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THE PROPERTIES OF INFRARED COLOR-SELECTED QUASARS[1]

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ABSTRACT

A sample of 11 quasars from the *IRAS Point Source Catalog* is compared to a larger sample of PG quasars detected by *IRAS*. Two of the IR-selected objects are Mg II BALs. IRAS 13218+0552 has a rich optical spectrum and a ratio of L_{ir}/L_{opt} of 90, much higher than the median for the IR or PG samples (6.1 and 2.1, respectively). Fe II emission is prominent in quasars with strong L_{ir} relative to L_{opt}. Two of the seven quasars discovered by *IRAS* have energy distributions indistinguishable from the typical PG quasars while the others are much redder. All PG quasars detected by *IRAS* and IR-selected quasars have $0.25 \leq F_\nu(25)/F_\nu(60) \leq 2.0$. The optical-IR spectral energy distributions are complex and frequently show unexplained structure. The two QSOs with the greatest values of L_{oir} are radio-loud, while the remainder are radio-quiet.

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

I. INTRODUCTION

Low *et al.* (1988) reported that 12 quasars were found in a sample of nearly 200 "warm extragalactic objects" (WEOs) selected from the *IRAS Point Source Catalog* (1985, hereafter PSC). Their sample was defined as having $0.25 \leq F_\nu(25)/F_\nu(60) \leq 3.0$, compared to the median value of $F_\nu(25)/F_\nu(60) = 0.13$ for a 60 μm flux-limited sample. The WEO study covered only 15,000 deg^2 and was incomplete because it was a color-selected sample drawn from a flux-limited survey. Nonetheless, over half of the QSOs in that sample were previously unknown. This result was unexpected, since the range of redshifts for the *IRAS* sources is much lower than that of the sources found in the bright quasar sample (Schmidt and Green 1983; hereafter these sources are called PG quasars), which was drawn from an area of sky that was of comparable size and largely overlapping that studied by Low *et al.* (1988). The discovery of so many new quasars by *IRAS* raises the following questions:

1. Are the new quasars primarily a measure of the incompleteness of previous surveys, or do they represent a previously unrecognized class of quasar phenomenon which would increase the local space density of quasars?
2. Do the physical properties of IR-selected quasars differ from those of other quasars?
3. Do the physical properties of these new objects add support to suggestions that ultraluminous *IRAS* galaxies are the progenitors of all quasars?

To address these issues we compare the properties of quasars found by *IRAS* to the properties of the PG quasars. In this study, we make use of photometry at optical, near-IR, and far-IR wavelengths. We also contrast our optical spectra of the IR-selected quasars to those of typical quasars, introducing the IR-to-optical luminosity ratio as an index.

II. THE SAMPLE

For the purposes of this study, the IR sample is limited to 11 of the 12 IR color-selected quasars reported by Low *et al.* (1988); 04207−0127 is eliminated because the *IRAS* detections are marginally significant. Thus, the IR color-selected sample contains seven objects discovered by *IRAS*, two from radio surveys and two from the PG survey.

Many nearby quasars are not bright in the IR and were missed in the *IRAS* survey. To address the question of how *IRAS* quasars compare with optically selected quasars, we have extended the number of PG quasars detected by *IRAS* by co-adding all available survey scans using the ADDSCAN procedure carried out at IPAC. To avoid duplication, our flux densities are not tabulated here since Neugebauer and coworkers will publish reductions of the same *IRAS* scans using another method.

III. OBSERVATIONS

a) Optical and IR Photometry

Table 1 contains the results of recent broad-band photometry extracted from images obtained with electronic cameras on the Steward Observatory 2.3 m and KPNO 1.3 m telescopes; accuracies range from 5% to 10% depending on calibration errors and repeatability. For 3C 273 (= 12265+0219) and 3C 345 (= 16413+3954), which are known to vary at optical and IR wavelengths, we have listed ground-based data from mid-1983, to match the dates of the *IRAS* observations.

b) Optical Environment

Preliminary assessments were made for all objects in our IR sample by examination of the POSS/SRC plates, our CCD images from the 2.3 m telescope, and reference to the literature where possible. Hutchings and Neff (1988) interpret their CCD

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

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TABLE 1

THE OBSERVED PROPERTIES OF INFRARED COLOR-SELECTED QSOs

			Flux Density (mJy)												
IRAS NAME	Cat.	z	K	H	J	I	R	V	B	Log L_{oir}	Log L_{ir}	L_{ir}/L_{opt}	Opt. Spec.[a]	Radio	Ref.[b]
13218+0552	IRAS	0.190	11.8	3.2	0.9	----	0.3	----	0.1	11.7	11.7	91.0	U,0	Q	1
14026+4341	IRAS	0.320	8.7	4.5	3.1	----	----	----	1.1	12.1	12.0	12.7	BAL,3	Q	1
13349+2438	IRAS	0.107	54.5	24.6	13.2	8.6	6.4	4.8	3.9	11.6	11.5	8.7	2	Q	1
03450+0055	IRAS	0.031	39.8	20.7	12.4	----	7.7	4.8	1.8	10.3	10.2	6.4	2	Q	1
16413+3954	3C	0.593	19.5	11.8	8.0	----	----	2.4	2.1	12.7	12.7	6.1	?	L	4
07598+6508	IRAS	0.150	31.6	20.9	9.6	8.7	7.6	6.4	6.5	11.8	11.7	5.3	4	Q	1
21219-1757	IRAS	0.110	20.5	11.6	10.8	----	9.7	7.7	5.1	11.4	11.3	4.1	4	Q	1
17002+5153	PG	0.292	12.3	7.2	5.4	4.6	3.9	3.5	3.0	11.9	11.8	3.7	BAL,2	Q	3
04505-2958	IRAS	0.286	10.4	6.9	5.9	----	----	----	1.8	12.0	11.9	3.6	0	Q	1
13517+6400	PG	0.087	11.7	8.7	6.9	6.5	6.5	6.0	5.5	11.1	11.0	3.6	0	Q	1,3
12265+0219	3C,PG	0.158	87.1	53.9	38.8	37.8	30.7	31.4	29.9	12.2	12.1	2.3	1	L	2

[a] Description of optical spectrum; see text for definitions.

[b] REFERENCES.—(1) This *Letter*; (2) Cutri *et al.* 1985; (3) Neugebauer *et al.* 1987; (4) Bregman *et al.* 1986.

image of 04505−2958 as a quasar with a double nucleus. The two sources were well resolved at the MMT and their separation, 1''.6, permitted separate spectra for both objects. The secondary component is an ordinary G star and the quasar appeared unresolved. The object 13218+0552, the quasar whose optical spectrum resembles those of luminous objects centrally located in clusters, is in a crowded field suggestive of a cluster; however, the colors of these objects are not consistent with this hypothesis. This preliminary study of all sources in the IR sample, including 03450+0055 at a redshift of only 0.031, shows no clear evidence for interactions between the QSOs and nearby objects, either in the form of strong tidal tails or disturbed outer isophotes. Some objects have faint halos, others are unresolved, and some have very faint extensions or, in the case of 3C 273, a jet.

c) Spectroscopic Properties

Spectra taken with the MMT blue channel spectrograph were evaluated for all 11 QSOs. Table 1 includes the following spectral designations: BAL, broad absorption line quasar spectrum; U, unique in our sample; qualitative estimates of the strength of Fe II emission lines, strong, moderately strong, moderate, weak and absent, denoted by 4, 3, 2, 1, 0, respectively. The redshift of 3C 345 is too high too allow a consistent measure of the Fe II emission.

Surprisingly, two of the IR objects are BALs, both are of the rare variety detected by their Mg II absorption. Since only one PG object is a BAL, detection of two Mg II BALs in our sample of only six quasars in which the relevant lines could have been detected (because their redshifts are high enough) contrasts sharply with prior expectations. We suggest UV spectra be obtained of the lowest redshift quasars in this sample.

With the exception of 13218+0552, Table 1 shows that the prominence of Fe II emission lines is empirically related to the ratio L_{ir}/L_{opt}. Thus, we find evidence that strong IR emission may be related physically to the presence of a region giving rise to low-excitation lines, either in absorption or emission.

As indicated, the spectrum of 13218+0552 is unique within our sample and runs counter to the other objects in that strong, low-excitation Fe II lines are absent. It is the "reddest known quasar" and will be discussed in more detail in a later paper. Here we point out that its rich spectrum and very red IR continuum closely resemble those of the ultraluminous galaxy 09104+4109 (Kleinmann *et al.* 1988).

d) Radio Properties

Adopting the definition of Neugebauer *et al.* (1986), and using published radio observations and surveys, Table 1 includes a designation of radio-loud or radio-quiet by L or Q, respectively. Although random viewing geometry may be important, it is worth noting that the two quasars with the highest values of optical-IR luminosity are the only radio-loud sources in the sample.

IV. ANALYSIS

Figure 1 displays the observed SEDs plotted versus rest frame frequency. To compress the vertical scale and to emphasize how the emitted energy is distributed, we plot νF_ν. These distributions consist of four distinct spectral domains starting at the highest frequencies: (1) the optical band, characterized by a range of slopes from positve to negative, with a break at about 14.5 in log (ν) (Neugebauer *et al.* 1987); (2) the near-IR from about 14.5 to 13.5, characterized by a relatively steep increase to lower frequencies; (3) the *IRAS* frequencies over which the slope is generally flat or peaked; and (4) the far-IR characterized by a cutoff or, in the case of radio-loud quasars, a smooth connection to the radio continuum. Since it seems likely that photons of wavelength shorter than 1 μm are emitted by different processes than those at longer wavelengths, we use this intrinsic characteristic of the SEDs to separate optical from IR emission even when the break near 1 μm is not apparent. The objects are ordered in Figure 1 by their values of L_{ir}/L_{opt}, as computed below, with the largest value of IR to optical luminosity ratio at the top.

We find no obvious sign of increased reddening of the optical spectra associated with increased L_{ir}/L_{opt}, as might be expected. The only exceptions to this are 13218+0552 and 03450+0055, which have extremely red optical continua. The complex structure seen in several objects, especially 13218+0552 and 07598+6508, is greater than seen before in quasars and may offer clues to the radiative mechanisms involved.

Using an adopted value of 100 km s^{-1} Mpc^{-1} for H_0 and the observed flux densities, the IR and optical luminosities listed in Table 1 were computed. Working in the rest frame of

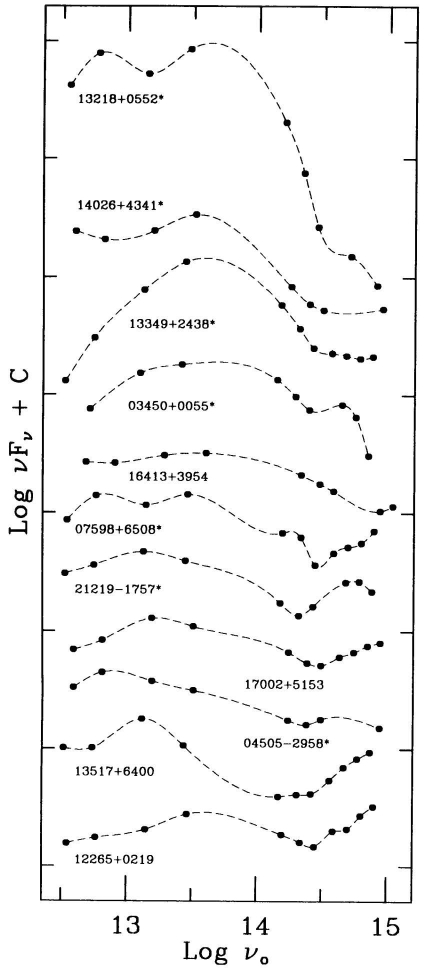

FIG. 1.—Relative spectral energy distributions of infrared color-selected QSOs. Spectra are displayed in descending order of the ratio of IR-to-optical luminosity. QSOs discovered in the *IRAS* PSC are indicated by an asterisk. Tick marks on the vertical scale indicate decades.

each object, a power-law fit was used to interpolate between data points in the spectrum and all the energy between 120 μm and 1 μm was assigned to the IR and all the energy between 1 μm and 0.45 μm was assigned to the optical. These values for the *IRAS*-selected QSOs and for the PG sample are used in Figure 2 to display the relationship between L_{ir}/L_{opt} and $L_{oir} = L_{opt} + L_{ir}$.

The total luminosity observed in the optical-IR bands and the ratio of luminosities in the two bands vary over wide ranges for both samples. The median values for the log of total observed luminosity, L_{oir}, is 11.8 for the *IRAS* sample and 11.1 for the PG sample. In Figure 2 upper limits are indicated for individual PG quasars not detected by *IRAS*. More sensitive observations of these objects should move these points down and to the left in this plot, but probably will not change the overall distribution significantly. The IR-selected objects are systematically redder, i.e., higher in L_{ir}/L_{opt}, than the optically selected objects but with substantial overlap in the two distributions. The respective medians are 5.3 and 2.1 and there is an apparent deficiency of IR-quiet quasars at the highest luminosities. For reference, the blue luminosity criterion of Schmidt and Green (1983) has been converted to solar units and is indicated by vertical dashed lines. According to a luminosity criterion and/or judged by their optical morphology, a number of PG objects are type 1 Seyfert galaxies rather than quasars (Schmidt and Green 1983).

There is a large overlap between the two samples seen in Figure 2, and Figure 1 shows little difference in the SEDs for some of the new quasars and those already known. Clearly, *IRAS* has found some quasars that were simply missed by other surveys. Of the 11 quasars listed in Table 1, three were detected by the PG survey, five or six of the "new" sources lie outside or near the boundaries of the PG survey fields, and three are too faint at B to be included in the PG, while one may have been too faint because of variability. We have not addressed the question of which quasars fail the color criterion, $U-B < -0.44$, used in the PG survey. In extending these preliminary results to larger samples, it is important to consider the small numbers now involved and the fact that our sample is incomplete. Until more data are available, we cannot reassess the local space density of quasars with confidence.

Using the combined sample of IR color-selected quasars and optically selected quasars, the efficiency of our color selection can be tested by plotting L_{ir}/L_{opt} versus $F_\nu(25)/F_\nu(60)$, as shown in Figure 3. Upper and lower limits are indicated for individual PG quasars which were detected in only one band. Note that the distribution in the flux density ratio is sharply limited to values between 0.25 and 2.0 and is not restricted by IR color limitations for the optical sample as it is for the IR sample. The vertical dashed line indicates the lower color limit used in

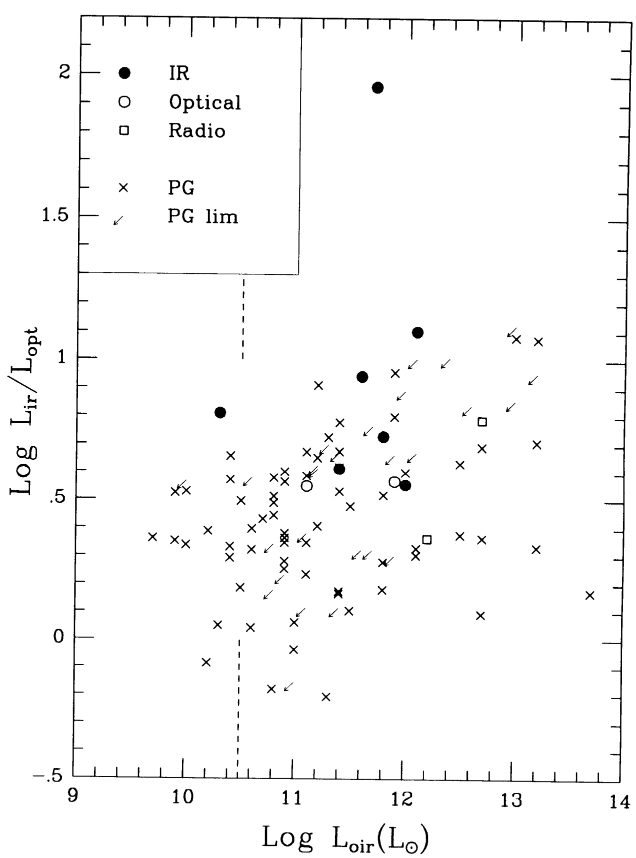

FIG. 2.—IR-to-optical luminosity ratio vs. total IR-to-optical luminosity. *IRAS* QSOs are denoted by filled circles, open circles, or open squares, depending on the type of survey in which they were first discovered. Dashed vertical lines indicate the *B* luminosity criterion for quasars from Schmidt and Green.

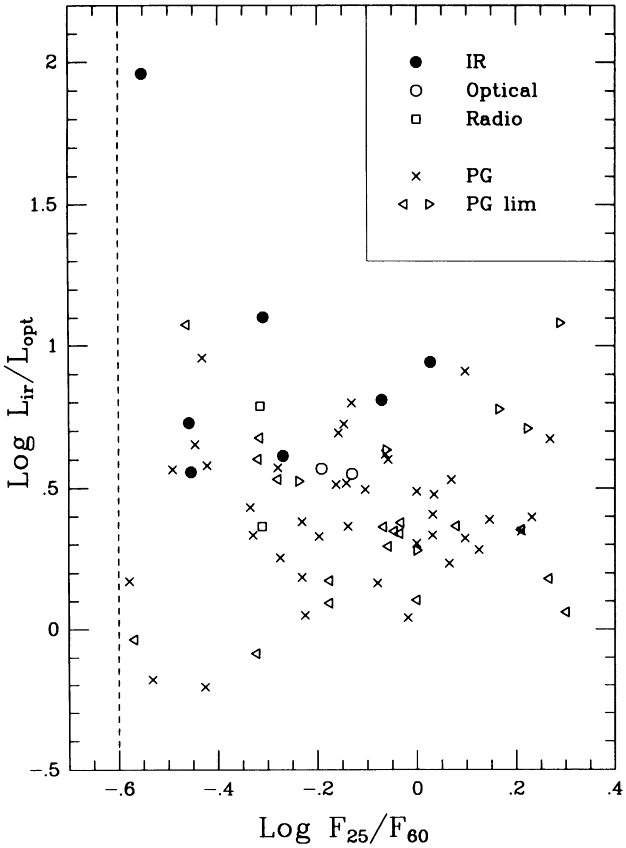

FIG. 3.—IR-to-optical luminosity ratio vs. the ratio of 25 to 60 μm flux density for IR color-selected QSOs from the *IRAS* PSC, and for PG QSOs. *IRAS* QSOs are denoted by filled circles, open circles, or open squares, depending on the type of survey in which they were first discovered. PG QSOs are denoted by X's, or by arrows when only a color limit is available. The dashed line is a graphic representation of the color-selection criterion used to find QSOs in the *IRAS* databases.

selecting the IR sample. This lower limit was chosen earlier on the basis of a much smaller and more heavily biased sample. It is noteworthy that after including the PG sample we find no need to adjust either the upper or lower limits to admit more quasars. It is even more noteworthy that the observed cut-off in this flux density ratio at the lower limit is so well defined for both the IR color-selected and optically selected quasars. A large sample of type 1 and 2 Seyfert galaxies detected by *IRAS* contains many objects cooler than this limit (Miley, Neugebauer, and Soifer 1985).

A second conclusion from the data of Figure 3 is that both samples have overlapping but different average distributions in $F_\nu(25)/F_\nu(60)$. The medians are 0.49 and 0.72 for the IR and optical samples, respectively, and only two of the IR objects exceed the mean of the optical sample. This suggests that cooler quasers may exist.

Sanders *et al.* (1988) presented a model in which all quasars are formed in the nuclei of strongly interacting gas-rich galaxies which undergo a burst of massive star formation near their nuclei. In the context of this investigation, their ideas suggest a simple evolutionary scheme in which the IR-bright quasars emerge from the nuclei of their host galaxies still surrounded by dust. As the quasar consumes matter from its dusty environment, the dust density decreases, either by vaporization near the central energy source or by ejection, thus revealing an optically brighter nucleus with much bluer colors in all bands. Unfortunately, the results presented here do not show that quasars with strong IR emission are strongly influenced by dust. However, the existence of an empirical relationship between strong IR emission and low-excitation lines may prove important in understanding the way in which these objects release their energy and may also lead to a better understanding of the evolutionary states of these systems.

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