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UNIDENTIFIED IRAS SOURCES: ULTRAHIGH LUMINOSITY GALAXIES

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ABSTRACT

Optical imaging and spectroscopy has been obtained for six of the high galactic latitude infrared sources reported by Houck, *et al.* (1984) from the IRAS survey to have no obvious optical counterparts on the POSS prints. All are identified with visually faint galaxies that have total luminosities in the range $5 \times 10^{11} L_{\odot}$ to $5 \times 10^{12} L_{\odot}$. This luminosity emerges virtually entirely in the infrared. The origin of the luminosity, which is one to two orders of magnitude greater than that of "normal" galaxies, is not known at this time.

INTRODUCTION

The high-galactic-latitude, low-color-temperature point sources discovered in the IRAS survey that have no obvious optical counterparts on the Palomar Observatory Sky Survey (POSS)(Houck, *et al.* 1984; henceforth paper 1) are among the mission's most interesting discoveries. Because of the relative limits of the IRAS and POSS surveys, these sources must have infrared to visible luminosity ratios greater than 50, compared with values between 0.1 and 1 for normal galaxies (de Jong, *et al* 1984).

Aaronson and Olszewski (1984) have identified four of the sources as very red galaxies and have measured the redshift of one of them, 0422−009. In this paper we identify six of the nine fields reported in paper 1 as galaxies and report on optical photometry and spectroscopy leading to luminosities for five of the objects. In all, eight of the original nine objects from paper 1 have been shown to be extragalactic. One source reported in paper 1, 0412+085, has proven, upon closer examination of the IRAS data, to be a faint example of "infrared cirrus" (Low, *et al.* 1984) and will not be discussed further in this Letter.

One interpretation of these objects is that they are examples of the infrared-bright galaxies found in the IRAS survey (Soifer, *et al.*, 1984). Such an interpretation would place them in the range of the most extreme "infrared galaxies" currently known. Peculiar high-latitude Galactic objects, while an unlikely explanation, would also be quite interesting.

OBSERVATIONS

Observations of six of the blank field IRAS sources described in paper 1 were obtained in January and June 1984 using the PFUEI camera/spectrograph system (Gunn and Westphal, 1981) mounted at the prime focus, and the double spectrograph (Oke and Gunn, 1982) mounted at the Cassegrain focus of the 5m

Hale telescope. An 800×800 Texas Instruments CCD served as the detector in the PFUEI, while a similar detector was used for the double spectrograph observations.

Direct imaging of six of the fields from paper 1, 0358+223, 0404+101, 0413+122, 1703+049, 1712+100, and 1732+239 were obtained in the g (5000Å), r (6600Å), and i (7900Å) filters of Thuan and Gunn (1976) and Wade, *et al.* (1979); exposure times varied from 100 to 400 seconds. The seeing during the January and June observations were ~2" and ~1.3" FWHM; respectively. The internal scatter of the standard star photometry indicates a photometric accuracy of ~2% for the January data and 5% for the June observations. The field flattening, calibration procedures and the transformation to photoelectric magnitudes are described in Schneider, Gunn, and Hoessel (1983).

In all cases there are one or more obvious candidates for an optical counterpart to the infrared source, and without exception these counterparts are galaxies. At the magnitudes of the galaxies found within the IRAS position uncertainty ellipses, the probability of a random galaxy falling within the ellipse must be calculated. From galaxy counts of Tyson and Jarvis (1979), the probability of finding the faintest identified galaxy (0404+101) within the 3 σ IRAS position is about 0.1 (assuming the number counts of Tyson and Jarvis at J are equivalent to the g magnitudes used here) and is significantly less for the brighter galaxies. Coupling this with the fact that the positional agreements appear excellent, and all appear to be emission line galaxies, leads to the conclusion that the proposed identifications are quite firm. The rms positional difference between the IRAS and optical positions is 13", as compared to a 1 σ positional error of 15" for IRAS sources identified with galaxies having well measured optical positions.

The photometric measurements of the candidate identifications were made using circular diaphragms, and are listed in Table 1. The colors are independent of diaphragm size, indicative of accurate sky subtraction. The statistical uncertainties associated with the magnitudes and colors are typically less than 0.05 mag. The r magnitudes are total magnitudes; in the case of the galaxies in close groups the diaphragms used in obtaining total photometry proved to be rather subjective.

The fields are located in the direction of significant extinction in the Galaxy. The extinction for each field was determined from Burstein and Heiles (1982); the corrections for this filter system are given in Schneider, Gunn, and Hoessel (1983). The absorption in the r band ranges from 0.2 mag for the objects at 17^h to 0.5 mag for 0413+122. The flux densities but not the magnitudes listed in table 1 have been corrected for the effects of Galactic extinction.

The quantity νf_ν (5000Å) is taken as a measure of the "visible flux" for these objects and is used for comparison with the infrared flux. The integrated infrared flux was determined by fitting the 60 and 100 μm observations with a Planck curve with an emissivity proportional to frequency. (See discussion below.) The infrared fluxes are those reported in paper 1 corrected to the June 1984 IRAS calibration (Aumann, *et al.* 1984). The measure of the infrared flux obtained by fitting the observed data to a blackbody convolved with an emissivity law gives a larger flux than the estimate of νf_ν(60μm) used by Soifer *et al.* (1984), and is a better estimate of the true bolometric flux. In most cases this value is roughly 50% larger then previous estimates, but in the case of 0404+101 the color temperature is so low (26 K) that the difference is a factor of three.

Spectra were obtained for the optical counterparts of 0404+101, 0413+122, 1703+049, 1712+100, and 1732+239. In the case of 0404+101 and 0413+122, the spectra were acquired with the PFUEI. A 400 line/mm transmission grating and a 1.5" slit yield spectra from 4500Å to 8500Å at 25Å resolution. For the other objects, spectra from 5500Å to 8000Å with 6Å resolution were obtained with the double spectrograph, using a 316 line/mm grating and a 1" slit. Integration times of 2000 - 2500 seconds were used for all objects. Unambiguous emission line redshifts were obtained for all the objects but 0404+101, and are reported in table 1. These data will be given more fully elsewhere.

RESULTS

Figure 1 displays images of the central regions of the fields discussed above. Below we briefly summarize the optical data for all these sources.

0358+223 - The POSS image (paper 1, Aaronson and Olszewski, 1984) shows a possibly non-stellar image at the IRAS position. The CCD image (fig. 1a) demonstrates clearly that this object is a galaxy, associated with a faint jet-like structure that extends ~ 15" to the west of the core object. No spectrum was obtained for this candidate.

0404+101 - The POSS prints do not show any objects in the IRAS error ellipse. CCD images (fig. 1b, and that of Aaronson and Olszewski, 1984) show a galaxy within 9" of the IRAS position. The galaxy is almost spiral-like but somewhat peculiar. Several significantly fainter galaxies are within 100" of the IRAS position. The identification of the IRAS source with galaxy a is based on its position agreement, its appearance as an almost spiral galaxy, and the fact that it is significantly brighter than any other object in the error ellipse. The spectrum does not have a sufficient signal-to-noise ratio to yield an unambiguous redshift, but given the similarities with the other objects, the identifications of H alpha emission at 7790Å, NaI absorption at 7000Å, and CaII absorption at ~4690Å yield a consistent and plausible redshift of 0.187. Until a higher quality spectrum is obtained, this must be regarded as a tentative redshift.

0413+122 - The POSS prints again did not show any objects in the IRAS error ellipse. The CCD images of Aaronson and Olszewski (1984) and ours (fig. 1c) shows a chain of three 19th-magnitude galaxies, separated by ~5", very near the IRAS position. The spectrum of object a (G3 in the notation of Aaronson and Olszewski) has an unambiguous redshift of 0.203 determined from strong emission lines of H alpha, H beta, and [OIII]. A much lower confidence redshift of 0.204 can be assigned to the other objects in the error box, based on a tentative identification of H alpha in emission very near the same wavelength as in object a. We make the identification of galaxy a with the IRAS source because of its strong emission line spectrum in the visible, but the positional uncertainties of the IRAS source are sufficiently large that the other galaxies in the group could be the IRAS source. Aaronson and Olsewski suspected that object b (G2 in their notation) is the IRAS source on the basis of its disturbed appearance, but its Hα flux is a factor of 3 weaker than that of a.

1703+049 - There are five objects in the error box on the POSS image. The CCD image (fig. 1d) and spectra obtained of all of these objects reveal that the brighter ones are clearly stars, and the most likely identification is with the emission line galaxy indicated as object a in the figure. The spectrum of this object shows strong emission lines of H alpha, [NII], and [SII], and yields a redshift of 0.118.

1712+100 - The POSS image shows four objects in the error box. Beichman, *et al.* (1984) have detected radio emission from a position 21" from the IRAS position of this source (well within the IRAS positional uncertainty for this source), and the object indicated in figure 1e is within 1" of the position of the radio source. The spectrum of this galaxy contains strong H alpha, [NII], and [SII] in emission and is undoubtedly the optical counterpart. The redshift from the emission lines is 0.114.

1732+239 - The POSS image shows multiple objects in the error box. The object indicated in figure 1f has a very similar emission line spectrum to 1703+049 and 1712+100 and is the likely identification. The redshift of this object is 0.144. The other objects within the error ellipse showed stellar-like spectra.

DISCUSSION

The observations described above, and the results of Aaronson and Olszewski (1984), show that all of the "unidentified" IRAS sources reported in Paper I that are bona fide point sources at the IRAS resolution ($\lesssim$ 30") can be identified with galaxies. While this short list of unidentified sources is by no means inclusive of all high latitude "unidentified" IRAS sources, this result is consistent with the previous suggestions (paper 1, Aaronson and Olszewski) that the majority of such sources are indeed galaxies that represent even more extreme examples of infrared-to-visible energy outputs than found in the infrared selected galaxy sample of Soifer, *et al.* (1984).

The morphology of the identified objects is quite interesting. For seven of the eight identifications, the optical image identified with the IRAS source is a peculiar galaxy or is in a group of galaxies. Aaronson and Olszewski (1984) report that 0422+009 has an odd morphology and seems to be in a small cluster while the objects reported here have been described above. These findings are consistent with the results of Lonsdale, *et al.* (1984) and Soifer, *et al.* (1984) that suggest that galaxy interactions are associated with a significant fraction of the extreme infrared bright galaxies found by IRAS.

The colors of the optical galaxies are not extreme, compared to normal galaxies. In most cases the optical counter part of the IRAS source has a g-r color consistent with, or bluer by $\lesssim$ 0.2 mag than, that of a giant elliptical galaxy at that redshift (Schneider, Gunn, and Hoessel, 1983). Only one object, 0404+101, has a color as much as 0.4 mag bluer than that of an elliptical galaxy at the appropriate redshift. In no case does the galaxy color corrected for Galactic extinction appear significantly affected by extinction, as none of the galaxies are redder than the reddest normal galaxies, i.e. giant elliptical galaxies.

The absolute visual magnitudes in Table 2 are within the range found for normal galaxies. However, the relative infrared to optical flux ratios are far larger than those of normal galaxies (de Jong, *et al.*, 1984), ranging from approximately 30 to 500. These objects appear to be extreme examples of the infrared bright galaxies discussed by Soifer, *et al.* (1984).

It is important to note that the present study, while involving a small sample of objects, shows that the large infrared to optical ratios result from an enormous infrared excess, rather than from the nearly complete conversion of the optical light of a normal galaxy to infrared radiation. The most simplistic model of these objects would consist of a galaxy containing a "near normal" stellar population, plus a powerful infrared source.

The luminosity of the infrared source is extremely large, ranging from 5×10^{11} $L_\odot$ to 5×10^{12} $L_\odot$, roughly two to three orders of magnitude larger than the infrared emission from a "normal" spiral galaxy (de Jong, *et al.*, 1984) and roughly one to two orders of magnitude larger than the total luminosities of such galaxies. Indeed these luminosities are comparable to the luminosities of quasars and the most luminous Seyfert galaxies. However, unlike optical, radio, ultraviolet, or X-ray selected objects, these objects emit the overwhelming bulk of their luminosity in the infrared.

The energy distributions of these extreme infrared galaxies from the optical through the radio resemble those of well known infrared bright galaxies such as M82 and NGC 1068, in having very strong peaks in flux density in the far infrared. We will therefore assume that the emission mechanism producing the infrared emission is thermal radiation by dust. The major unknown is the mechanism by which the luminosity is initially generated. Unfortunately, the relatively small amount of optical radiation (including the line emission) emerging from these objects may not be representative of the physical conditions inside the infrared sources, and the final determination of these important properties may have to await spectroscopic observations in the infrared.

While the origin of the infrared luminosity in these galaxies remains uncertain, it is perhaps striking that there is no evidence for a dominant active nucleus in any of these galaxies. Joseph, Wright and Wade (1984), Emerson, *et al.* (1984), and Rieke *et al.* (1984) have recently presented evidence that Arp 220 and NGC 6240, are powered by energetic starbursts, and our data are consistent with a similar interpretation for the "unidentified" IRAS objects. There is also evidence that Arp 220 contains an active nucleus (Rieke *et al.* 1984 and Norris 1984). If luminous young stars are indeed powering the luminosities of "unidentified" galaxies, the rate at which interstellar matter is being converted into stars is 40 - 400 solar masses per year (Scoville and Young, 1983). In this case such galaxies would process a galaxy mass of interstellar matter into stars in 10^8 to 10^9 years. If this amount of matter is actually being converted in these events, then clearly such an event must be a major turning point in the entire evolution of the galaxy. Whether a significant fraction of galaxies pass through such a stage will require the determination of the space density of these spectacular events from analysis of the entire IRAS survey.

SUMMARY

These observations, plus the results of Aaronson and Olszewski (1984), establish that all eight bona fide IRAS point source "blank" field objects from paper 1 are identified with galaxies. Five, and probably six, of these galaxies are at redshifts in the range 0.1 to 0.2. These galaxies represent a class of extremely luminous galaxies, emitting as much energy as the most extreme Seyfert galaxies, comparable even to the luminosities of quasars. The nature of the underlying energy source is as yet not firmly established.

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Table 1 - Observed Properties of IRAS "Unidentified" Sources

Object	Redshift	Observed Magnitudes			Reddening	Infrared Flux Densities[a]	
		r	g-r	r-i	E(B-V)	60μm	100 μm
		mag	mag	mag	mag	Jy	Jy
0358+223		17.4	0.89	0.50	0.15	0.58	1.3
0404+101	0.187[b]	19.5	1.17	0.76	0.24	0.48	3.7
0413+122	0.203	20.0	0.54	0.67	0.24	1.87	3.0
0422+009	0.154[c]	17.49[c]		0.80	0.09	0.58	2.7
1703+049	0.118	18.9	0.47	0.49	0.10	0.61	1.5
1712+100	0.113	18.1	0.49	0.56	0.09	0.55	1.7
1732+239	0.144	19.2	0.47	0.53	0.09	0.54	1.6

[a]flux densities corrected from those in Houck, et al. (1984) by June 84 IRAS calibration factors (Aumann, et al. 1984).

[b]uncertain

[c]from Aaronson and Olszewski (1984), magnitudes on Kron-Cousins systems.

Table 2 - Derived Properties of IRAS "Unidentified" Sources

Object	Fluxes		Ratio	Color Temp	Absolute Luminosities[a]	
	F_{IR} [b]	F_{OPT} [c]	F_{IR}/F_{OPT}		M_t [d,e]	L_{IR}
	$W/m^2 \times 10^{-14}$	$W/m^2 \times 10^{-15}$		K	mag	$\times 10^{12} L_\odot$
0358+223	4.8	1.6	30	44		
0404+101	15	0.22	660	26	-20.7	4.8
0413+122	13	0.27	480	53	-21.1	4.6
0422+009	9.1	1.0	90	31	-21.5[f]	1.8
1703+049	5.3	0.52	100	42	-20.3	0.59
1712+100	5.7	1.1	50	38	-21.0	0.57
1732+239	5.5	0.38	150	26	-20.5	0.96

[a]assuming $H_o = 60$ km sec $^{-1}$ Mpc^{-1}, $q_o = 0$.

[b]calculated fitting a $\nu B_\nu(T)$ function to the 60 μm and 100 μm data, and integrating this function over all frequencies.

[c]Calculated as νf_ν (5000Å)

[d]k correction taken from Schneider, Gunn, and Hoessel, (1983) assuming intrinsic colors are those of a giant elliptical galaxy.

[e]No attempt has been made to correct for extinction internal to the IRAS source.

[f]assuming m_b as given by Aaronson and Olszewski (1984).

BIBLIOGRAPHY

Aaronson, M., and Olszewski, E. W. 1984, *Nature*, 309, 414.

Aumann, H. H., et al. 1984, in preparation.

Beichman, C. A., Wynn-Williams, G. C., Miley G 1984, private communication.

Burstein, D., and Heiles, C. 1982, *Astron. J.*, 87, 1165.

de Jong, T., *et al* 1984, *Ap. J. (Letters)*, 278, L67.

Emerson, J. P., Clegg, P. E., Gee, G., Cunningham, C. T., Griffin, M. J., Brown, L. M. J., Robinson, E. I., Longmore, A. J., 1984, *Nature*, 311, 37.

Gunn, J. E., and Westphal, J. A. 1981, *Proc. SPIE*, 290, 16.

Houck, J. R., et al. 1984, *Ap. J. (Letters)*, 278, L63 (Paper 1).

Joseph, R. D., Wright, G. S., and Wade, R., 1984, *Nature*, 311, 132.

Lonsdale, C. J., Neugebauer, G., and Soifer, B. T. 1984, *BAAS*.

Low, F. J., et al. 1984, *Ap. J. (Letters)*, 278, L19.

Norris, R. P., 1984, preprint.

Oke, J. B., and Gunn, J. E. 1982, *Pub. A. S. P.*, 94, 586.

Rieke, G. H., Cutri, R. M., Black, J. H., Kailey, W. F., McAlary, C. W., Lebofsky, M. J. and Elston, R., 1984, *Ap. J.*, in press.

Schneider, D. P., Gunn, J. E., and Hoessel, J. G. 1983, *Ap. J.*, 264, 337.

Scoville, N. Z., and Young, J. S. 1983, *Ap. J.*, 265, 148.

Soifer, B. T. *et al* 1984, *Ap. J. (Letters)*, 278, L71.

Thuan, T. X., and Gunn, J. E. 1976, *Pub. A. S. P.*, 88, 543.

Tyson, J. A., and Jarvis, J. F. 1979, *Ap. J. (Letters)*, **230**, L153.

Wade, R. A., Hoessel, J. A., Elis, J. H., and Huchra, J. P. 1979, *Pub. A. S. P.*, **91**, 35.

Figure Captions

Figure Caption 1: The r images of 0358+223, 0404+101, 0413+122, 1703+049, 1712+100, 1732+239 obtained with the 5m telescope. The IRAS position is indicated and the identified galaxy is either indicated as object a or is the only object close to the IRAS position.

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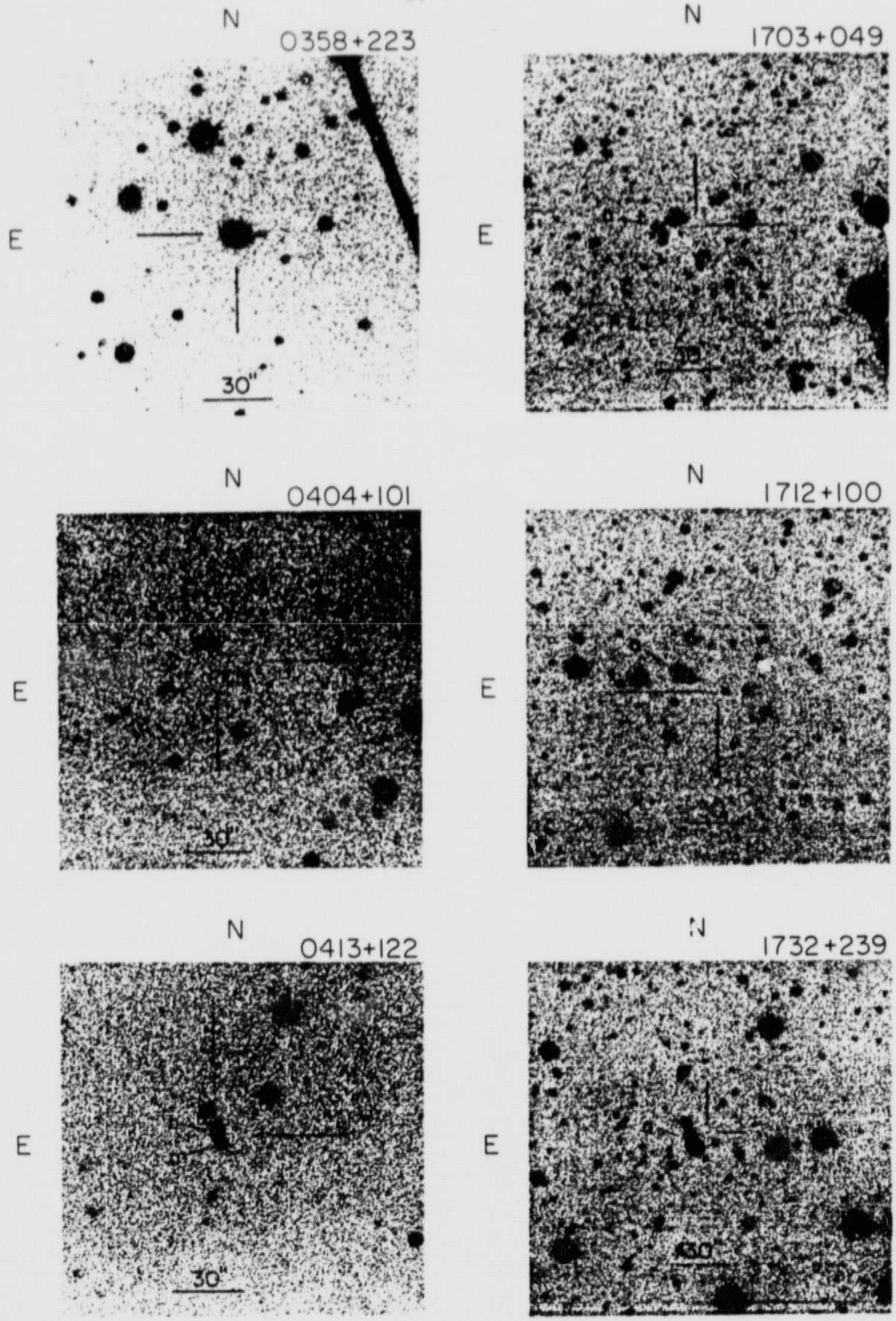
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