of the KPNO 4 m telescope. Because the observations were entirely incidental to other purposes, they were often obtained under abominable observing conditions (various combinations of cloud, bad seeing, and moonlight) and without benefit of what would normally be considered sound observing practice. As one consequence, photometric standardization is barely adequate, and refined definition of the various instrumental color systems is virtually impossible. The best of the material did, however, yield such astonishing results that we announced the existence of the arcs last year and summarized the essential morphological and photometric facts (Lynds and Petrosian 1986). Here we give a fuller account of that material and present the results of subsequent polarization observations, spectroscopy, and radio observations.

II. SUMMARY AND ANALYSIS OF NEW OBSERVATIONS

In this section we will summarize the results from our own observations, as well as those from related work by others that has come to our attention. And because the interpretation of the arcs has been and may still be somewhat in doubt, some information is presented for the sake of completeness and not necessarily because we believe it likely to be germane to the ultimate, correct explanation for the arcs.

a) Pictures of the Arcs

The new pictorial observations were obtained with whichever CCD happened to be under evaluation at the time. Principally, these were the following: Texas Instruments, 800 × 800 format, 15 μm pixels, known as TI-2; RCA, 320 × 512 format, 30 μm pixels, known as RCA-3; and Tektronix, 512 × 512 format, 27 μm pixels, the first such CCD in use at KPNO. The scale at the CCD camera is approximately 19″.83 per millimeter, a datum that may be useful in estimating angular measure on the pictures reproduced here. The photometric passbands included *U*, *B*, *V*, *R*, *I*, and what we choose to call *J*, defined by an RG-1000 filter and having an effective wavelength near 1 μm.

i) *Abell 370*

Three sequences of pictures of Abell 370 were obtained. On account of bad seeing, one sequence (in *UBVRIJ* with RCA-3) was useful only for photometric purposes. A second sequence

[1] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
[2] Also Department of Applied Physics, Stanford University.

was made with TI-2 in *VRIJ*: 12 exposures of various durations totaling 2806 s. A 256 × 336 submatrix of the weighted average of all pictures is reproduced in Figure 1 (Plate 1); it shows most of the dense central region of the cluster. The arc appears prominently about 9″ south of the southernmost of the two cD galaxies in the cluster. Also appearing at the very bottom of the illustration is a long bar-shaped feature that is very blue.

The third sequence of pictures was obtained with RCA-3 through clouds and consisted of 34 128 s exposures in *BVRI* and one 1024 s exposure in the *U* passband. The weighted average of all pictures in the sequence has much the same appearance as the TI picture reproduced in Figure 1. (The region of the arc from this data set will be shown as part of Fig. 3.)

A little of the history of the Abell 370 arc is known to us. Westphal (1973) published pictures of the cluster (known to him as Cl 0237−0138) obtained with the Hale Telescope at Palomar as a demonstration of the superiority of SIT television camera tubes over photographic emulsions. Although the presence of the arc could scarcely have been guessed from the best of this material, the observations did inspire Arthur Hoag to use the same cluster (known to him as Zw 0237.2−0146) as a test object for comparing the performance of image tubes and photographic emulsions at KPNO. To our knowledge, the first published mention of the arc and specifically of its filamentary character was by Hoag (1981). Hoag has kindly provided us with a print of his best 4 m plate; the arc shows well, and there would be little doubt as to its filamentary character. Another 4 m plate of Abell 370 which shows the arc fairly well was published by Butcher, Oemler, and Wells (1983), although those authors make no mention of the arc. Finally, Soucail *et al.* (1987*a*), in a report of photometric and spectroscopic observations of galaxies in Abell 370, refer to a "ring-like structure of galaxies" that evidently includes in part "a typical alignment of blended features" which seems to be the same feature that other material shows as a filament, plus the four or five proximate galaxies. The remainder of their "ring-like structure" seems to consist of various galaxies and regions north of the nearby cD galaxy that appear to be blue in their photometry.

ii) *Cluster 2244−02*

One photometrically useful sequence of pictures of Cl 2244 was obtained in *UBVRI* with RCA-3, but under bad seeing conditions. Three sequences in the *V* passband were obtained with the Tektronix CCD, two with fairly good seeing. The average of the best sequence, six 1024 s exposures, is reproduced in Figure 2 (Plate 2) for the dense central region of the cluster; the portion shown is a 128 × 168 submatrix expanded by interpolation to 256 × 336, so that the scale and sampling interval are similar to those for the Abell 370 picture in Figure 1.

The arc that is seen to the west of the major cluster members is outstanding in its nearly perfect circularity and degree of isolation from other, more normal objects. Unlike the arc in Abell 370, which has a relatively smooth appearance, the Cl 2244 arc is seen to be highly structured, with many prominent knots in evidence. This structure is confirmed in detail by the other good data set.

b) General Morphology of the Two Arcs

In support of subsequent discussion, Figure 3 (Plate 3) presents comparable submatrices of the arc regions: two for Abell 370 and one for Cl 2244. They are ordered from top to bottom: Abell 370 with TI-2, the same with RCA-3 (after a two fold interpolated expansion), and Cl 2244, respectively. Orientation has been rotated by 180° for Abell 370 and by 90° counterclockwise for Cl 2244; the approximate centers of curvature of the arcs are at the center of the bottom row of pixels in each case. The dimensions of the submatrices are equivalent to 36″ × 16″ for Abell 370 and 33″ × 14″ for Cl 2244, corresponding to absolute linear dimensions of 245 × 109 and 198 × 84 kpc, respectively. (Absolute dimensions quoted in this paper are calculated for the distances of the clusters, without any intended implication that the arcs are physical objects within those clusters; also, we have assumed $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$, and $\Lambda = 0$ in making such calculations.)

One of the first questions is whether the arcs and their respective clusters are related in any way or represent merely accidental superpositions. In both cases we see long, narrow arcs that have similar lengths and radii of curvature and that are concave toward both a major cluster member and the apparent center of gravity of the cluster. This juxtaposition of circumstances for two such rare and remarkable features strongly suggests that there is, indeed, some kind of relationship between the arcs and the clusters in which they appear. That is what we will assume, though without implying that the arcs are actual physical members of the clusters; the special geometrical relationships would naturally arise if the arcs were merely gravitational images of background objects in coincidental alignment with the gravitational potential wells of the clusters. We also assume that the two arcs are examples of essentially the same phenomenon and that an explanation, in order to be correct, must encompass the diversity of character exhibited by the two arcs separately.

Also fundamental to an assessment of the arcs is the question of whether or not chance arrangements of "normal" objects are responsible for their appearance. The appearance of the arc in Cl 2244 clearly excludes such a possibility. Likewise, the Abell 370 arc is not a conspiratorial arrangement of galaxies, but in this case there is apparent encroachment by four or five objects. The condensation at the right-hand end of the arc (as seen in Fig. 3) has the appearance of a flattened system seen somewhat edge-on and gives an impression of possible physical association with the arc, more so than do the other four objects. The bright object next to the left appears to be an interacting group of two or more galaxies, but there is no clear morphological evidence for a physical association with the arc.

How nearly circular are the arcs? As an aid to an objective assessment, Figure 4 (Plate 4) presents the data for the three pictures in Figure 3 mapped into polar coordinate space centered at the average center of curvature of the arcs. Radius increases toward the top of each picture from 11″.08 to 19″.03 and from 7″.05 to 14″.20 for the Abell 370 and Cl 2244 arcs, respectively. An azimuthal range of 128° is displayed horizontally and corresponds to 33″.3 and 23″.7 at the arc radius for the Abell 370 and Cl 2244 arcs, respectively. The adopted radii of curvature were 15″.1 and 10″.6 for the Abell 370 and Cl 2244 arcs, respectively; the corresponding lengths of the arcs are 21″ and 19″ or 143 and 114 kpc at the distances of the clusters.

It is seen in Figure 4 that the condensation at the right-hand (eastern) end of the Abell 370 arc breaks away at such a sharp angle that it seems less a part of the arc than it did in Cartesian space. Aside from this, the largest deviation from rectilinearity is the upturn at the left end of the arc. Otherwise the arc is reasonably straight in polar space. The transformed Cl 2244

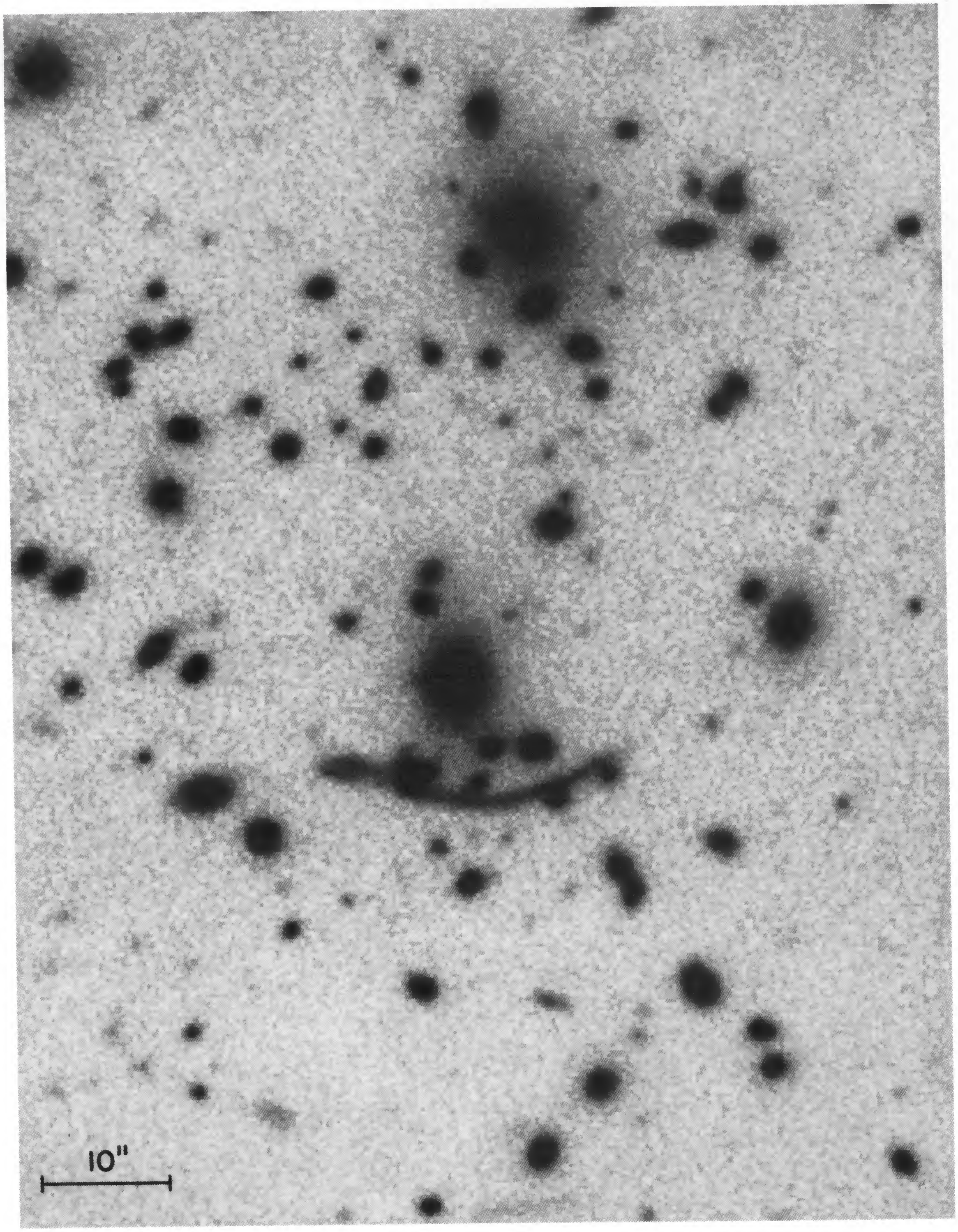

FIG. 1.—Central region of Abell 370 showing the arc. North is at the top, and east is to the left.

LYNDS AND PETROSIAN (*see* **336**, 2)

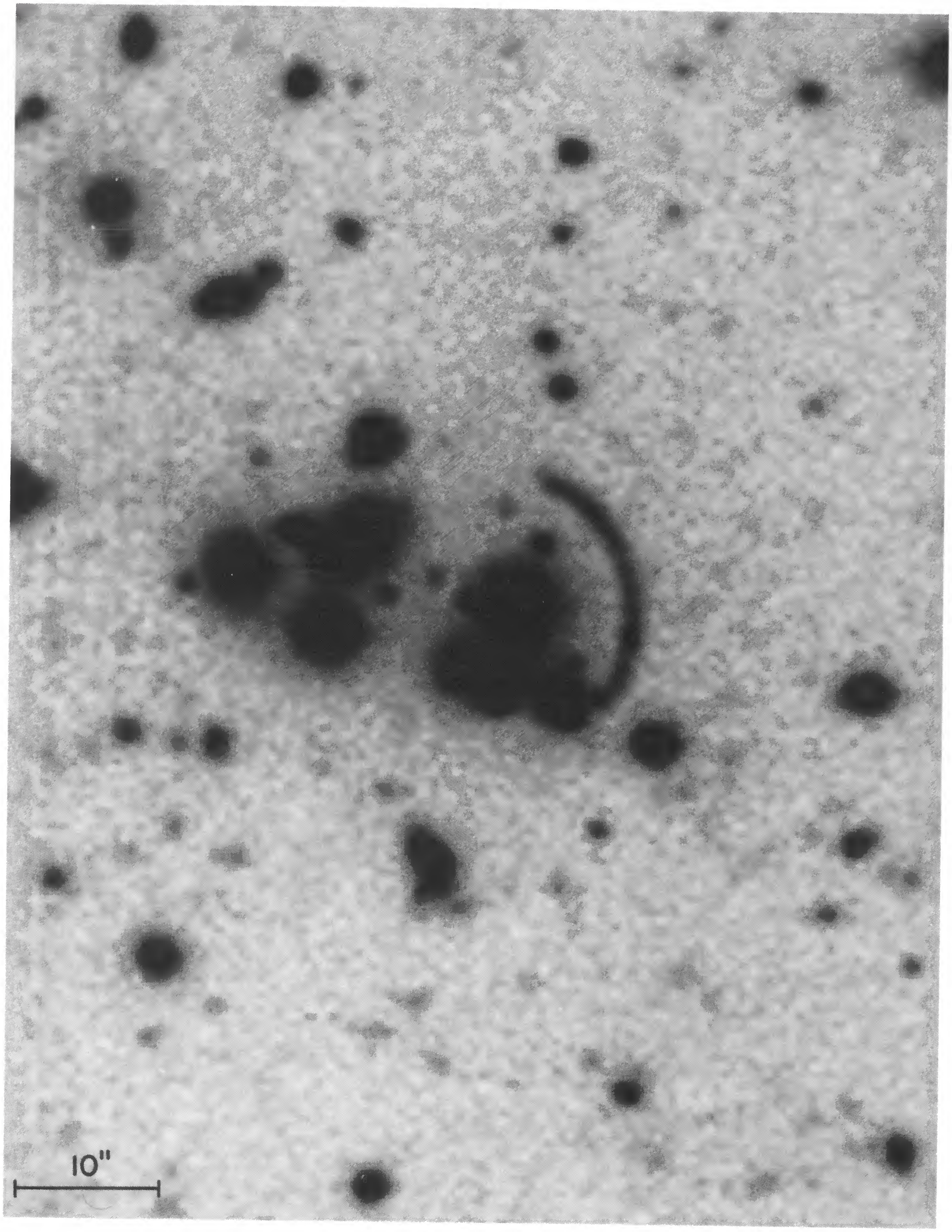

FIG. 2.—Central region of Cl 2244 – 02 showing the arc. North is at the top, and east is to the left.

LYNDS AND PETROSIAN (*see* **336**, 2)

1989ApJ...336....1L

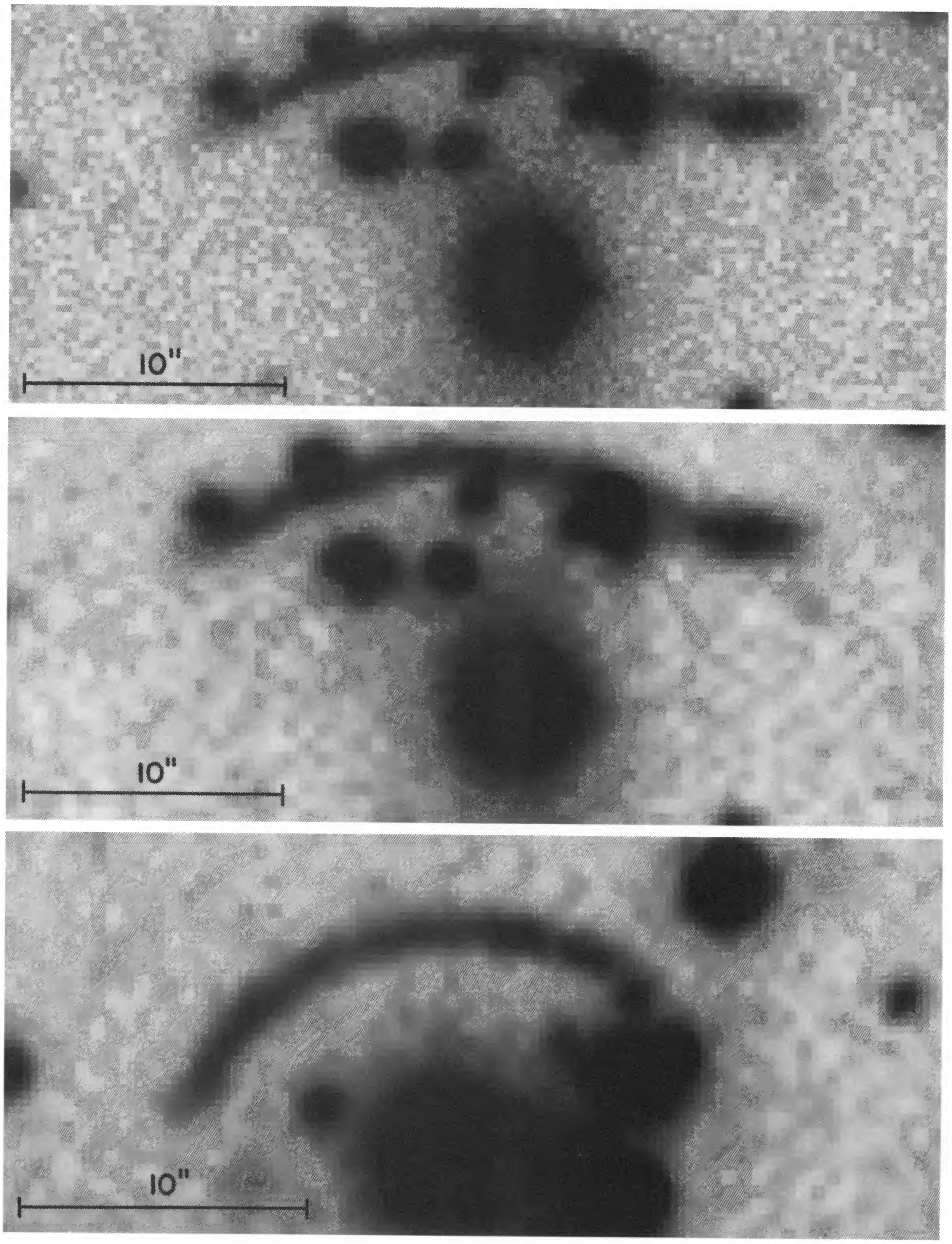

FIG. 3.—Enlargements of the two arcs, from top to bottom: the Abell 370 arc, TI CCD data (north is down and east is to the right); the Abell 370 arc, RCA CCD data (same orientation); and the Cl 2244 arc (north is to the left and east is down).

LYNDS AND PETROSIAN (*see* **336**, 2)

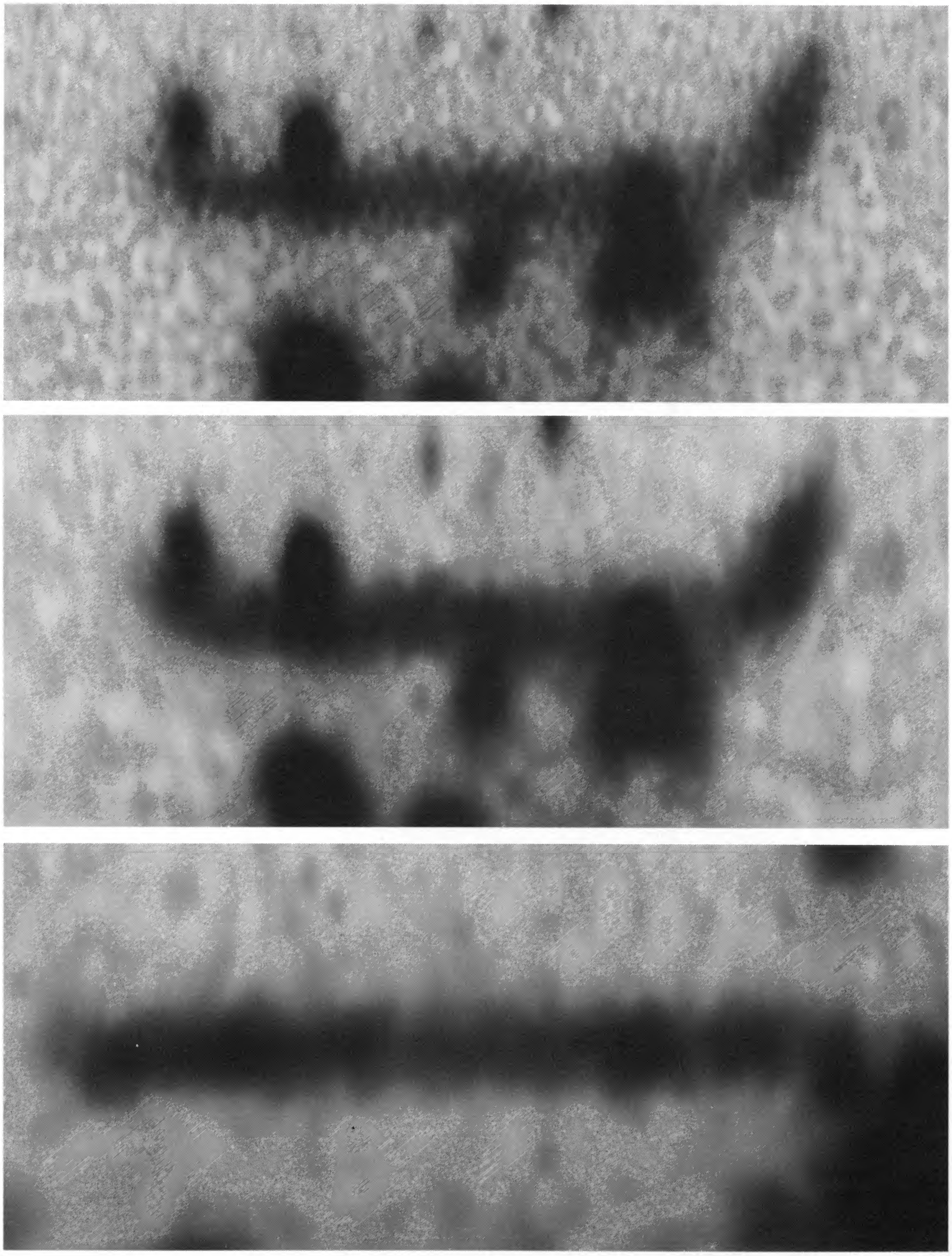

FIG. 4.—Same pictures as in Fig. 3, but mapped into polar coordinate space with the origin at the average center of curvature of the arcs. Radius increases toward the top (from 11″ to 19″ and from 7″ to 14″ for the Abell 370 and Cl 2244 arcs, respectively); 128° of aximuth is displayed horizontally.

LYNDS AND PETROSIAN (*see* **336**, 2)

arc is straight throughout nearly its entire length, thus implying a more perfect circular arc. The left (northern) end is slightly irregular and frayed, and the knot at the far right drops to slightly smaller radius as though it might not be a part of the arc.

Are the arcs genuinely filamentary in form, or merely fragments of shells seen in tangential projection? The strongest evidence bearing on this question is the high degree of symmetry shown by the radial surface brightness distributions of the arcs. These radial profiles, as convolved with the observational point-spread function, are almost exactly Gaussian with no evidence for a more gradual diminution of brightness toward smaller radius, as would be expected for a distribution of emission that was significantly shell-like. There is also no consistent evidence for a systematic narrowing and dimming of the arcs toward their ends.

The radial profiles also provide estimates of the widths of the arcs. In terms of full width at half-maximum (FWHM) values, these are 1".36 and 1".26 for the Abell 370 and Cl 2244 arcs, respectively. The FWHM values for the corresponding point-spread functions are 1".08 and 1".02. Assuming both the profiles and the point-spread functions to be closely approximated by a Gaussian function (which they are), the calculated intrinsic FWHM values are 0".82 and 0".74 (or 5.6 and 4.4 kpc) for the Abell 370 and Cl 2244 arcs, respectively.

However, the width of the Abell 370 arc is known to vary with color; the width just quoted is from the average of the *VRIJ* data with TI-2. The FWHM values from the RCA-3 data in *U*, *B*, *V*, *R*, and *I* are 2".23, 1".79, 1".54, 1".35, and 1".23, respectively, while the corresponding values for the point-spread functions are 1".08, 1".09, 1".26, 1".17, and 1".16. The calculated intrinsic arc widths are, therefore, 1".95, 1".42, 0".89, 0".66, and 0".42, in sequence. In the *U* band the intrinsic width of the arc is over 4 times the width in the *I* band, and the overall effect is not unlike the result of smearing a face-on Sb galaxy across the sky!

Although the seeing was not as stable for the TI-2 sequence of observations, the widths of the arc profiles show the same variation with color, although the intrinsic widths are about 20% smaller than for the RCA-3 data—an effect likely due to spatial undersampling in the case of the RCA-3 data.

We cannot say whether or not there is a similar variation of width with color for the Cl 2244 arc; the resolution is simply too bad on our only multispectral data set.

c) Photometry

Photometry has been performed for both arcs and also, as a means of providing a measure of confidence in the results, for large representative samples of galaxies and a few stars in the observed regions of the clusters. Standard fields in NGC 2264 and NGC 7790 (Christian *et al.* 1985) were used. Simple, linear color transformations were fitted, except for $I-J$, where only an estimated zero-point correction was applied to the instrumental colors. Although only the observations obtained under photometric conditions were used in the standardization of the photometry, relative photometry for the nonphotometric observations was used to add statistical weight to the results. Similarly, while photometric standardization was accomplished solely by means of simple aperture photometry applied to the CCD data, several statistically more powerful covariance techniques were employed in establishing the relative photometry of objects. The photometric results for the arcs and cD galaxies relevant to this report are given in Table 1.

TABLE 1

PHOTOMETRY OF THE ARCS AND cD GALAXIES

Object	V	$U-B$	$B-V$	$V-R$	$R-I$	$I-J$
Abell 370:						
Arc	20.04	−1.25	1.04	0.88	0.95	0.10
cD	19.50	0.23	1.62	1.28	0.82	0.00
Cl 2244−02:						
Arc	20.09	...	0.92	0.69	0.18	...
cD	19.32	...	1.83	1.20	0.95	...

The *V*-magnitudes and all color indices refer to the integrated light of the arcs and galaxies.

The two cD galaxies in Abell 370 are nearly identical photometrically; average values have been quoted in the table. The cD in Cl 2244 is the major galaxy nearest the center of curvature of the arc—the only E galaxy in the cluster judged to have cD characteristics. Owing to the difficulty in distinguishing the extended envelopes of the cD galaxies from the background contributions of nearby galaxies, the brightnesses of the cD galaxies in both clusters may be underestimated by several tenths of a magnitude. Also, there is considerable uncertainty in the color system for $I-J$. Otherwise, the general tendencies of the colors seem to be valid. Our *V*-magnitude for the two galaxies in Abell 370 is about 0.5 mag larger than those from aperture photometry by Kristian, Sandage, and Westphal (1978), but our $B-V$ and $V-R$ colors agree with theirs within 0.1 mag. We obtain similar results from a comparison with photometry by Butcher, Oemler, and Wells (1983). The colors of the cD galaxies may be considered as reference standards, since they are essentially the same as the colors of "typical" E galaxies in the clusters. We note, however, that Abell 370 is unusually rich in blue galaxies (see Butcher, Oemler, and Wells 1983); at our resolution many of these cannot be distinguished from E galaxies.

Figure 5 shows a plot of observed flux density versus frequency for the cD galaxies and for the arcs. As can be seen from the figure, both arcs are significantly bluer than the cD galaxies, but the Abell 370 arc is unusual in that it is about the same color as a cD in the far red, yet becomes increasingly blue toward the ultraviolet. This is what one might expect if the light were coming from two populations of stars: an old population dominating the light in the red and a very young population dominating in the ultraviolet (approximately 2600 Å in the rest frame of the cluster). Alternatively, the colors of the Abell 370 arc may be said to be compatible with a nonthermal power-law spectrum with a spectral index of -1.9 ± 0.2. By contrast with the Abell 370 arc, the Cl 2244 arc has colors that are more nearly compatible with those expected for a single population of fairly young stars, but undoubtedly not as young as suggested for the Abell 370 arc by the latter's strong ultraviolet; the *U* exposure of Cl 2244 showed no trace of the arc.

There is no significant variation in color along either of the arcs; variation in $B-V$ and $V-R$ is estimated to be less than 0.1 mag on scale lengths of a few arcseconds, or a total range of color of about 0.5 mag. The galaxy-like condensation at the eastern end of the Abell 370 arc has the same unusual colors (within the same limits) as are found for the arc proper, this fact providing some support for the possibility that the condensation is more than superficially associated with the arc.

The observed average surface brightnesses of the two arcs are comparable, ~ 23.6 *V* mag arcsec^{-2}. This value reduces to

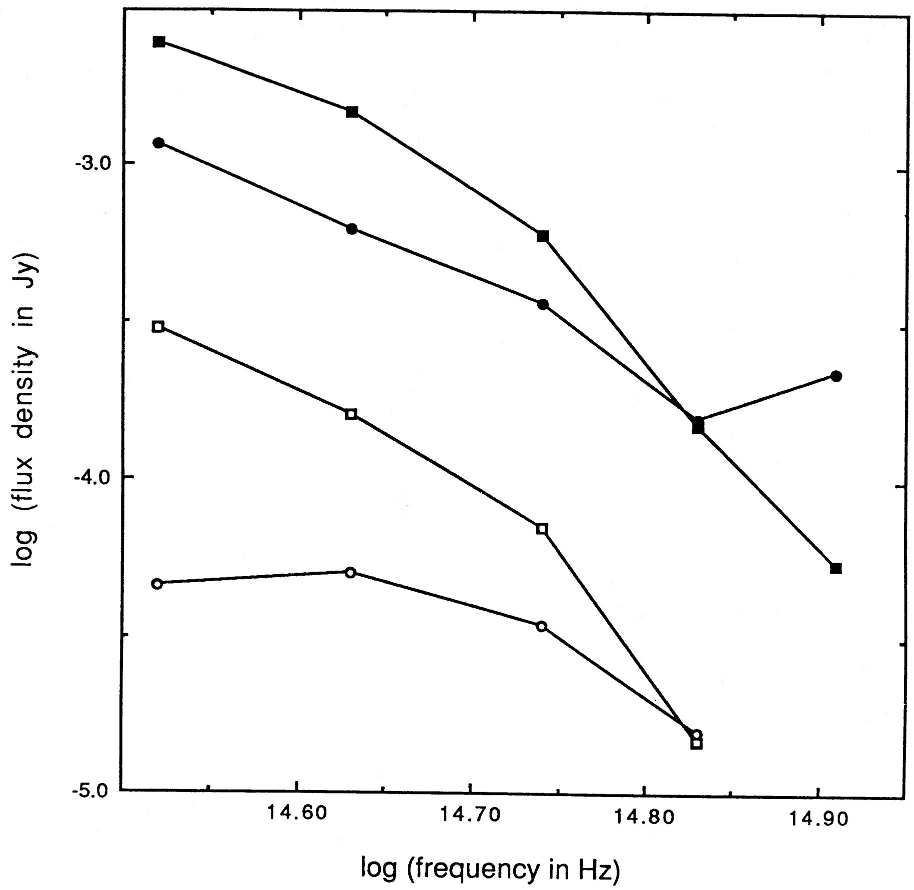

FIG. 5.—Flux density vs. optical frequency for the cD galaxies (*squares*) and the arcs (*circles*) from the wide-band photometry given in Table 1. The points for the Abell 370 cD and arc (*filled squares and circles*) are shifted upward by a factor of 10.

23.2 for the Abell 370 arc, where we have enough partial resolution to correct for the seeing effect. Moreover, this value reduces to 21.8 after correction to the rest frame of the cluster ($z = 0.373$) or to 20.8 at the redshift of the arc, $z = 0.725$ (given in § II*e* below).

d) Optical Polarization Observations

In 1986 September, extensive pictorial observations of the two arcs were made with the TI-2 CCD and polarization analyzers, in a broad spectral bandpass defined by a BG-38 filter. No polarization was detected in either arc. However, the seeing was consistently bad, and it is not possible to place stringent limits on the amount of polarization; estimates suggest that the degree of polarization is not more than 10%–20% integrated over element sizes of a few arcseconds, for either arc. Recent polarimetric observations of the Cl 2244 arc by Miller and Goodrich (1988) establish better polarization upper limits of 6% for portions of the arc taken by quarters and 4% for the arc as a whole.

e) Spectroscopic Observations

Spectroscopic observations of the two arcs have been made with the KPNO 4 m Cassegrain spectrograph configuration known as the Cryogenic Camera (CCD). For these observations focal-plane masks were prepared with apertures that exactly fit the arcs, as well as identical apertures for simultaneously obtaining spectra of the sky, two in the case of the Abell 370 arc and three for the Cl 2244 arc. Because of the faintness of the arcs, subtraction of the sky spectrum was of paramount importance, and great care was exercised at the data analysis stage in distortion correction and in precise registration of the spectra. Nevertheless, the efficacy of the sky subtraction was ultimately limited by point-spread function variations attributable to interaction between CCD surface irregularities and the fast f/1 focal ratio of the spectrograph camera. Spectroscopic resolution was approximately 20 Å, and wavelength coverage extended from about 5000 Å, below which there is virtually no sensitivity, to about 9000 Å, but with increasing harassment from airglow emission bands longward of 6800 Å.

One short exposure on the Cl 2244 arc was obtained in 1986 October before bad weather prevented further attempts. The weakly recorded spectrum was successful only in establishing the presence of continuum radiation and in excluding the presence of very strong emission lines within the accessible spectral range. In 1987 September, through generally cloudy skies, we accumulated the equivalent of about 10 hr of exposure time on each of the arcs (Lynds and Petrosian 1988). These two data sets will be discussed separately.

i) *The Abell 370 Arc*

The combined observations of the Abell 370 arc show one very strong emission line at 6429 Å (±5 Å), strong enough to be detectable in exposure times of only a few minutes, and three somewhat broad absorption lines at approximately 6617, 6713, and 6787 Å. These lines may be seen in the section of spectrum reproduced in Figure 6 (Plate 5), where line curvature due to the curved entrance apertures has been accurately removed. The same data have been averaged and are plotted in Figure 7 to better show the relative strengths of the lines. We have chosen to identify the emission lines as [O II] λ3727 at a redshift of 0.725, the two absorption lines at 6617 and 6713 Å with two well-known blends (primarily lines of CN and of neutral and ionized metals) having rest wavelengths of approximately 3834 and 3887 Å, and the absorption line at 6787 Å with the K line of Ca II. The H line is present but sufficiently compromised by OH (7–2) *R*- and *Q*-branch emission in the airglow spectrum as to add little to the overall interpretation.

We gave a lot of attention to interpretations of the spectrum at the cluster redshift of 0.373. Indeed, at that redshift the strong emission line happens to occur near the expected wavelength of the He II λ4686, but no evidence could be found for the presence of other expected lines such as Hβ of hydrogen or the N_1 and N_2 lines of [O III]. Although astrophysical situations are not unknown in which He II λ4686 is the dominant emission line (e.g., certain types of WC stars), it would seem to challenge credulity to suppose that such conditions could obtain over the very great apparent extent of the arc or to require a hitherto unknown physical situation. In any case, the absorption lines find no reasonable identifications at the cluster redshift, yet at the proposed redshift 0.725 they represent a pattern familiar in late-type spectra. Thus, we feel that the given interpretation is likely to be correct.

In the spectrum reproduced in Figure 6, the horizontal streaks are due to the light from nearby galaxies spilling into the arc mask, except for the topmost, which is due to the condensation at the eastern end of the arc. It is seen that the [O II] emission which extends all along the arc overlaps the spectrum of that eastern condensation and is, in fact, strongest at that point. From this fact and the previously described continuity of color, it seems conclusive that the condensation is an integral part of the arc.

It may also be seen in Figure 6 that the emission line exhibits a slight, reverse S-shaped curvature. The curvature appears to be real and tends to be confirmed by combined measurements of the absorption lines—although those measurements are not of sufficient quality as to represent, by themselves, compelling evidence. We have not thought of any instrumental effects that might produce the curvature, but independent confirmation is desirable on account of important constraints which the curvature places on explanations of the arcs—the indicated velocity range is nearly 500 km s^{-1}.

In related work on Abell 370, Hoag (1981) reported seeing no emission lines from the arc in slitless spectroscopy. Soucail *et al.* (1987*a*) obtained spectra of many of the galaxies but did not report any results for the arc itself. From more recent work, Soucail *et al.* (1987*b*) reported spectroscopic results for the condensation at the eastern end of the arc. However, these results were not correct and have been superseded by still more recent work, in which Soucail *et al.* (1987*c*, *d*) give spectroscopic results for the entire arc. They report the strong emission line and two of the absorption lines which we see and arrive at the same identifications we have chosen: [O II] λ3727, CN λ3883 (our λ3887), and Ca II K. In addition, they report absorption lines which they identify as Mg II λ2800, Ca II H, Hδ, and other unspecified Balmer lines of hydrogen. The redshift quoted is 0.724, nearly the same as our value. Finally, Miller and Goodrich (1988) report spectroscopy of the Abell 370 arc. However, initially they saw no discrete features, not even the strong emission line, because for some unfortunate reason their spectral coverage stopped just short of the line. In a spectrum obtained after Soucail *et al.* (1987*d*) reported the

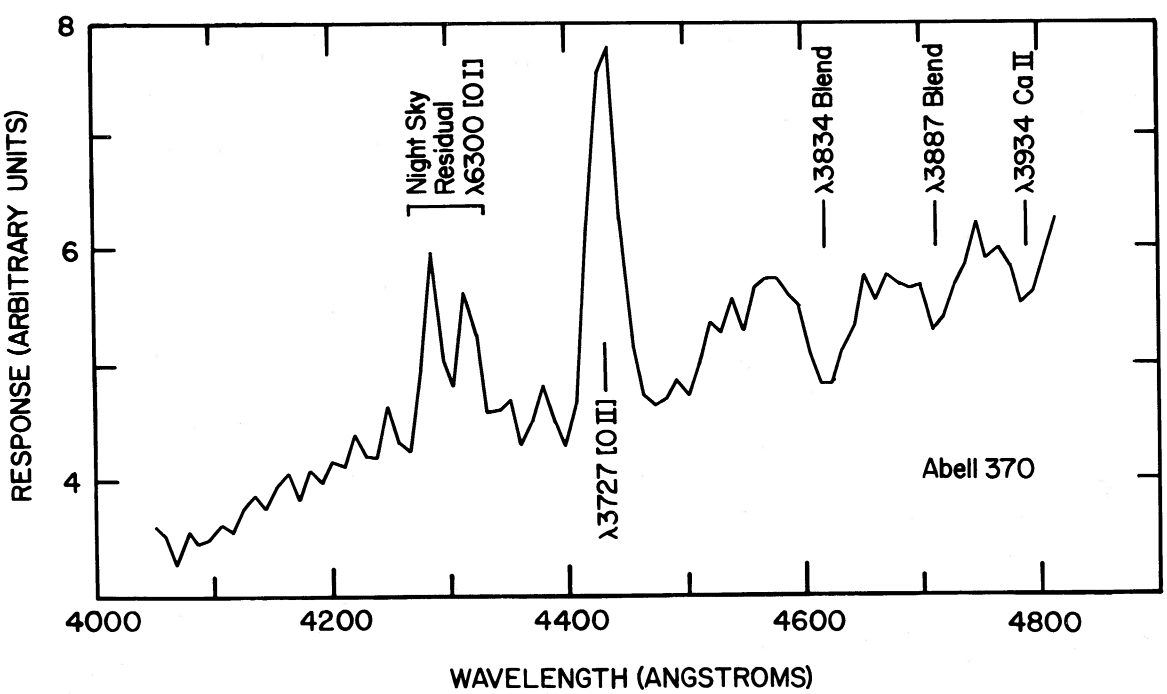

FIG. 7.—A plot of the average spectrum of the Abell 370 arc for the same spectral region as in Fig. 6

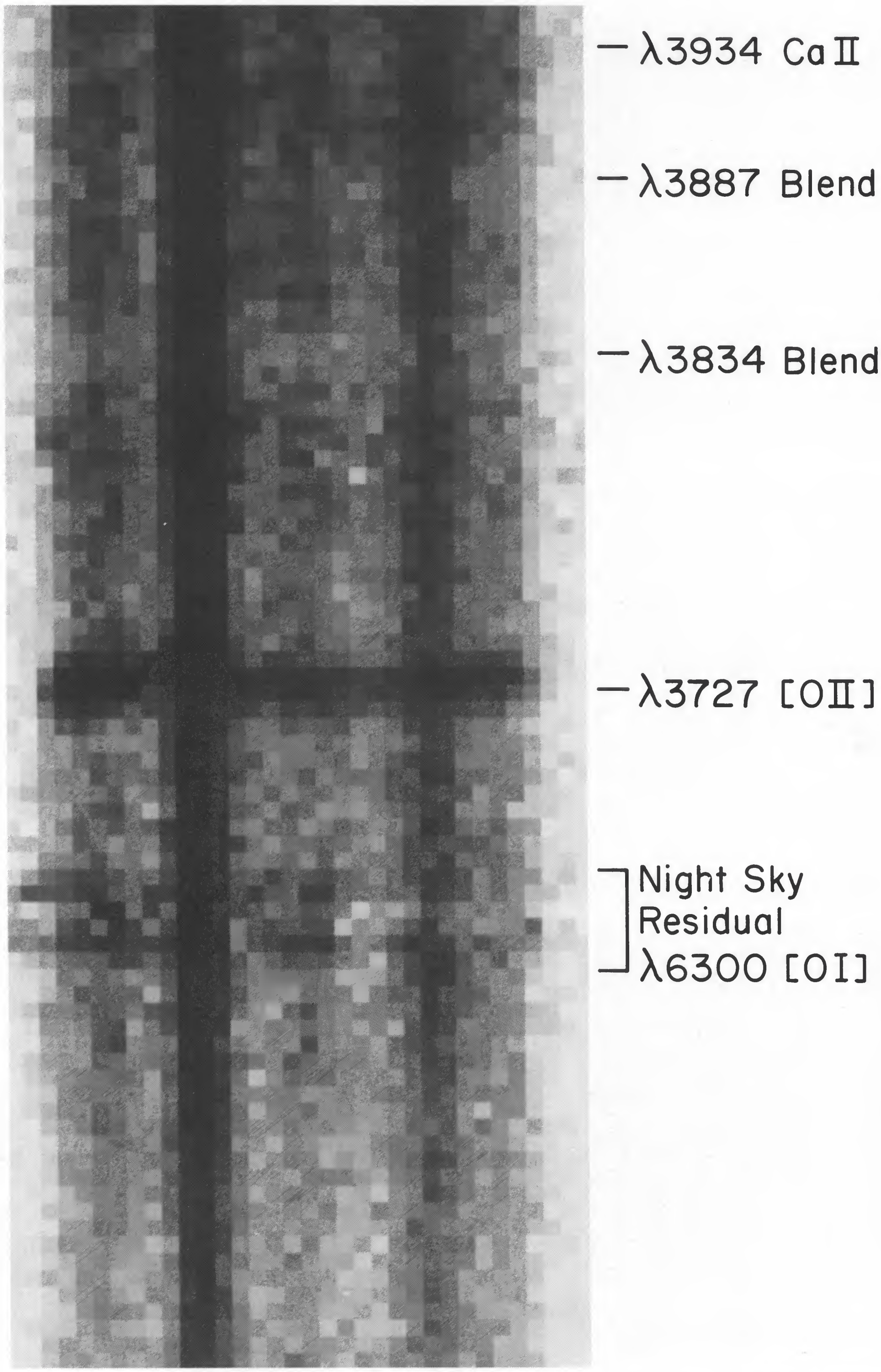

FIG. 6.—Section of the spectrum of the Abell 370 arc showing the strong emission line and three absorption lines. The dispersion is approximately 9.4 Å per pixel, and east is at the top.

LYNDS AND PETROSIAN (*see* **336**, 5)

existence of a strong emission line at ~6400 Å, Miller and Goodrich claim existence of a weak feature representing this same line.

In view of the fact that the redshift of the Abell 370 arc is nearly twice that of the cluster, it is tempting to state with certainty the conclusion that this arc (as well as the one in Cl 2244) is a gravitational image of a background object, with the mass responsible for the imaging to be found within the cluster. However, we are continually reminded by colleagues that not all astronomers place unrestrained faith in the cosmological interpretation of redshift for extragalactic objects. Therefore, we defer our conclusions on this point until the close of the discussion section, when all evidence and alternative explanations will have been considered.

ii) *The Cl 2244 Arc*

Our combined spectroscopic observations of the Cl 2244 arc have not led to a definite result, as was the case for the Abell 370 arc. If absorption lines are present, the data are not good enough to show them, and the one emission line which we seem to detect at 6831 Å is uncomfortably close to a moderately strong airglow emission line, the *R*-branch of the OH (7–2) band. The worry is that the feature represents a residual from the subtraction of the sky spectrum. We have explored a comprehensive range of distortion corrections, registrations, and aperture transmissivity ratios but have had no success in eliminating the feature. Nevertheless, our concern remains. The situation is illustrated in Figure 8 (Plate 6), where a section of the sky-subtracted spectrum is reproduced, together with a corresponding section of the sky spectrum for comparison. It is seen that the entire (7–2) band has been removed with scarcely a remaining trace, except for the emission at 6831 Å near the *R*-branch.

Independent confirmation or rejection of the reality of the emission feature is of paramount importance. If it is found to be real, it has no reasonable identification at the redshift of the cluster.

Related spectroscopic observations of the Cl 2244 arc include those reported by Soucail *et al.* (1987*e*). They report "a very flat and non-stellar continuum without any easily identifiable features" between 4400 and 7200 Å. Miller and Goodrich (1988) also report a featureless spectrum.

f) X-Ray Emission from the Clusters

Abell 370 and Cl 2244, like most rich Abell clusters of galaxies (including Abell 2218), have been observed to be strong X-ray sources (Jones and Forman 1984; Henry *et al.* 1982). Such clusters are understood to contain a hot ($kT \sim 10$ keV), tenuous ($n \sim 10^{-3}$ cm^{-3}) intracluster plasma radiating bremsstrahlung. Unpublished *Einstein Observatory* isophotal contour maps, kindly made available to us by Dr. Forman, show a source approximately 150″ in extent at half of peak brightness with the position of peak brightness centered between the two cD galaxies. Although the source shows no structural features corresponding to the arc, the source is strongly skewed to the north, with a steep gradient to the south beginning just south of the arc.

g) Radio Observations

We have not found mention of either Abell 370 or Cl 2244 as known radio sources. In his 1981 announcement of the filament in Abell 370, Hoag reports that "VLA 'snapshot' mapping" by Frazer Owen does not show the filament to be a radio source down to the flux density limit of 2 mJy. These observations were carried out with the A-array configuration at a wavelength of 20 cm.

We have conducted a new mapping of the regions of the arcs in both clusters with the A-array configuration of the VLA at 20 cm to a flux density limit of about 0.1 mJy. These new observations do not show any radio emission from either of the arcs but do reveal a source in the vicinity of each, a double source for the Cl 2244 arc. Table 2 gives, for each cluster, the optical position of the cD galaxy nearest the center of curvature of the arc and the positions and approximate flux densities of the radio sources. The weak point source in Abell 370 is about 2″ west and 5″ south of the cD. The centroid of the double point source in Cl 2244 is about 20″ east and 4″ north of the cD. For the moment, we draw no conclusions regarding the significance of the radio sources.

h) Frequency of Occurrence of Arcs

The observations of the 58 sample clusters upon which our own awareness of the arcs was based were performed on the 4 m telescope in 1976 with a doubly intensified silicon-target Vidicon (ISIT) having a quantum efficiency less than half that of modern CCDs and providing at the Cassegrain focus a field of view of 1 square arcminute. The observations where mostly made in the *V* and *R* passbands, with a few in *B* and *I*. The accumulated exposure time per cluster ranged from 15 to 150 minutes (depending somewhat upon cluster redshift) with a mean of about 60 minutes. The cluster sample included most of the clusters having high redshifts (greater than 0.1) known to us at the time. Most of the redshift determinations were by Sandage and various collaborators, by Gunn and Oke, and some (mostly 3CR radio sources) by Spinrad and his colleagues. The distribution of cluster redshift ranges from 0.022 to 0.75 with a median value of 0.228.

Because the redshifts for both arc clusters are well above the median redshift and because detection of similar arcs at the highest redshifts would have been difficult, we are inclined to think that arcs as a cluster-associated phenomenon may be more common at the larger redshifts. Since there are 27 clusters (26 if we exclude one 3CR source) in our sample with redshifts between 0.2 and 0.4, we suggest 8% as a conservative estimate for the frequency of occurrence of arcs for clusters in that redshift range.

III. DISCUSSION AND INTERPRETATIONS

We now discuss several suggestions as to the possible explanation for the arcs. Here we will emphasize the degree to which ideas are confounded or rendered awkward by the facts. Our goal is to converge upon explanations that seem to be simplest and most naturally harmonious with facts known to us. We

TABLE 2

POSITIONS OF cD GALAXIES AND RADIO SOURCES

Object	Right Ascension (1950)	Declination (1950)	Flux Density (mJy)
Abell 370:			
cD	02ʰ37ᵐ20ˢ.62	−01°47′48″.2	...
Source	02 37 20.48	−01 47 53.0	0.2
Cl 2244−02:			
cD	22 44 37.66	−02 21 29.0	...
Source 1	22 44 38.97	−02 21 25.5	1.7
Source 2	22 44 39.07	−02 21 25.5	1.5

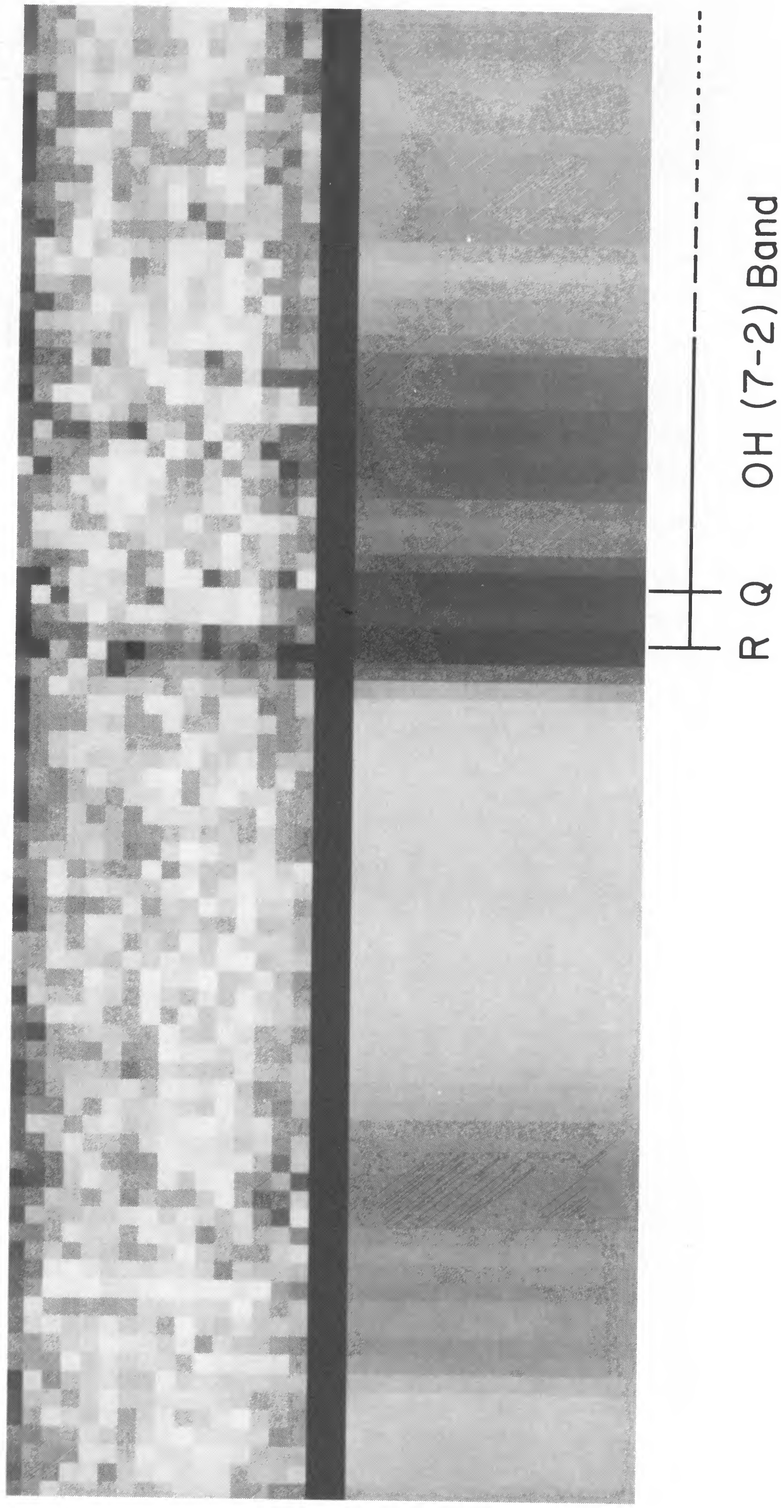

FIG. 8.—Section of the spectrum of the Cl 2244 arc showing the one possible emission line at 6831 Å. A corresponding section of the sky spectrum is reproduced at the bottom to illustrate the degree of success in removing the effects of the conflicting OH band. The scale is the same as in Fig. 6.

LYNDS AND PETROSIAN (*see* **336**, 6)

also do not expect that we will comprehensively mention, discuss, and credit all thoughts and results of investigations on this exciting topic that may have been published or otherwise circulated, whether or not they be known to us. Omission by intent may occur whenever ideas or their applications are judged by us to be commonplace or are sufficiently speculative or problematic as to seem beyond our ability to adequately expound.

Among the many possible explanations that we have considered, we list briefly the following: (1) gravitational disruption of an otherwise unremarkable galaxy, (2) light echo, (3) nonthermal optical jet, (4) gravitational wake phenomenon for an orbiting object, (5) cluster-centered shock waves or "bow shock," and (6) gravitational imaging of a background object. This subset simply comprises those explanations concerning which we are most often asked and about which we are most prepared to comment.

We seek, first of all, to abbreviate the discussion by assuming that the redshift for the Abell 370 arc determined by Soucail *et al.* (1987*d*, *e*) and by ourselves is certain. This immediately divides the list of explanations into two categories: explanations 1–5, which do not provide a natural accounting for the redshift being nearly twice that of the cluster, at least according to traditional interpretation of extragalactic redshifts, and explanation 6, for which the larger redshift seems rather a necessity. Thus, for any of explanations 1–5 to inspire any credence, they must persuasively account for all facts other than the redshift—in which case they become interesting. If, at the same time, explanation 6 fails to account for one or more critical facts, those other explanations that were successful assume greater importance, suggesting, as they would, other than conventional interpretations for the redshift. However, we are inclined toward some leniency in allowing explanation 6 certain contrivances in rationalizing the facts. For example, a requirement for an unexpectedly large mass concentration in the foreground cluster would represent for us more acceptable latitude than would, say, a requirement for a new physical law of nature. We anticipate in this way any bias that may be detected in the following treatment.

a) *Tidal Disruption of a Galaxy*

Two kinds of circumstances for gravitational disruption might be considered: (1) disruption by the general gravitational field of the cluster, which may be dominated by the field of some centrally located supermassive object, and (2) disruption in a close two-galaxy encounter of the type abundantly studied by Alar Toomre and others. In the first case, we at least have a rationale for the similar orientation of the two arcs with respect to their respective cluster centers. But we fail to see how other cluster members could have escaped similar disruption.

In the case of tail-forming galaxy-galaxy interactions, we lose any natural rationale for the similar and provocatively special geometrical relationship between the arcs and their respective clusters. It is also difficult to identify what it is that has been disturbed. Moreover, the disturbing object is not evident in either case. The great apparent luminosity and general shape and end-to-end uniformity in brightness (exepting fine structure) of the arcs are uncharacteristic of observed or simulated tidal tails known to us.

b) *Light Echo*

It has been proposed by Katz (1987) that the arcs might represent the scattering of light in an intergalactic medium resulting from a burst of light from a quasar. Other special circumstances seem to include a more or less planar distribution of material located only on one side of the source (unless the radiation field is supposed to be nonisotropic). The observed variation of the width of the Abell 370 arc with color would seem to require a special color change from blue to red to blue during the outburst from the illuminating quasar. Also, the geometrical circumstances required to explain the lack of substantial polarization appear to be a problem.

c) *Nonthermal Optical Jet*

One of the astrophysical situations in which long, narrow features are known to occur is in radio sources having jets and curved tails at radio frequencies. In two such cases, 3C 273 and M87, radio jets have a corresponding optical counterpart where synchrotron radiation from relativistic particles is the likely source of the light. One might well ask whether the arcs could, by analogy, consist of long collimated distributions of relativistic particles. However, the arcs are substantially more luminous and larger than the jets in 3C 273 and M87. Equipartition energy requirements would be 10^{57} ergs (combined magnetic and electron energy) at a magnetic field of 3×10^{-6} G, which gives a synchrotron lifetime of $\sim 10^4$ yr—not very long in comparison with the apparent frequency of occurrence of the arcs. For such a source with spectral index -2 and area 20 arcsec^2, self-absorption will set in below 10^9 Hz. Therefore, it is not easy to understand why the arcs would not be reasonably strong radio sources, unless there is a steep cutoff in electrons with Lorentz factors less than 10^6. It is also difficult to understand why the Abell 370 arc should be much broader in the ultraviolet than in the far-red. The constancy of the color of the arcs from end to end seems to require continuous *in situ* injection at all points along the length of the arcs. Finally, one might reasonably expect the arcs to be polarized, as in the M87 jet, but such is not the case.

d) *Gravitational Wake Phenomenon for an Orbiting Object*

One of the more natural ways of explaining the regular shape of the arcs is to imagine them as one of several kinds of phenomena induced in the wake of an object in gravitational orbit. There might, for example, be an accretion of intergalactic material onto the object and its trajectory with subsequent shock-induced star formation. However, the uniformity of the color of the arcs suggests an incompatibility between the evolutionary time scale for the stars and the gravitational time scale for the passing object. One would also have to hypothesize a massive ($> 10^{12}\ M_\odot$) compact object and a fairly dense intergalactic medium, as well as a somewhat special distribution, in order to account for the relatively abrupt termination of the arcs.

Alternatively, one might imagine an interaction between the X-ray plasma and a hypothesized magnetic field associated with the orbiting object, an interaction capable of accelerating particles to relativistic energies, thereby producing the observed luminosity by means of synchrotron radiation. The process is imagined as being qualitatively analogous to the acceleration of high-energy particles in the antisolar tail region of the Earth's magnetosphere. However, the conversion process would have to be of very high efficiency, and the uniformly abrupt termination of the arcs would imply an unreasonably special distribution of the plasma. It is also difficult to see how the acceleration process would be sustained throughout the length of the arc over the long gravitational (free-fall) time scales.

e) Cluster-centered Shock Waves

An obvious possible explanation is that the arcs are a result of rapid star formation behind a shock produced either by the blast wave of an explosion located near the center of the cluster or, as suggested by Begelman and Blandford (1987), behind a bow shock formed by the relative motion of the giant cD galaxy with respect to gas in a cooling accretion flow. However, as mentioned in the previous section, we believe that observations exclude the possibility that the arcs are sections of spherical shells, which is what one would expect given the nearly spherical symmetry of the X-ray gas in these clusters. Therefore, these and similar models require an additional assumption that the star-forming material was originally distributed in a sheetlike or filamentary fashion. The variation of arc width with color also poses a problem.

f) Gravitational Imaging of a Background Object

Because of the nearly circular shape of the arcs and the particular geometrical relationship which they share with respect to their respective clusters, it is natural to ask whether the arcs might simply be background objects imaged by the combined gravitational fields of objects in the clusters (Paczyński 1987). The width of the arc will represent the size of the object being imaged (in case of a point-mass lens there is a reduction in size by a factor of 2, but for an extended lens there could be some magnification), and the length-to-width ratio will be a measure of the luminosity amplification. The imaging mass required is a few times $10^{14}\ M_{\odot}$, depending on the redshift of the object.

Of course, in the case of a single imaging mass (possibly the nearest cD galaxy) there would be a second image of similar shape situated nearly symmetrically on the opposite side of the cD, which is not observed; and the width (or, if unresolved, the brightness) of the image should decrease toward the ends, which also is not well supported by the observations. However, early simulations (which we carried out in collaboration with Anton Bergmann) indicated that, for all practical purposes, the extra images could be eliminated if the lens consisted of two well-separated mass concentrations, as with the two cD galaxies in Abell 370 and the two main concentrations of galaxies in Cl 2244 (see also Soucail *et al.* 1987*b*). In addition, these simulations show that the ends of the images could be blunted and a certain amount of nonuniformity could be introduced. It has also been pointed out (Grossman and Narayan 1988; Blandford and Korner 1987) that, in general, for a nonspherical lens, one obtains a single prominent arclike image. Our more recent simulations (Bergmann and Petrosian 1987) indicate that much of the mass that is required can be reasonably distributed among the galaxies that are observed, and that the inclusion of low-mass galaxies that would be unobservable in our pictures can even explain the fine structure in the Cl 2244 arc, a fact that for long had dampened our enthusiasm for the gravitational lens model. We can also draw attention to the natural way in which the variation of width with color for the Abell 370 arc can be explained; all we have to do is to suppose that the object being imaged is a well-developed Sb spiral galaxy with an abundance of new star formation in its disk.

Finally, we now have what appears to be good evidence that the redshift of the Abell 370 arc is much larger than that of the cluster, a fact that is required by the gravitational lens model.

IV. CONCLUSIONS

We are encouraged that all facts known to us concerning the arcs can be naturally explained by the gravitational lens model. The other models we have discussed have various difficulties with the facts, even without introducing the redshift problem. Thus, it appears likely that gravitational images produced by clusters of galaxies have been found, as was envisioned by Zwicky (1937*a*, *b*) more than 50 years ago!

We gratefully acknowledge the assistance of Earl J. O'Neil, Jr., who performed diverse tasks that needed to be done correctly, and P. Leahy and P. Crane and other colleagues at the VLA for help in the reduction of radio data. This research was supported in part by National Aeronautics and Space Administration grants NCC 2-322 and NGR 05-020-668.

REFERENCES

Begelman, M., and Blandford, R. D. 1987, *Nature*, **330**, 46.
Bergmann, A. G., and Petrosian, V. 1987, *Bull. AAS*, **19**, 1081.
Blandford, R. D., and Korner, I. 1987, preprint.
Butcher, H., Oemler, A., Jr., and Wells, D. C. 1983, *Ap. J. Suppl.*, **52**, 183.
Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R., and Siegel, M. 1985, *Pub. A.S.P.*, **97**, 363.
Grossman, S. A., and Narayan, R. 1988, *Ap. J. (Letters)*, **324**, L37.
Henry, J. P., Soltan, A., Briel, U., and Gunn, J. E. 1982, *Ap. J.*, **262**, 1.
Hoag, A. 1981, *Bull. AAS*, **13**, 799.
Jones, C., and Forman, W. 1984, *Ap. J.*, **276**, 38.
Katz, J. I. 1987, *Astr. Ap.*, **182**, L19.
Kristian, J., Sandage, A., and Westphal, J. A. 1978, *Ap. J.*, **221**, 383.
Lynds, R., and Petrosian, V. 1986, *Bull. AAS*, **18**, 1014.
———. 1988, *Bull. AAS*, **20**, 644.
Miller, J. S., and Goodrich, R. W. 1988, *Nature*, **331**, 685.
Paczyński, B. 1987, *Nature*, **323**, 572.
Petrosian, V. 1976, *Ap. J. (Letters)*, **109**, L1.
Soucail, G., Fort, B., Mellier, Y., and Picat, J. P. 1987*a*, *Astr. Ap.*, **172**, L14.
Soucail, G., Mellier, Y., Fort, B., Hammer, F., and Mathez, G. 1987*b*, *Astr. Ap.*, **184**, L7.
Soucail, G., Mellier, Y., Fort, B., and Mathez, G. 1987*c*, *IAU Circ.*, No. 4482.
Soucail, G., Mellier, Y., Fort, B., Mathez, G., and Cailloux, M. 1987*d*, *Astr. Ap.*, **191**, L19.
Soucail, G., Mellier, Y., Fort, B., Mathez, G., and d'Odorico, S. 1987*e*, *IAU Circ.*, No. 4456.
Westphal, J. A. 1973, *Science*, **18**, 930.
Zwicky, F. 1937*a*, *Phys. Rev.*, **51**, 290.
———. 1937*b*, *Phys. Rev.*, **51**, 679.

ROGER LYNDS: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726

VAHÉ PETROSIAN: Center for Space Science and Astrophysics, ERL 304, Stanford University, Stanford, CA 94305