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COMPACT RADIO SOURCES IN THE DIRECTIONS OF RICH CLUSTERS OF GALAXIES

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ABSTRACT

Observations with the National Radio Astronomy Observatory (NRAO) interferometer at 2695 and 8085 MHz are reported of 16 radio sources with total angular sizes less than 5″. These sources are a subset of a larger sample of 94 sources in the directions of rich clusters of galaxies, which have been observed with the NRAO interferometer. Flux densities, angular structure down to 0.1″, accurate radio positions, and optical identifications are reported. Only one of these compact sources is possibly identified with a cluster galaxy, while most of the extended sources in the sample are clearly associated with dominant cluster galaxies. This suggests that all or almost all radio galaxies in rich clusters have extended structure greater than 10 kpc. Compact sources with steep spectra in the sample seem likely to be very distant radio galaxies, while the nature of the sources with flat spectra is unclear, although they may also be background sources.

Subject headings: galaxies: clusters of — radio sources: general — radio sources: spectra

Since the discovery of the existence of radio sources in rich clusters of galaxies (Mills 1960), increasingly higher resolution observations have been made of these sources. Recent observations have been able to resolve most of these sources (e.g., Jaffe and Perola 1973; Slingo 1974*a*, *b*; Riley 1975). However, a small subset has remained unresolved. The recent debates about the possible associations of quasars and Lacertids with rich clusters make these objects potentially quite interesting (e.g., Burbidge and O'Dell 1973; Wills and Wills 1974; Disney 1974). During the last year (1974) we have been observing a sample of nearly one hundred sources in the directions of rich clusters using the NRAO four-element interferometer with a maximum resolution of $\sim 0.1''$. This paper deals with 16 of these sources which have overall angular sizes less than 5″. The remaining, more extended sources will be discussed fully in a later paper.

I. OBSERVATIONS

All observations were made between 1974 April and November, using the NRAO interferometer at 2695 and 8085 MHz. This instrument consists of three 85 foot (26 m) steerable antennas with a maximum baseline separation of 2700 m and a steerable 45 foot (14 m) antenna located roughly 35 km southwest of the other elements. Thus observations can be made on six simultaneous baselines. During our observations "short" baselines of either 900, 1800, and 2700 m, or 300, 1200, and 1500 m were used while the "long" baselines ranged from 33.1 to 35.3 km. Typically, five to ten 10 minute observations (*scans*) well distributed about the $u - v$ plane were made on each source. During each scan both left and right-hand circular polarizations were recorded simultaneously, while every 30 seconds the array was switched from one frequency to the other.

Calibrations on known sources were made once per hour to determine system gain and phase factors. All observations were normalized to the KPW flux density scale (Kellermann *et al.* 1969; Kellermann and Pauliny-Toth 1973). For the short baselines, the calibration rested heavily on observations of 3C 48, 3C 147, and 3C 286. A number of very compact sources were observed to calibrate the long baselines. These included DA 267, OQ 208, 3C 84, 3C 345, and BL Lac. Since most of these sources are variable, their flux densities were normalized to the values measured on the short baselines.

Program sources were selected from a variety of surveys at lower frequencies as summarized in Table 1. The sample was selected to be representative of sources in the directions of rich clusters, but is by no means complete. In particular, the sample is clearly biased toward sources with steeper spectra than average for a complete sample at 2695 MHz. Sixty-two of the total of 94 sources meet three well-defined criteria which will be used later in this paper for statistical arguments. These sources are all north of 20°, have $S_{2695} \geq 200$ mJy, and are within 0.3 corrected Abell radii (see Owen 1974) of an Abell cluster center. Total flux densities were obtained for most of these sources with the 91 m telescope as reported in Owen (1975). Based on our selection process, we estimate that for these well-defined criteria our sample is roughly 70 percent complete for sources with steep spectra ($\alpha > 0.5$, $S \propto \nu^{-\alpha}$) and 30 percent complete for sources with flat spectra ($\alpha < 0.5$).

* Operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

SUMMARY OF ORIGIN OF PROGRAM SOURCES

Survey	Frequency (MHz)	Number of Sources	Reference
OW.........	1400	43	Owen 1974
4C...........	178	34	Pilkington and Scott 1975; Gower *et al.* 1967
4CT.........	178	5	Caswell and Crowther 1969
B2...........	408	7	Colla *et al.* 1970, 1972
WKB........	38	3	Williams *et al.* 1966
GO..........	365	2	Ghigo and Owen 1973

II. REDUCTIONS

The most suitable reduction procedures for sources resolved on the short baselines differed from those for sources which were not resolved. For sources which were significantly resolved on the short baselines, a model-fitting procedure was used to determine the parameters of each source. The data from the two radio frequencies were fitted separately. First, a vector average of the complex fringe visibility (amplitude and phase) was calculated for each scan on each baseline. Then one or more elliptical Gaussian brightness distributions were fitted to the averaged visibility data, using a simplex search technique (see, e.g., Nelder and Mead 1965). For the 2695 MHz data, the total flux density was used as a further constraint. The derived flux densities and sizes result from Gaussian approximations to the actual brightness distributions. Nevertheless, they probably present a fairly accurate description of each source. Fits to strong sources produce residuals only a few times the expected noise level, even though there are many more data points than derived parameters. Internal errors were derived independently for each parameter. A change in a given parameter equal to the internal error produces a fractional increase in the rms residual equal to N^{-1}, where N is the number of input data points.

For sources not significantly resolved on the short baselines, a different procedure was used. Vector averages were calculated for each scan as described above. The resulting rms visibility amplitudes for each source were then calculated separately over the short baselines and the long baselines. This process yields an average measure of the fringe visibility in each of the two distinct spatial frequency regimes sampled at each radio frequency. This procedure minimizes the effects of long-term system gain and phase variations, which are particularly important on the long baselines. Internal errors in the mean visibilities were calculated from the rms scatter in the measurements for each source. The observed scatter was divided by the fourth root of the number of data points, as is appropriate for incoherent averaging.

The radio centroid positions were derived for each source either from the model-fitting procedure for resolved sources or from the short baseline phase data alone for point sources. These positions were then used to examine the Palomar Sky Survey prints for possible identifications. Transparent overlays were used to find the appropriate region on the prints with an accuracy of about 5″. If no object was visible within 10 arcseconds on either the E or O prints, the source was considered to be unidentified. The positions of any objects within this range were then measured on the E prints, using a measuring machine and techniques very similar to those described by Jauncey and Durdin (1974), to a typical accuracy of 1 to 2 arcseconds.

III. RESULTS

Only 16 of the 94 observed sources were found to have total angular sizes less than 5″, although most have fine structure smaller than this scale. Table 2 summarizes the results for these sources.

Column (1) gives the Parkes-type name for each source.

Column (2) gives the number of the associated Abell cluster (Abell 1958).

Column (3) gives the projected separation of the radio centroid from the cluster center, expressed as a fraction of one corrected Abell radius (see Owen 1974).

Columns (4) and (5) give the 1950.0 right ascension and declination, respectively, of the radio source centroid. The positional errors in all cases are estimated to be 0.5″ in each coordinate and are due primarily to the uncertainty in the absolute coordinate system of the calibrators.

Column (6) gives the total flux density at 2695 MHz, as measured by Owen (1975), unless otherwise noted.

Columns (7) and (8) give the observed flux density and associated errors on the short 85 foot baselines (S_{85}) as measured at 2695 and 8085 MHz, respectively. The error estimates have been obtained by adding 0.05 S in quadrature with the internal errors in order to account for residual gain fluctuations after calibration.

Column (9) gives the spectral index α, derived from the observed flux densities on the short baselines (defined by $S \propto \nu^{-\alpha}$).

Columns (10) and (11) give the observed rms visibilities (unnormalized, in units of mJy) and errors for the long 45 foot baselines (S_{45}). The errors were calculated in the same manner as for the short baselines.

Columns (12) and (13) give estimates of the extent of each source (in arcseconds) at 2695 and 8085 MHz, respectively. Sizes for sources resolved on the short baselines or without long baseline data were estimated using the model-fitting procedure described earlier.

TABLE 2

SOURCE PARAMETERS

Source	Abell Cluster	D.R.	Right Ascension	Dec.	S_{91M}(MJY) 2695	S_{85}(MJY) 2695	S_{85}(MJY) 8085	Spectral Index	S_{45}(MJY) 2695	S_{45}(MJY) 8085	Angular Size 2695	Angular Size 8085	Notes
0219+428	347	.84	$02^h19^m29\overset{s}{.}98$	42°48′29″.7	1700	989(51)	813(43)	0.2(.1)	578(35)	591(41)	0″.4(0.1)	0″.1(.02)	1
0315+416	426	.17	03 15 29.24	41 38 43.8	-	321(19)	99(10)	1.1(.2)	-	-	3.2(1.5)	2.8(.5)	2,3
0646+692	562	.31	06 46 29.17	69 14 46.5	590	651(36)	284(29)	0.8(.2)	579(46)	125(31)	<0.3	0.2(.04)	
0655+699	564	.21	06 55 56.89	69 56 04.2	1020	1067(55)	437(30)	0.8(.1)	694(87)	239(52)	0.4(0.1)	0.2(.04)	
0725+267	584	.23	07 25 34.60	26 44 14.4	310	315(20)	127(16)	0.8(.2)	<60	<76	4.0(2.0)	2.2(1.0)	2
0727+409	585	.10	07 27 24.07	40 56 10.8	380	362(19)	518(37)	-0.3(.1)	399(35)	600(85)	<0.3	<0.1	
0752+639	600	.20	07 52 21.39	63 55 59.9	240	279(15)	303(17)	-0.1(.1)	282(19)	232(35)	<0.3	<0.1	6
0946+295	876	.28	09 46 53.88	29 34 54.2	180	170(10)	126(9)	0.3(.1)	179(19)	126(19)	<0.3	<0.1	
1010+350	951	.15	10 10 54.73	35 00 44.7	540	512(27)	577(34)	-0.1(.1)	534(35)	555(57)	<0.3	<0.1	
1045+352	1099	.23	10 45 45.84	35 13 16.8	630	633(33)	256(16)	0.8(.1)	618(41)	177(23)	<0.3	0.1(.03)	
1143+500	1374	.17	11 43 04.23	50 02 47.4	580	636(27)	162(12)	1.2(.1)	-	-	4.1(1.5)	4.1(.5)	2,3,5
1532+742	2105	.27	15 32 12.76	74 12 30.9	-	150(12)	51(7)	1.0(.2)	93(16)	<35	0.4(0.1)	>0.1	
1559+157	2147	.30	15 59 06.85	15 45 20.7	470	457(47)	153(45)	1.0(.4)	164(41)	<50	0.6(0.1)	>0.2	
2319+272	2584	.06	23 19 31.98	27 16 19.1	860	921(51)	1080(59)	-0.1(.1)	885(49)	1041(31)	<0.3	<0.1	
2335+270	2634	.24	23 35 10.62	27 00 59.7	190	193(11)	69(8)	0.9(.2)	-	-	<1.8	<1.5	2,4
2337+264	2634	.49	23 37 58.28	26 25 18.8	950	964(49)	593(33)	0.4(.1)	1025(62)	622(39)	<0.3	<0.1	

Notes to Table 2.—(1) 91 m flux density may be confused by the presence of 3C 66B. (2) Short baseline flux density and angular sizes from model fit. (3) Visibility varied significantly with hour angle on long baselines. (4) Not observed on long baselines. (5) Total 2695 MHz flux density (col. [6]) from Kellermann *et al.* 1968. (6) Total 2695 MHz flux density from unpublished observations with the 91 m telescope.

The angular extents of the other sources have been estimated from the relation

$$a = c[\ln (S_{85}/S_{45})]^{1/2} ,$$

where a is the equivalent diameter of a circular Gaussian source and c is a constant characteristic of the average projected long baseline ($\sim$25 km). At 2695 and 8085 MHz, c equals 0.6″ and 0.2″, respectively.

Table 3 gives the detailed results of the models fitted to the short baseline data.

Column (1) gives the component name.

Column (2) gives the observing frequency.

Column (3) gives the total flux density of the component from the model fit, along with its estimated error.

Columns (4) and (5) give the 1950.0 right ascension and declination, respectively.

Columns (6), (7), and (8) give the major diameter, minor diameter, and position angle, respectively, of the elliptical Gaussian fit, along with their associated errors. The diameters are given in arcseconds. The position angle is in degrees east from north.

Table 4 gives the optical positions of all objects found within 6 arcseconds of the radio centroid on the sky survey prints.

Column (1) gives the radio source name.

Column (2) gives a brief description of the optical object.

Columns (3) and (4) give the 1950.0 right ascension and declination, respectively, of the optical object measured from the E prints.

Column (5) gives the difference in arcseconds between the radio and optical positions.

Figure 1 (Plate 9) gives finding charts from the Sky Survey E prints (unless otherwise noted). The scale is identical for all charts and is noted in Figure 1.

Finding charts have been previously published for 1010+350 by Folsom *et al.* (1971) and for 2319+272 by Riley (1975). A finding chart for 0219+428 has been published by Wills and Wills (1974) and has not been included here.

TABLE 3

MODEL FIT PARAMETERS

Source	Freq.	Flux Density	Right Ascension	Declination	Major Axis	Minor Axis	Position Angle
0315+416 A	2695	210(19)	03 15 29.15	41 38 43.9	<2.6	<2.1	-
	8085	66(8)			1.6(.5)	<1.0	105(15)
B	2695	111(17)	03 15 29.41	41 38 43.5	<4.4	<4.1	-
	8085	33(7)			1.2(1.)	<1.2	99(40)
0725+267	2695	315(20)	07 25 34.60	26 44 14.4	3.2(1.)	2.7(.5)	-
	8085	127(16)			2.2(.8)	1.4(.3)	168(28)
1143+500 A	2695	292(11)	11 43 04.21	50 02 49.6	<1.2	<1.0	-
	8085	75(9)			1.0(.5)	<1.2	32(40)
B	2695	344(11)	11 43 04.24	50 02 45.5	<2.0	<2.0	-
	8085	87(9)			<4.8	<0.7	-
2335+270	2695	193(11)	23 35 10.62	27 00 59.7	<1.6	<1.0	-
	8085	69(9)			<1.8	<0.8	-

IV. DISCUSSION

Although all of the sources in Table 2 have small angular diameters, only seven have firm optical identifications, and none are identified with galaxies. Since at the distances of all the observed clusters all known radio galaxies would be easily visible on the Palomar Sky Survey prints, either these sources are random coincidences with the clusters or they are a new class of objects, at least for rich clusters. Two consistency tests can be made with the first hypothesis. First, we would expect background (or foreground) coincidences to be distributed randomly with respect to the cluster centers. Second, we would not expect the number of background sources to greatly exceed the total number of random coincidences predicted for all

TABLE 4

OPTICAL OBJECTS IN RADIO FIELDS

Source	Optical Description		Right Asc.	Declination	Sep.	ID
0219+428	$15^{\mathrm{m}}.5$	BO	$02^{\mathrm{h}}19^{\mathrm{m}}30^{\mathrm{s}}.03$	$42^{\circ}48'29''.9$	$0''.6$	YES
0725+267	19^{m}	G	07 25 34.66	26 44 17.9	3.6	?
0727+409	18^{m}	NO	07 27 24.13	40 56 11.5	1.0	YES
0752+639	18^{m}	G	07 52 20.68	63 56 03.2	5.7	?
0946+295	19^{m}	BO	09 46 53.92	29 34 55.3	1.2	YES
1010+350	19^{m}	BO	10 10 54.77	35 00 45.0	0.6	YES
2319+272	19^{m}	RO	23 19 31.85	27 16 19.5	1.8	YES
2335+270	19^{m}	RO	23 35 10.66	27 00 59.9	0.6	YES
2337+264	20^{m}	RO	23 37 58.24	26 25 19.4	0.8	YES

Notes to Table 4.—Magnitudes have been estimated from the E prints. BO = Blue object; NO = Neutral object; RO = Red object; G = Galaxy.

0219+428.—Optical identification from Wills and Wills 1974.

0727+409.—Two objects appear coalesced on the reproduction in Fig. 1. The identification is with the fainter of the two.

0752+639.—There may be an extended object at the plate limit, located within 2″ of the radio position.

0946+295.—Appears to be approximately 17th mag on the O print.

1010+350.—In addition to the BO identification, there is an extended red object approximately 10″ away.

TABLE 5

DISTRIBUTION OF SOURCE SEPARATIONS FROM THE CLUSTER CENTERS

Distance from Cluster Center in Abell Radii		0–0.1	0.1–0.2	0.2–0.3
> 5″	Number found	34	10	9
	Number expected ($N = 53$)	6	18	29
< 5″	Number found	2	3	4
	Number expected ($N = 9$)	1	3	5

clusters. For such tests, we must consider only the sources which meet all three primary criteria. The distribution with respect to the cluster centers is summarized in Table 5. As can be seen, the 53 sources in our sample with structure greater than 5″ are significantly bunched toward the cluster centers. However, the nine compact sources are not distributed significantly differently from the expected random distribution.

The second test depends more critically on selection effects in choosing the sample. Using the log N – log S_{2700} estimates of Fomalont *et al.* (1975), we find that for the 1280 Abell clusters north of 20°, 12 (± 4) random background sources which meet our three well-defined criteria are expected. Of these, 25 percent (3) are expected to have flat spectra and 75 percent (9) should have steep spectra (Balonek *et al.* 1975). Based on this division of spectra and the estimated completeness discussed above, we expect to find about seven sources with steep spectra and one with a flat spectrum by chance. This compares with five compact sources with steep spectra and four with flat spectra actually found in the well-defined sample. Thus this test is consistent with the hypothesis that the sources with steep spectra are random coincidences, while a small but not very significant excess of sources with flat spectra is found.

a) *Sources with Steep Spectra*

It seems best to conclude that most or all of the compact sources with steep spectra are likely to be very distant background objects. In addition to the negative evidence given above, two other arguments can be made for this hypothesis. First, none of these sources in the well-defined sample were found to have firm optical identifications, even though they are very compact and have very accurate radio positions. As discussed below, 0725+267 may be an exception. Second, all five of the sources in the well-defined sample were resolved on the long baseline. This may suggest that these sources are very distant radio galaxies such as those found on deep plates by Wlérick *et al.* (1971), Kristian *et al.* (1974), and Longair and Gunn (1975).

b) *Sources with Flat Spectra*

The situation with respect to sources with flat spectra is less clear, mainly because of the incompleteness of the sample. A small excess (4 detected, 1 expected) exists in the well-defined sample. Also, three of the four sources have firm optical identifications. However, the number of sources is too small to imply any statistical conclusions. Certainly, the cosmological or relatively local nature of quasars with flat spectra cannot be decided on the basis of this sample of four sources. Only one of these sources has a measured redshift (1010+350, $Z = 1.4141$; Wills and Wills 1975). It is important to determine the optical properties of the other identifications both in and out of the well-defined sample. But basically, a more complete sample is necessary to define the nature of these sources. Further observations are under way to achieve this goal.

c) *Individual Sources*

1. 0315+415 (*3C83.1A*), *1143+500*.—Both of these sources are classical doubles with spectral indices steeper than 1.0. These properties may suggest that both sources could be radio galaxies similar to 3C 295 and Cygnus A, only much more distant.

2. 0646+692, 0655+699, 1045+352, 1532+742, and 1559+157.—None of these sources have optical identifications, while all have $0.8 \leq \alpha \leq 1.0$. All have angular sizes of 0.6″ to 0.1″. If these sources are associated with typical radio galaxies, they must have $z \gtrsim 0.5$ for the galaxy images not to be visible on the sky survey prints. Assuming a standard Friedmann cosmology with $q_0 \approx 0.1$ and $H_0 \approx 50$ km s^{-1} Mpc^{-1}, if $0.5 < z < 5$, scales of a few tenths of an arcsecond correspond to linear sizes of a few kiloparsecs. Thus these sources may be events confined to the nuclear regions of very distant galaxies.

3. 2335+270.—This source appears similar to those listed under (2) above, except that it has an optical identification with a 19th red object. Also, it has not been observed on the 45 foot baseline, so the best limit on its angular size is 1.2 arcseconds.

4. 0725+267.—This source, with a spectral index of 0.8 and an extent of 2 to 3 arcseconds, may be identified with a 19th mag galaxy. However, the radio centroid is separated from the optical image by approximately 4 arcseconds, and the identification is therefore questionable. If the two objects are physically associated, and in the cluster, then the radio extent would be on the order of 10 kpc, assuming the same cosmological model as above and the redshift implied by the magnitude of the tenth brightest galaxy (Abell 1958).

5. 0727+409, 0752+639, 0946+295, 1010+350, and 2319+272.—These sources all have flat spectra and are unresolved on the 45 foot baselines. All except for 0752+639 have reliable optical identifications.

6. 2337+264.—This source has an unusual spectrum which peaks between 1400 and 2695 MHz and falls off fairly rapidly at both higher and lower frequencies (Colla *et al.* 1972; Owen 1974). It is unresolved and has an optical identification with a faint RSO.

7. 0219+428 (3C 66A).—This source is known to be identified with a 15.5 mag BL Lacertae type object (Wills and Wills 1974). This source has a flat spectrum at centimeter wavelengths but rises below 1000 MHz (Macdonald *et al.* 1969; Northover 1973). Our observations suggest that the source consists of a small component, less than 0.1″, and a more extended component, ~0.5″, with a steeper spectrum. The much larger flux density observed with the 91 m telescope for this source may result from confusion by 3C 66B or possibly from variations in 3C 66A itself.

V. CONCLUSIONS

Out of a total of 94 radio sources in the directions of rich Abell clusters, only 16 were found to have total angular sizes less than 5″. At most, only one of these sources is associated with an optically bright radio galaxy in these clusters. Of the more extended sources in the sample, the vast majority are associated with dominant cluster galaxies. This suggests that all or almost all radio galaxies in rich clusters have extended structure greater than 10 kpc. Our observations are consistent with the hypothesis that the compact sources with steep spectra are very distant radio galaxies. The situation with respect to sources with flat spectra is less certain and will require further radio and optical studies.

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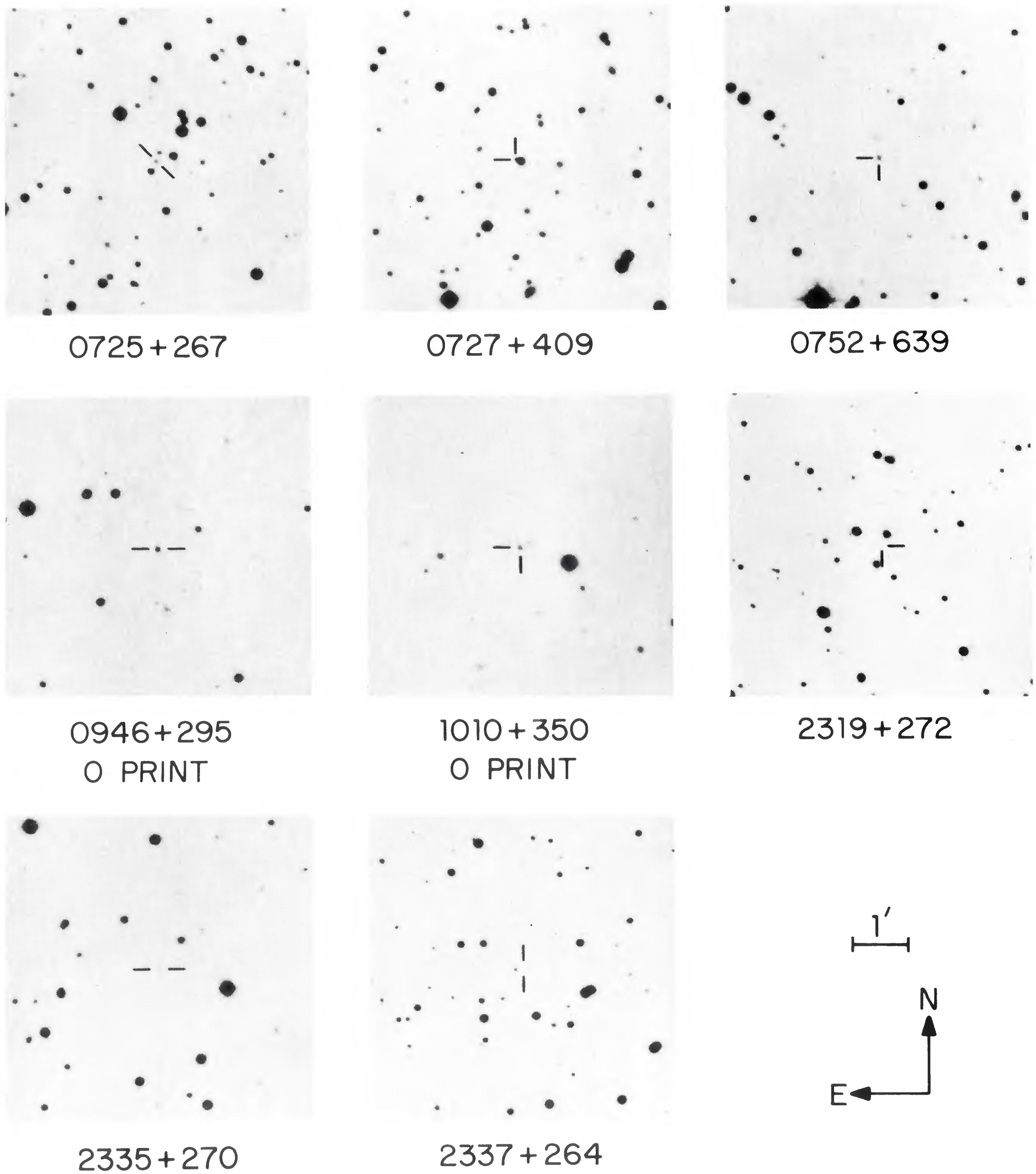

FIG. 1.—Finding charts for the identified sources

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