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IDENTIFICATIONS AND REDSHIFTS OF FAINT 3CR RADIO SOURCES[a]

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ABSTRACT

We report new and confirmed optical identifications of 12 3CR radio sources, and redshifts for nine of them. Seven have redshifts in excess of 1, with the highest being 1.841 for 3C 454.1; the remaining three sources are also likely to be at $z > 1$. One of the newly identified sources, 3C 194, shows a moderately strong Lyα emission, and may be a member of the new class of objects, possible young/forming galaxies, typified by 3C 326.1 and 3C 294. The optical identifications of the 3CR sources are now complete, and only six are lacking redshifts. Practically all of the new identifications are galaxies whose light appears to be dominated by stars, rather than nonthermal active nuclei, although their powerful radio emission argues that they are likely to be highly unusual objects. Their observed properties are similar to those of previously identified high-redshift powerful radio galaxies.

I. INTRODUCTION

The 3CR sample of radio sources (Bennett 1962) has been for many years the frontier playground for a variety of studies in extragalactic astronomy and cosmology. The usefulness of this sample for cosmological studies is based on the fact that many of the sources are extremely distant (up to $z \sim 2$), and yet the whole sample spans the full redshift range from the environs of the Local Group to the lookback times in excess of 2/3 of the Hubble time. Until recently, faint 3CR galaxies were the deepest sample of galaxies known, reaching to $z \simeq 1.8$, and they are still the only complete *galaxy* sample with over 30 objects at $z > 1$.

The 3CR sample represents the brightest few hundred radio sources on the northern sky, yet we are only now approaching the full optical identification of this classical radio survey. Previous efforts in this direction include the pioneering studies by Sandage and Wyndham (1965), Sandage, Véron, and Wyndham (1965), Véron (1966), and an impressive work by Wyndham (1966), followed by the deep studies by Wlérick, Lelièvre, and Véron (1971), Kristian, Sandage, and Katem (1974, 1978), Longair and Gunn (1975), Laing *et al.* (1978), Riley, Longair, and Gunn (1980), Gunn *et al.* (1981), and others. The latest summary of the identification contents of the 3CR sample was given by Spinrad *et al.* (1985). In this paper, we present new identifications and redshifts of some of the remaining few sources. Another set of new optical identifications, which will complete the identification content of the 3CR sample, will be presented in a future paper (Spinrad *et al.*, in preparation). At this time, there are secure or fairly secure optical identifications for *all* 3CR sources, with redshifts lacking for only 6.

Even though the enormous rest-frame radio power of these objects marks them as unusual, and their formation and evolution are probably unrepresentative of the general population of giant elliptical galaxies, the studies of distant 3CR galaxies presented us with the first glimpses of dramatic evolutionary effects in galaxies at large redshifts, $z > 1$, or the lookback times comparable to the Hubble time (Lilly and Longair 1984; Djorgovski, Spinrad, and Marr 1985; Lebofsky and Eisenhardt 1986; Eisenhardt and Lebofsky 1987; Djorgovski, Spinrad, and Dickinson 1988; cf. also the reviews by Spinrad 1986, or Djorgovski 1987a,b, 1988). It may even be possible to use these galaxies as "standardizable candles" in the Hubble diagram test in the near IR, where the evolutionary effects are not very strong (Spinrad and Djorgovski 1987). Some of the most distant 3CR galaxies known, near $z \simeq 1.8$, may even be examples of gE/cD galaxies or cluster cores in the process of formation (e.g., 3C 326.1, McCarthy *et al.* 1987a; or 3C 294, Spinrad *et al.* 1988; see also the reviews by Spinrad 1988, and Djorgovski 1988).

One essential feature of the 3CR sample that makes such cosmological studies possible is its completeness: the sample is well defined in the radio, and is now completely identified in the optical—there is no "hidden" population of ultrafaint 3CR galaxies. Achieving the complete identification content is important in order to examine rigorously the possible selection effects that may be affecting the evolutionary and cosmological tests that utilize this sample (cf. Yates, Miller, and Peacock 1986). New optical IDs presented here have observable properties similar to the previously discovered 3CR galaxies with comparable redshifts, and extend the evolutionary trends already identified in the works mentioned above.

[a] Based in part on the data obtained at Lick Observatory, University of California, and the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and University of Arizona.

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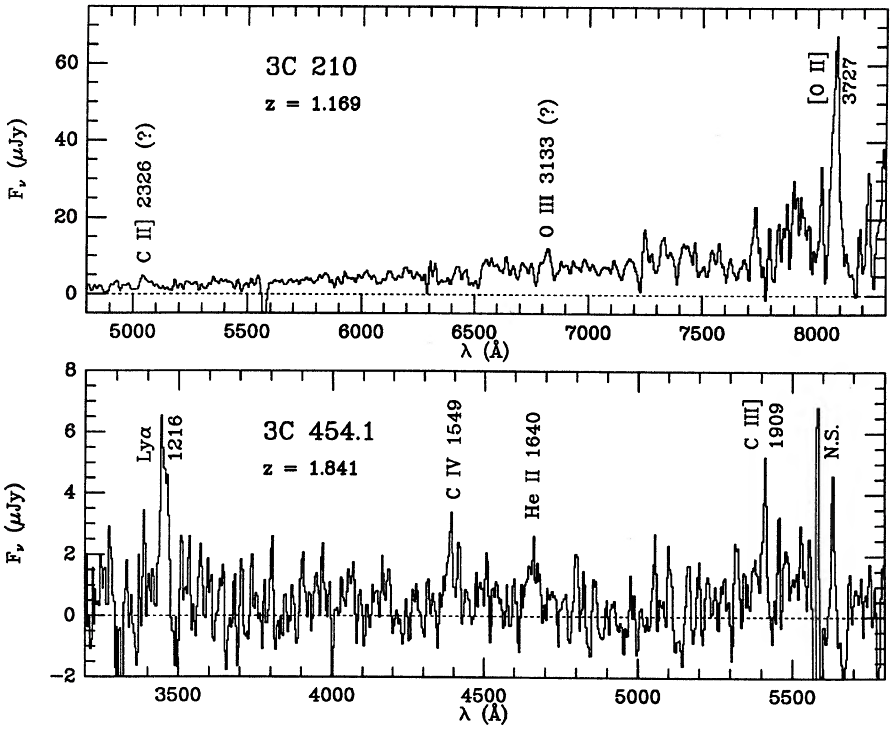

FIG. 2. Examples of long-slit CCD spectra. Top: the spectrum of 3C 210 ($z = 1.169$), obtained with the Cryocam spectrograph at the KPNO 4 m telescope. This is an example of a relatively low-ionization object. Note the enormously strong [O II] 3727 line; other tentative line identifications are also shown. Bottom: the spectrum of 3C 454.1 ($z = 1.841$), obtained with the Cassegrain spectrograph at the Lick 3 m telescope. All line identifications are fairly secure. The Lyα line is suppressed by a factor of ~ 7 due to the Galactic extinction. This is an example of a relatively high-ionization object.

II. THE RESULTS

The data presented here include deep CCD imaging, spectroscopy, and radio maps, obtained in numerous observing runs at several observatories over the last couple of years, and some new astrometry.

The images were obtained mostly at the prime focus of the Kitt Peak 4 m Mayall telescope, using the TI #2 800×800 CCD; some were obtained at the prime focus of the CFHT, using the RCA #2 640×1024 CCD; and some were obtained at the prime focus of the CTIO 4 m telescope, using the RCA #1 320×512 CCD. The data were processed using standard methods, and the details of imaging and photometry will be given by Djorgovski, Spinrad, and Dickinson (1988). Here, we show in Fig. 1 [Plates 39 and 40] the best image we have for each source.

The spectroscopic measurements were obtained at the Cassegrain focus of the Kitt Peak 4 m Mayall telescope, using the long-slit Cryocam CCD spectrograph (De Veny 1983), the Intensified Reticon dual-aperture spectrograph at the MMT (Latham 1982), and the Cassegrain long-slit CCD spectrograph at the Lick 3 m Shane telescope (Miller and Stone 1988). The spectra were extracted and calibrated using standard techniques. The complete analysis of these and other spectra of distant 3CR galaxies will be presented in a forthcoming paper. Here we show two typical examples in Fig. 2. The spectra of the remaining sources are qualitatively similar to these two, and to those of other high-redshift 3CR galaxies (e.g., Spinrad and Djorgovski 1984).

Many of the new IDs are faint galaxies found in "empty fields" which defied the previous investigators. For some sources it was necessary to obtain new radio data, because the previously available radio positions were insufficiently precise. Thus, some of our new identifications supersede previous incorrect IDs. Several new radio positions were kindly communicated to us by other workers, as indicated in the references to Table I. Most of the remaining cases are based on the new radio positions derived in our survey. The radio maps were obtained using the Westerbork Synthesis Radio Telescope, and the VLA.* Further discussion and analysis of our radio data will be presented elsewhere.

In the cases where the previously available optical astrometry was ambiguous or nonexistent, we performed our own measurements, mostly using the paper or glass copies of the Palomar Observatory Sky Survey, or photographic enlargements therefrom. The measurements were performed with the PDS scanner at U.C. Berkeley, the dual-axis measuring machine at the Center for Astrophysics, and the plate-measuring machine at Lick Observatory. The plate solutions were generally based on the measurements of some 15–25 nearby SAO stars. Positions of a number of fainter stars, visible in our CCD frames, were derived and used to transfer the equatorial-coordinate system to the CCD pixel positions. The typical final accuracy of our measurements is $\sim 0.5''$ in each coordinate. We list the sources of the radio positions and the optical astrometry in Table I; epoch 1950.0 is used throughout. The table also lists the approximate optical magnitudes of the new IDs, the redshifts, if available, and the positions of nearby offset stars, marked in Fig. 1.

III. SOME COMMENTS ON INDIVIDUAL SOURCES

3C 68.2. Our new ID, based on the improved radio core position and confirmed spectroscopically, supersedes the previous, provisional ID by Gunn *et al.* (1981). The object appears to be a member of a faint group or a cluster, but no redshifts for other galaxies in this field are available at this time.

*The VLA is operated by Associated Universities, Inc., under a contract with the NSF.

TABLE I. Positions, magnitudes, and redshifts of new identifications.

3CR	RA (1950) Radio / Optical / Offset Star	DEC	Position ref.	V mag	z
	02 31 24.84	31 21 11.24	1		
68.2	02 31 24.79	31 21 11.5	0	23.5	1.575
	02 31 24.25	31 21 21.4	8		
	04 09 49.93	-01 07 11.0	2		
107	04 09 50.07	-01 07 11.1	0	22	0.785
	04 09 50.20	-01 06 50.4	0		
	06 58 56.39	38 01 44.5	3		
173	06 58 56.67	38 01 46.1	4	21.3	1.035
	06 58 53.49	38 01 41.4	0		
	08 06 38.00	42 36 57.0	0		
194	08 06 37.88	42 36 56.0	0	24:	1.779
	08 06 37.61	42 36 54.0	0		
	08 55 10.86	28 02 31.8	5		
210	08 55 10.81	28 02 32.4	0	22.0	1.169
	08 55 08.27	28 02 02.9	9		
	09 33 55.16	04 35 38.6	6		
222	09 33 55.15	04 35 39.2	0	23:	?
	09 33 54.93	04 36 00.4	0		
	11 06 11.25	25 17 10.27	0		
250	11 06 11.25	25 17 10.1	0	24:	?
	11 06 11.61	25 17 31.5	8		
	11 16 52.14	-02 46 25.6	0		
255	11 16 52.10	-02 46 27.1	0	23	?
	11 16 54.46	-02 45 21.7	0		
	14 25 56.60	-01 10 44.1	7		
300.1	14 25 56.64	-01 10 44.6	0	23	1.159
	14 25 57.65	-01 10 47.4	0		
	15 33 46.40	55 46 47.7	0		
322	15 33 46.40	55 46 47.1	0	23:	1.681
	15 33 49.91	55 46 36.0	0		
	15 40 48.5	60 25 03	0		
323	15 40 48.03	60 25 03.3	0	21	0.679
	15 40 48.80	60 25 11.4	0		
	22 48 58.94	71 13 23.3	0		
454.1	22 48 58.96	71 13 23.9	0	22.0	1.841
	22 48 54.78	71 13 24.0	0		

Position and astrometry references:

0 = This work.
1 = Laing & Owen, priv. comm.
2 = Wills & Douglas, priv. comm.
3 = Adgie et al. (1972)
4 = Wlerick et al. (1971)
5 = Rudnick, priv. comm.
6 = Wade (1970)
7 = van Breugel et al., priv. comm.
8 = Gunn et al. (1981)
9 = Grueff & Vigotti (1975)

3C 107. Kristian, Sandage, and Katem (1974, 1978) mention "a faint smudge" near the radio position, which is almost certainly our ID.

3C 173. We confirm the old ID by Wlérick, Lelièvre, and Véron (1971). Our CCD images show a nucleated appearance, and a very blue color. MMT spectra show it to be a high-redshift N galaxy.

3C 194. Identification based on a new VLA map. This is one of the more interesting sources in the present paper. Its diffuse continuum appearance and a moderately strong Lyα emission line suggest that it may be similar to the possible forming galaxies 3C 326.1 (McCarthy *et al.* 1987) and 3C 294 (Spinrad *et al.* 1988). This object requires a more careful study before its physical properties and evolutionary state can be established more reliably. We are now obtaining additional data, which will be presented and analyzed in a future publication.

3C 210. New radio core position by Rudnick (private communication) confirms the old ID by Grueff and Vigotti (1975). Spectrum shows a prominent [O II] 3727 line (see Fig. 2), characteristic of many powerful, high-z radio galaxies.

3C 222. Based on the new optical astrometry, and the radio position by Wade (1970), Douglas *et al.* (1973), and reinforced by our more recent Westerbork map. Despite the low declination, the latter shows that in addition to the 1.2 arcsec central double (P.A. = 58°, cf. Roland *et al.* 1982), some 5% of the flux density at 6 cm resides in two components separated by 1 arcmin in P.A. = 3°, which straddle the central source. The ID is the W member of an apparent faint quartet.

3C 250. Our new VLA radio position rules out the old, provisional ID by Gunn *et al.* (1981). Possible vary faint cluster in the field.

3C 255. Based on the new optical astrometry, and a new VLA map. Complex, multimodal structure; the optical ID position listed in Table I corresponds to the brightest condensation.

3C 300.1. A new VLA map by van Breugel, Baum, and Heckman (in preparation) indicated that the old ID by Wyndham (1966) was incorrect; this was kindly first communicated to us by T. Heckman. The new ID is based on their radio position, and our new optical astrometry and CCD imaging. The redshift is based on a strong [O II] 3727, and weak [C II] 2326 and [Ne IV] 2424 lines.

3C 322. Our deep CCD images, Westerbork and VLA maps, and subsequent spectra confirm the marginal ID proposed by Riley, Longair, and Gunn (1980). The object has relatively weak emission lines compared to most other 3CR galaxies at similar redshifts.

3C 323. Based on a Westerbork radio position (the geometrical center of outer ends of the radio components), and the new optical astrometry.

3C 454.1. Our new CCD images, astrometry, VLA maps by Pearson *et al.* (1985) and us, and the subsequent spectroscopy confirm the marginal ID by Longair and Gunn (1975). At $z = 1.841$, this is the most distant galaxy in the 3CR sample now known. The object is in a crowded, obscured field; C. Heiles (private communication) kindly estimated from the H I maps the Galactic extinction in the line of sight to be $E_{B-V} \simeq 0.43$. Note that its optical morphology closely resembles the radio morphology: two "lobes" separated by ~1.6–1.7 arcsec in P.A. ≃ 170°. A zoom-in section of the optical image is shown in Fig. 3. We cannot tell whether the optical and the radio components also coincide *precisely* positionally, although that possibility is certainly allowed by our astrometric measurements (our optical–radio relative coordinate-system shift is uncertain by ~0.5 arcsec). This morphological similarity may suggest gravitational lensing (cf. Le Fevre *et al.* 1987). However, we discount that possibility on the account of a steep spectral index of the radio source ($\alpha \simeq -0.85$), subarcsecond morphology of radio lobes from our VLA maps, and the fact that such morphologies and alignments are relatively common in high-redshift powerful radio galaxies. The object also has a fairly extended Lyα emission, about twice the size of the red continuum detected in our CCD images. If one pleads special circumstances, 3C 454.1 may be interpreted as a gravitationally lensed galaxy, but we consider that explanation unlikely.

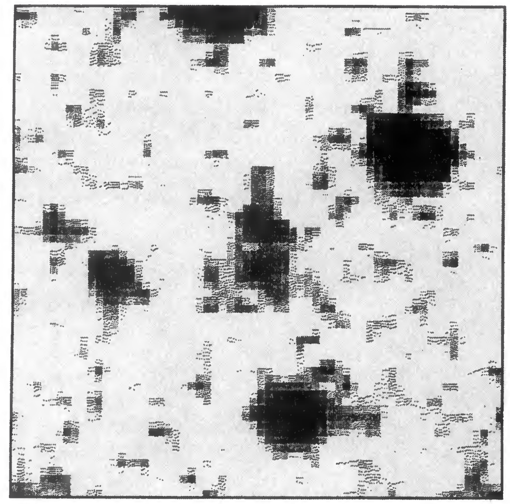

FIG. 3. A section of an R band CCD image of 3C 454.1, obtained with the RCA #1 prime-focus CCD at the KPNO 4 m telescope. The field size is 18.7 arcsec square, with east to the left, north to the top. The optical morphology is very similar to the radio map published by Pearson *et al.* (1985).

We note that all of the sources in the present paper with elongated optical structure, particularly 3C 454.1, show the optical/radio alignment effect, discovered by McCarthy *et al.* (1987b) and Chambers, Miley, and van Breugel (1987). With the exception of 3C 173, the new IDs have extended, nonnucleated optical-continuum morphology, and spectra characteristic of radio galaxies (as opposed to Seyfert 1's or QSOs), namely, emission lines with relatively narrow velocity widths, large equivalent widths, and generally low ionization. Overall, their properties are very similar to those of other, previously identified high-redshift 3CR galaxies, and we believe that their observed visible light is dominated by the stars, rather than active nuclei or other nonthermal radiation. Pending a better understanding of the optical–radio alignment effect, we may hope to use these distant galaxies for the studies of radio galaxy evolution at large lookback times, and conceivably even for the Hubble diagram cosmological test in the near IR.

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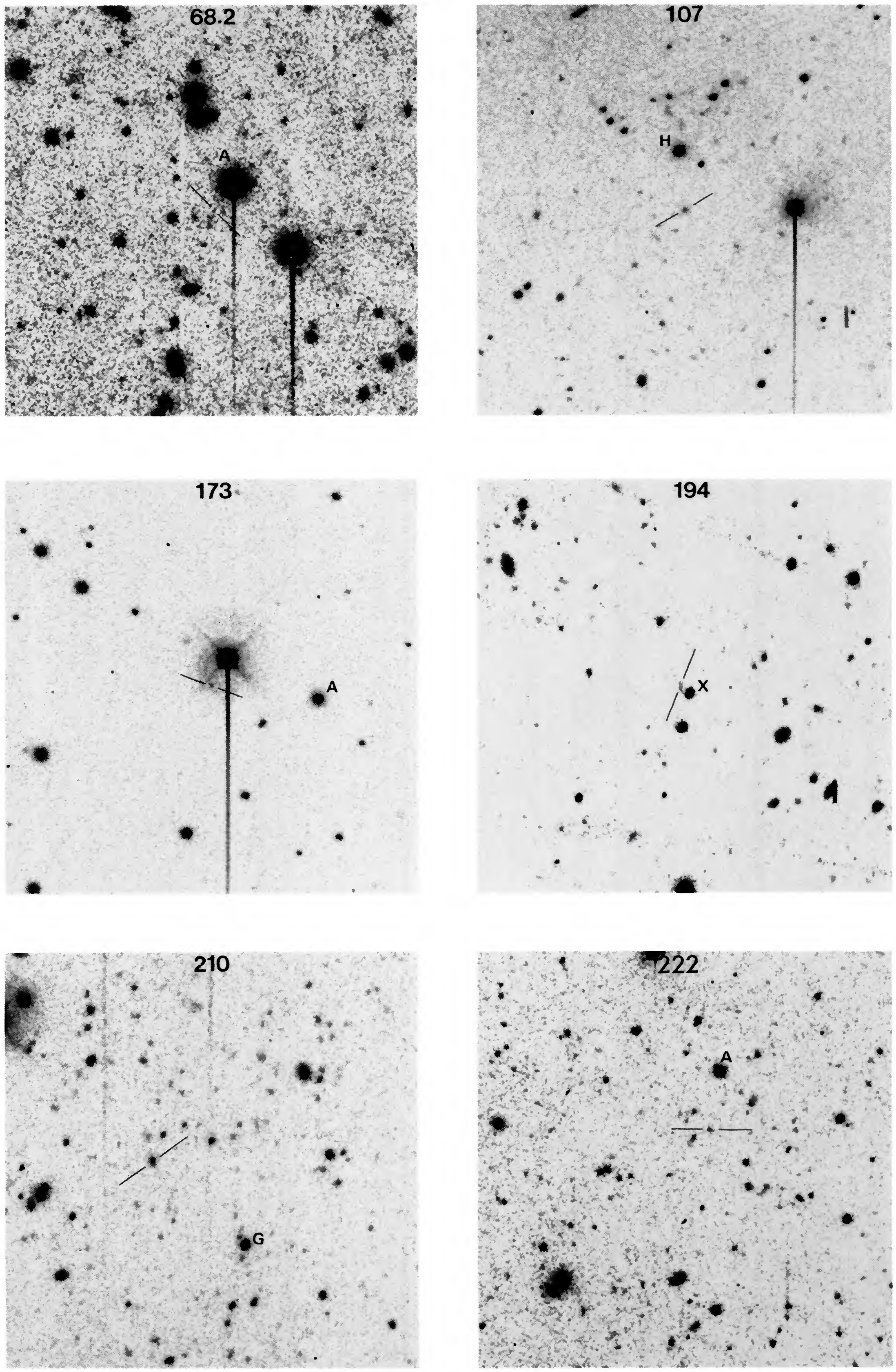

FIG. 1. Gray-scale images of fields containing the proposed identifications. All fields are 2.5 arcmin square, except the image of 3C 255, which is 2×2.5 arcmin. North is on the top, east to the left, except for the image of 3C 255, which is tilted 8.8°, as indicated. Most images are reproduced from R band CCD frames, except for 3C 173, which is from a B frame, and 3C 322, which is from a stack of $B + V + R$ frames. The exposure times and intensity stretches vary. The offset stars are indicated with the letters, generally following the original notation from the references listed in Table I.

Djorgovski *et al.* (see page 837)

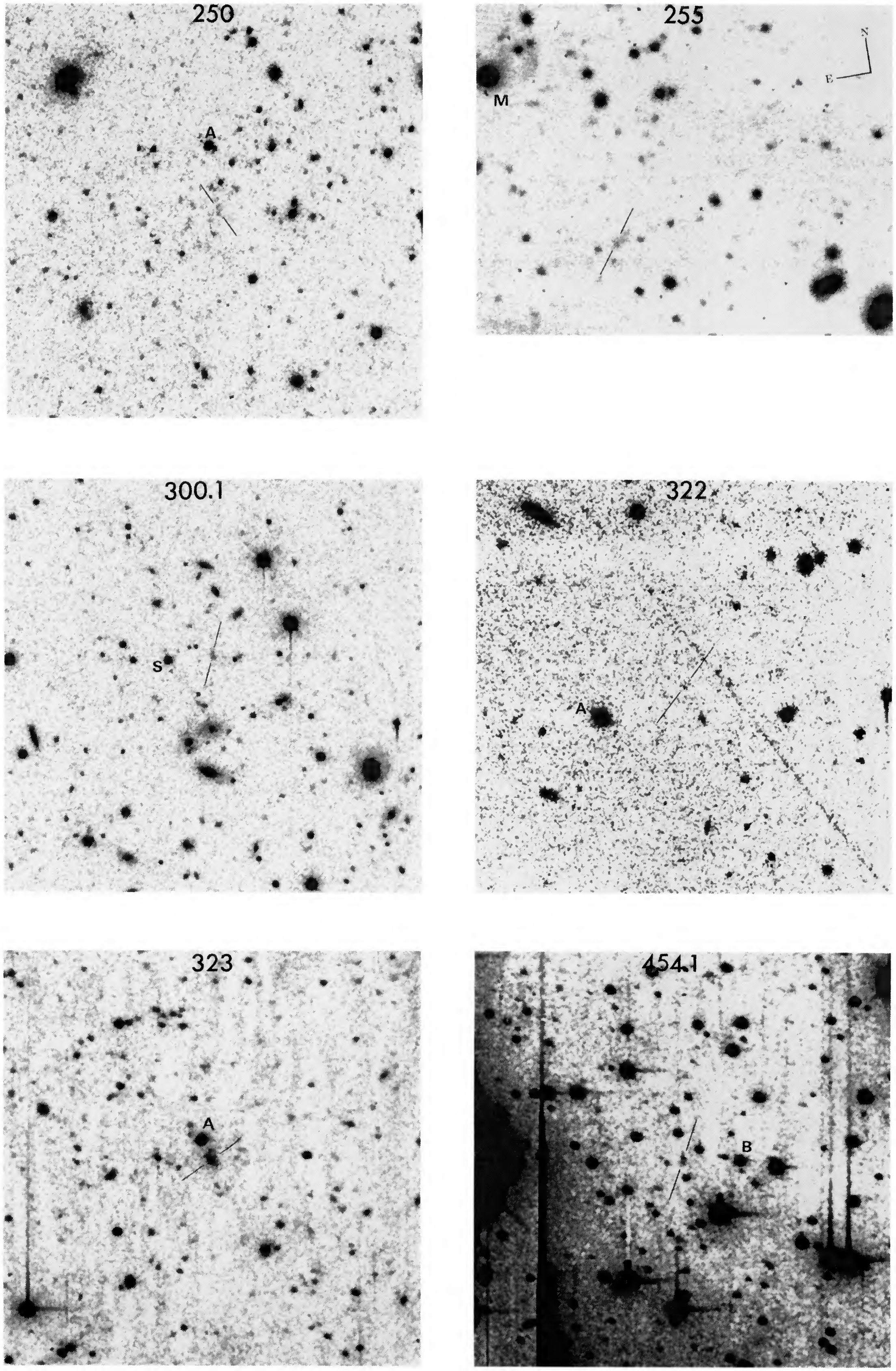

FIG. 1. (continued)

Djorgovski *et al.* (see page 837)