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INFRARED COLOR-SELECTED QUASARS AND SEYFERT 1 GALAXIES[1]

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ABSTRACT

To search for high-luminosity galaxies and quasars, a large sample of warm extragalactic objects (WEO) was selected from the *IRAS Point Source Catalog.* All sources in an area of 14,000 deg^2 were subjected to an IR color requirement, $F(25)/F(60) > 0.25$, optimized to find quasars. Based on optical spectra and morphology, the extragalactic sample of 187 sources contains 12 quasars, 27 Seyfert 1, 73 Seyfert 2, and 65 other emission-line galaxies; 10 sources are not yet classified. Seven of the confirmed quasars were discovered by the *IRAS* survey and indicate that the local space density of these objects may be significantly higher than deduced from current optical searches. Comparison of the distributions of IR luminosity for the quasar and S1 samples shows noticeable differences. Larger, more complete samples of these systems are needed to confirm the suggestion of a bimodal luminosity distribution reported here and to refine our knowledge of space densities for these related populations.

Subject headings: galaxies: general — infrared: sources — quasars

I. INTRODUCTION

It was recognized early in the *IRAS* mission that IR color selection would be important in finding specific classes of objects. Using "quick look" data, G. Miley and R. de Grijp selected a set of "warm" sources based on their relatively high ratios of flux density measured at 25 and 60 μm, $F(25)/F(60)$. A list of 54 such sources was published in *IRAS Circular 11* (1984). De Grijp *et al.* (1985) showed that about 70% of their sample are Seyferts. Neugebauer, Soifer, and Miley (1985) also showed that 116 of 186 known Seyferts were detected by *IRAS*; the flux ratio $F(25)/F(60)$ for 71 Seyferts ranges from 0.07 to 1 and is broadly distributed around a median of 0.38. The range for a flux-limited sample, $F(60) > 2$ Jy, of *IRAS* galaxies is 0.04–0.40 with a median of 0.14 (Smith *et al.* 1987), and the Seyfert population comprises only a few percent of the total. When Neugebauer *et al.* (1986) published an extensive list of known quasars detected by *IRAS* it became apparent that a range of $F(25)/F(60)$ from 0.25 to about 1 should include almost all quasars. Even though the 60 μm flux in many cases is strongly affected by cool emission from star-forming regions outside the active nucleus, the 25 μm flux can be even more strongly influenced by activity in the nucleus and serves as an indicator of either warm dust heated by an intense radiation field or nonthermal emission.

The first QSO discovered by *IRAS* (Beichman *et al.* 1986) and the ultraluminous galaxy IRAS 09104+4109 (Kleinmann and Keel 1987) also show strong flux at 25 μm relative to 60 μm when compared to typical *IRAS* galaxies. To investigate the possibility of finding more quasars or other highly luminous objects in the *IRAS Point Source Catalog* (1985, hereafter PSC), we defined a large sample of color-selected "warm extragalactic objects" (WEO) for further study (Kleinmann *et al.* 1987). We now have optical spectra suitable for classification and redshift measurement for 177 of 187 WEO in nearly 14,000 deg^2 of sky. No more objects similar to IRAS 09104+4109 have been found, so it remains the most luminous galaxy known. However, a significant number of new QSOs have been discovered, and it is now possible to assess what this implies for the local space density of QSOs. The characteristics of these new IR-selected QSOs can be compared to those of QSOs found by other methods and to Seyferts with similar IR colors.

Combining optical spectroscopy, photometry, and imagery with improved *IRAS* photometry we have separated the WEO sample into four classes, quasars, Seyfert 1, Seyfert 2, and other emission-line galaxies, and have computed both IR and optical luminosities. IR color selection reveals ultra–high-luminosity objects in each class, but this initial *Letter* treats only those objects in the subset of the WEO sample having spectra classified as QSO/S1 because of clear evidence of a broad emission line region.

II. THE WEO AND QSO/S1 SAMPLES

The selection process was tuned to reject galactic objects and to include all known quasars, while utilizing the minimum number of constraints. Using the PSC (Version 2), an area of 14,400 deg^2 was chosen, such that $|b| > 30°$ to facilitate rejection of galactic sources and $\delta > -30°$ for access from northern observatories. Of 11,659 sources detected at 60 μm, only 2,063 were detected at 25 μm. By applying the IR color selection, $0.25 < F(25)/F(60) < 3$, and associations between *IRAS* sources and known stars, we reduced the list of WEO candi-

[1] Work reported here is based on observations obtained with the MMT, a joint facility of the Smithsonian Institution and the University of Arizona.

dates to 248. The accuracy and signal-to-noise ratio of the *IRAS* observations were then improved by coaddition of all available survey scans using the ADDSCAN program at IPAC.[2] The improved photometry altered the colors somewhat and reduced the sample to 194 sources. As explained below, optical identifications and spectra were obtained for all but 10 objects not already identified with published sources. After removal of seven stars, 187 candidate WEO remain of which 177 are confirmed WEO.

The WEO list, defined above, is a color-limited sample where the limit is a function of flux, giving rise to variation in completeness with the brightness and intrinsic color distributions of the sources. The combination of our flux ratio limit, $F(25)/F(60) > 0.25$, and the completeness limits of the PSC (Beichman *et al.* 1985) means that for sources fainter than 2 Jy at 60 μm the WEO sample is incomplete. An estimate can be made by fitting the relation $N[F(60)]$ proportional to $F(60)^{-1.5}$ for the 37 sources brighter than 2 Jy. By extrapolation this implies that there should be 300 sources brighter than 0.5 Jy. There are only 187, indicating a completeness of about 60%. Work now in progress should refine this estimate of the incompleteness.

III. NEW OBSERVATIONS

Optical identifications, based on PSC positions, were deduced by inspection of the POSS except in a few cases where the choice was made after spectra were examined. Positions of all candidates accurate to about 2″ were measured on the Grant two-axis measuring engine at NOAO.[3] Optical photometry was obtained from the literature or by use of the PDS machine at NOAO and the POSS plates; for the latter cases errors of 1 mag are likely. Where unavailable from the literature, optical spectra were obtained at the F. L. Whipple 1.5 m telescope and at the MMT using a photon counting Reticon system (Latham 1982). The 1.5 m spectra have a resolution of 6–7 Å and cover 4600–7200 Å. The MMT spectra have a resolution of 8 Å and cover 3200–7300 Å. Spectra were classified Seyfert 1 or QSO if the emission lines contained components broader than 5,000 km s^{-1} (FWZI).

Schmidt and Green (1983) use a blue luminosity criterion to distinguish between quasars and S1 galaxies, but our IR-selected sample suggests other approaches may be needed. Because we wish to make the separation of quasars from galaxies based on dominance of bolometric nuclear luminosity and because CCD images are not yet available for each of our objects, it was decided to use the criterion of stellar appearance on the POSS (Matthews, Morgan, and Schmidt 1964). Judging by our sample, it is difficult to mistake an S1 for a QSO because if, in the sense of a gedanken experiment, the S1 galaxies are shifted to greater distances they disappear from the sample before they become quasi-stellar. The converse also appears true: the closest QSO, IRAS 03450+0055, at a redshift of 0.031 is clearly quasi-stellar on the POSS and at the telescope.

Table 1 summarizes statistical results for the WEO sample as a whole. The four dominant classes are QSO, S1, S2, and Em (i.e., other emission-line galaxies including those with H II region spectra). Objects denoted "other" are not currently classified. Consistent with previous studies of warm galaxy samples, the WEO are rich in Seyferts, 53%, and S2 galaxies outnumber S1 galaxies by about 2 to 1. Only 27 S1 galaxies are listed, and only five are new. For a similar sample Kailey and Lebofsky (1988) estimated a larger proportion of Seyferts, 79%.

Table 2 summarizes our results for the broad-line objects. The first column gives the *IRAS* name, the second and third columns give positional data (epoch 1950) for each of the identified optical sources, and the fourth column lists names of known sources; note that the hours and minutes from the first column are to be added to seconds from the second column, and similarly for declination. The *IRAS* flux densities, given in units of Jy, differ from PSC values because the accuracy is much improved by the use of ADDSCAN and because of small, <10%, calibration differences between the PSC and ADDSCAN results. The B magnitudes and redshifts of previously known sources were taken from the literature. Our measurements of these quantities are described above. References (1), (2), and (3) indicate that the source was discovered by *IRAS*. The IR luminosities were derived from the tabulated flux densities using a color correction and relativistic correction algorithm similar to that described by Smith *et al.* (1987). The total observed IR luminosity, $L(\mathrm{IR})$, is defined as the integrated luminosity from 8 to 120 μm computed in the rest frame of the source, under the assumption that $H_0 = 100$ km s^{-1} Mpc^{-1}. $L(B)$ is defined as $\Delta\nu * L_\nu$, where L_ν is the luminosity density in the B band referred to the rest frame of the source. All luminosities are given in solar units, $L_\odot$.

Examination of the 12 QSO listed in Table 2 shows that five were known prior to *IRAS* and seven were found in the *IRAS* PSC, one by study of 12 μm sources with faint optical counterparts (Beichman *et al.* 1986) and six by this program. Neugebauer *et al.* (1986) compiled *IRAS* observations of previously known quasars, and in the region of sky considered here, they list the five known QSOs in Table 2 along with nine other

[2] IPAC is funded by NASA as part of the *IRAS* Extended Mission Program, under contract to JPL.

[3] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

SELECTED PROPERTIES OF THE WEO SAMPLE

Category	Number of Objects	z Median	z Minimum	z Maximum	F(25)/F(60) Median	F(25)/F(60) Minimum	F(25)/F(60) Maximum
WEO	187	0.037	0.003	0.915	0.42	0.25	1.27
QSO	12	0.174	0.031	0.915	0.52	0.28	1.06
S1	27	0.033	0.008	0.163	0.43	0.27	1.27
S2	73	0.039	0.004	0.442	0.46	0.27	0.98
Em	65	0.029	0.003	0.23	0.33	0.25	1.00
Other	10	...	...	...	0.40	0.26	1.14

TABLE 2

QSOs AND SEYFERT 1 GALAXIES IN WEO SAMPLE

IRAS NAME	α (s)	δ (")	Name	F(12)	F(25)	F(60)	F(100)	m(B)	z	Refs.	F(25)/F(60)	log L(IR)	log L(IR)/L(B)
						a. QSOs							
03450+0055[a]	05.5			0.29	0.51	0.60	<2.4	16.0	0.031	1	0.85	10.51	1.665
04207-0127	43.5	29	PKS	<0.1	0.25	0.26	<1.0	18.3	0.915	4	0.96	12.73	1.745
04505-2958	33.0	31		0.10	0.23	0.71	0.88	16.0	0.286	1	0.32	12.14	1.305
07598+6508	53.0	22		0.36	0.61	1.75	1.81		0.150	1	0.35	12.06	1.0
12265+0219	33.4	42	3C273	0.70	1.08	2.21	3.30	12.9	0.158	4	0.49	12.32	0.785
13218+0552	48.5	40		0.27	0.35	1.25	1.11	19.0	0.190	1	0.28	12.05	2.784
13349+2438	57.3	18		0.68	0.82	0.77	0.55	16.0	0.107	2	1.06	11.81	1.866
13517+6400	46.3	28	PG	0.17	0.60	0.81	1.35	15.2	0.087	4	0.74	11.44	1.360
14026+4341	37.6	27		0.19	0.29	0.59	1.15	16.5	0.320	1	0.49	12.30	1.563
16413+3954	17.6	11	3C345	0.16	0.32	0.66	1.12	16.3	0.593	4	0.48	12.73	1.316
17002+5153	13.4	37	PG	0.11	0.27	0.42	0.58	15.43	0.292	4	0.64	12.12	1.038
21219-1757	54.3	43		0.25	0.62	1.15	1.63	16.50	0.110	1	0.54	11.73	1.954
						b. Seyfert 1 Galaxies							
00037+1955	45.1	27	Mk335	0.35	0.42	0.33	<0.5	14.0	0.026	5	1.27	10.31	0.818
00509+1225	57.8	20	IZw1	0.53	1.24	2.02	3.25	14.3	0.060	6	0.61	11.52	1.393
01378-2230	54.0	00	543-G	0.12	0.44	0.61	0.40	17.0	0.086	1	0.72	11.26	1.909
01572+0009	15.8	10	Mk1014	0.17	0.64	2.31	2.41	15.2	0.163	5	0.28	12.14	1.497
02321-0900	10.1	14	Mk1048	0.22	0.57	1.34	1.92	14.1	0.043	5	0.43	10.94	1.028
02553-1642	20.9	45		0.13	0.30	0.98	1.36	16.0	0.068	1	0.31	11.12	1.569
04124-0803	27.0	08		0.25	0.55	0.56	0.79	15.7	0.039	7	0.98	10.72	1.538
04339-1028	59.7	40	Mk618	0.41	0.87	2.71	4.59	14.5	0.035	5	0.32	11.05	1.497
07431+6103	07.4	23	Mk10	0.18	0.30	0.85	2.67	14.0	0.029	5	0.35	10.46	0.856
09453+5043	24.3	26	Mk124	0.14	0.29	0.71	0.84	16.0	0.057	5	0.41	10.89	1.504
11033+7250	22.6	25	N3516	0.44	1.03	1.84	2.83	12.3	0.008	6	0.56	9.71	0.550
12159+3005	06.8	46	Mk766	0.40	1.60	3.95	5.14	13.7	0.013	5	0.41	10.31	1.298
12370-0504	04.5	12	Mk1330	0.42	0.90	3.03	6.85	11.9	0.009	5	0.30	9.88	0.478
12495-1308	35.4	28		0.22	0.35	1.06	2.63	14.5	0.014	3	0.33	9.88	1.130
12540+5708	05.0	37	Mk231	2.01	9.45	32.7	35.3	14.1	0.041	5	0.29	12.13	2.267
13519+6933	51.9	13	Mk279	0.24	0.36	1.33	2.74	14.5	0.031	5	0.27	10.61	1.164
14047+2841	45.9	35	Mk668	0.75	0.53	0.76	1.01	16.0	0.080	5	0.70	11.51	1.822
14156+2522	44.0	01	N5548	0.48	0.87	1.00	1.99	13.1	0.017	6	0.87	10.27	0.778
14349+5900	58.0	40	Mk817	0.43	1.33	2.19	2.54	14.3	0.032	5	0.61	10.95	1.395
15015+1037	36.4	59	Mk841	0.26	0.57	0.53	<0.5	14.0	0.036	5	1.08	10.65	0.854
15091-2107	55.5	27		0.29	0.62	1.53	2.11	15.5	0.044	3	0.41	11.02	1.648
15572+3510	16.6	13	Mk493	0.15	0.24	0.73	1.54	14.9	0.031	5	0.33	10.41	1.103
16062+1227	15.6	41	Mk871	0.12	0.39	0.73	1.11	14.9	0.033	5	0.53	10.48	1.131
16267+5153	48.5	05	Mk1498	0.13	0.34	0.42	0.35	15.5	0.055	5	0.81	10.81	1.240
17216+3633[b]	38.1			0.15	0.14	0.33	0.88	16.0	0.040	1	0.42	10.42	1.336
22340-1248	07.1	15	Mk915	0.15	0.52	0.56	0.98	15.0	0.024	5	0.93	10.25	1.218
22377+0747	46.5	34	ZG	0.17	0.38	0.82	1.62	14.3	0.025	8	0.46	10.27	0.925

[a] $\delta = +00°56^{m}02^{s}$.

[b] $\delta = +36°32^{m}52^{s}$.

REFERENCES.—(1) This *Letter*; (2) Beichman *et al.* 1986; (3) De Grijp *et al.* 1985; (4) Hewitt and Burbidge 1987; (5) Mazzarella and Balzano 1986; (6) Weedman 1977; (7) Steiner, Grindlay, and Maccacaro 1982; (8) Huchra, Wyatt, and Davis 1982.

sources from the PSC. Four objects in their list, I Zw 1, Mrk 231, Mrk 668, and Mrk 1014 are classified as S1 galaxies rather than QSOs by our criteria; Mrk 463 is a Seyfert type 2. Four other objects, Mrk 478, Mrk 876, BL Lac, and 3C 459.0, are examples of QSO/S1 which satisfy our color requirement but are not included in the WEO sample because they did not have 25 μm detections listed in the PSC. Vader and Simon (1987) also found a QSO, IRAS 00275−2859, not included in the WEO because it was not listed as a detection at 25 μm in the PSC. The absence of these five objects from our QSO sample shows that our search is at least 30% incomplete, consistent with our previous estimate.

Though formally not a question of incompleteness, there appear to be many highly luminous *IRAS* galaxies not included in our sample because they are cooler than the limit of our sample. Only two or three of the 10 ultraluminous systems studied by Sanders *et al.* (1988) meet our color criterion and all are drawn from the $F(60) > 5$ Jy flux limited sample of Soifer *et al.* (1987) taken from essentially the same area of sky. Mrk 231 is the only S1 in their sample, and the remainder have S2 spectra and values of log $L(\mathrm{IR})/L_{\odot}$ between 11.5 and 12. The clear implication is that in this extreme luminosity range there may be of order 300 galaxies brighter than the completeness limit of the PSC and 60 or more should have WEO colors. Neglecting spectral class, the current WEO sample contains only 26 objects having log $L(\mathrm{IR})/L_{\odot} > 11.5$. Since nearly half

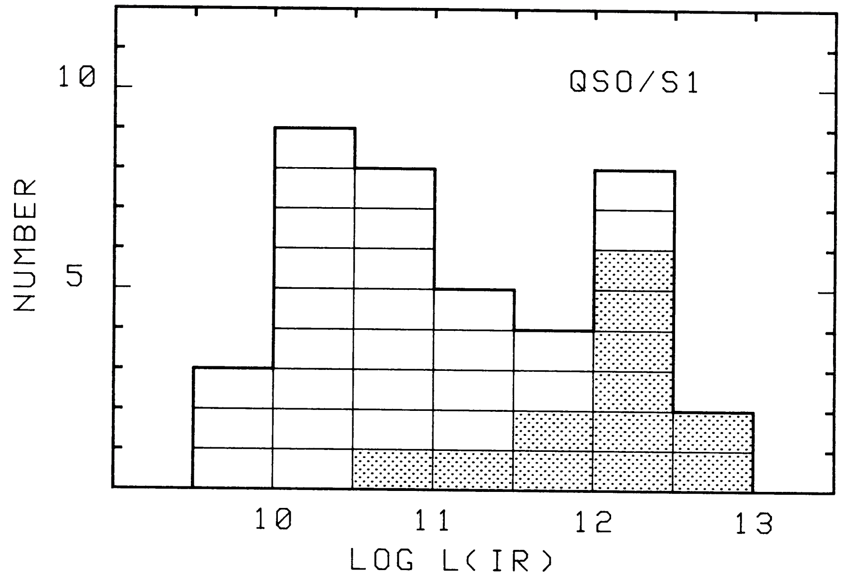

FIG. 1.—Infrared luminosity distributions as measured by *IRAS* for IR color-selected QSOs and Seyfert 1 galaxies. QSOs are indicated by filled boxes.

of these most luminous WEO are quasars, this suggests even higher incompleteness in our sample than estimated above, but larger and deeper flux-limited samples are needed.

IV. DISCUSSION

Among the noteworthy sources in Table 2 are Mrk 1014 and Mrk 231, which are often treated in the literature as quasars. These two objects represent the upper limit to luminosity in Seyfert galaxies. IRAS 03450+0055 is the least luminous quasar in the sample.

The infrared luminosity distribution for the QSO/S1 sample is shown in Figure 1. The apparent deficit of objects in the range log $L(\mathrm{IR})/L_{\odot}$ from 11 to 12 suggests a bimodal distribution. Assuming the morphological criterion for distinguishing quasars from S1 galaxies is valid, we can test whether the objects in our sample are drawn from different parent populations by the Wilcoxson rank-sum test or by the Kolmogorov-Smirnov test (Press *et al.* 1986). Using these tests the luminosity distributions of the two classes of objects differ by more than 4 σ. This could result from small sample size, incompleteness, or an intrinsic property of the two populations as defined here.

The final column of Table 2 lists the ratio of IR to blue luminosity, a parameter found to be strongly correlated with $L(\mathrm{IR})$ in the flux limited samples of Smith *et al.* (1987) and Soifer *et al.* (1987); it is also used to indicate the level of star formation in galaxies. As the data in Table 2 show, optical and IR-selected quasars and the S1 galaxies differ widely in this ratio, from <10 to >200, with no obvious correlation to IR luminosity or morphology.

In the PSC the detection rate for quasars is not high, only 12 in 14,000 deg^2. However, the sampled volume is small compared to optical surveys, only out to a maximum z of about 0.30, and arguments given above indicate an incompleteness of 50% or more. To the same distance, the Palomar Bright Quasar Survey (PBQS) of optically selected quasars in an area of 11,000 deg^2 contains, after application of our morphological criteria, 38 quasars (Schmidt and Green 1983); only two quasars listed in Table 2 were found by the PBQS survey. This suggests that the local space density of quasars may be higher than known previously by as much as 50% or more.

Work is in progress on the *IRAS Faint Source Catalog*, FSC, which will soon provide the means for extending this investigation to lower fluxes by about a factor of ~ 3.5 with improved accuracy and positions. If the number of QSO increases as $F(60)^{-1.5}$ out to a z of 0.5, then the expected number of quasars in 14,000 deg^2 would be in the range 100–200, 2–4 times that found in the PBQS survey at that depth. In any case, a significantly larger sample should resolve several of the issues raised in this preliminary study.

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