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The Search for Red AGN with 2MASS

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Abstract. We present the results of a simple, highly efficient 2MASS color-based survey that has already discovered 150 previously unknown, red AGN and QSOs. These objects are near-infrared-bright and relatively nearby; the median redshift of the sample is $z=0.25$, and all but two have $z<0.7$. The ratio of Type 1 AGN (Seyfert 1 and QSO) to Type 2 (Seyfert 2 and LINER) among the newly discovered objects is 3:1. The extrapolated surface density of the red AGN is $\sim 0.5 \text{ deg}^{-2}$ for $K_s \leq 14.5$ mag. The space density of the 2MASS-discovered Type 1 AGN inferred from the K_s luminosity function is comparable to that of optical- and UV-selected samples.

1. Introduction

The Two Micron All-Sky Survey (2MASS; Skrutskie et al. 1997) is producing a highly uniform point source catalog of ~ 350 million objects covering the entire sky complete to $\sim 1 \text{ mJy}$ in the J ($1.25 \mu\text{m}$), H ($1.65 \mu\text{m}$) and K_s ($2.17 \mu\text{m}$) photometric bands. The uniformity and coverage of 2MASS make it a powerful resource with which to search for statistically rare classes of astronomical objects. One such class is the population of red, presumably obscured active galactic nuclei (AGN) in the local universe that has been suggested by the results of far-IR (Low et al. 1988) and radio surveys (e.g. Webster et al. 1995). An obscured population of AGN is also believed to account for at least a part of the hard X-ray background (e.g. Comastri et al. 1995). A characteristic of known AGN and QSOs is a near-IR color excess relative to a normal galactic stellar population (Rieke 1978; Neugebauer et al. 1987), so a reddened AGN population should be even more distinct in a near-IR survey such as 2MASS.

2. Candidate Selection

We utilize the uniform set of photometry 2MASS provides for large samples of *known* AGN to define a simple color selection criterion to search for new, red AGN. Figure 1a shows the $J - K_s$ versus K_s color-magnitude diagram for all

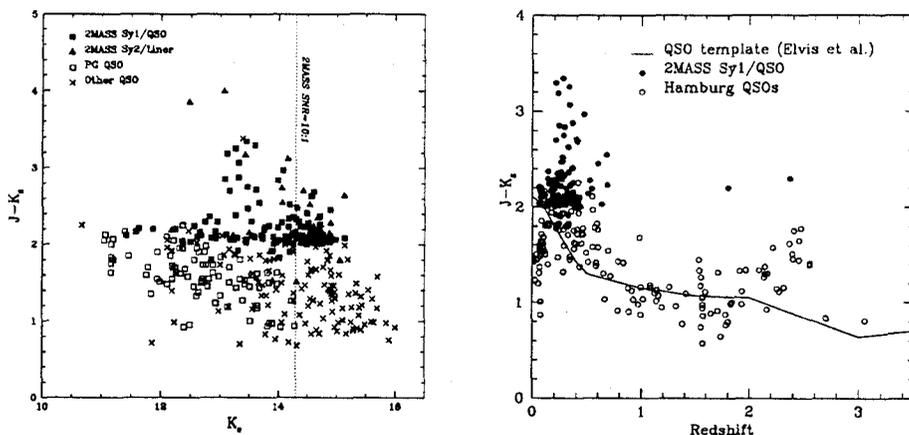


Figure 1. (left) Near-IR color-magnitude diagram showing PG QSOs (open boxes), miscellaneous optical/UV/radio-selected QSOs (crosses) and 2MASS-discovered AGN (solid points). (right) $J - K_s$ plotted versus redshift for the radio-quiet QSO template SED of Elvis et al. (1994) (line), Hamburg QSOs (open circles), and 2MASS Type 1 AGN (solid circles).

PG (Schmidt & Green 1986) and a number of miscellaneous UV/optical/radio selected QSOs. Virtually all of these known QSOs have $J - K_s \leq 2.0$, so we use that color as the lower limit for the search for new, red AGN in the 2MASS catalogs. This limit is red enough to exclude most normal galaxies and galactic objects detected by 2MASS, but is sensitive to finding AGB and carbon stars in and near the Milky Way.

A search of the 2MASS Working Database for objects with $J - K_s > 2.0$, $|b| > 30^\circ$, excluding $\sim 150\text{deg}^2$ encompassing the Large and Small Magellanic Clouds, yields 16,027 candidates with $K_s \leq 15.0$ mag in an effective area of $\sim 18,400\text{deg}^2$. Less than 5% of the candidates are previously identified objects, and $\leq 1\%$ are known AGN. Spectroscopic observations have been obtained for 231 of the red AGN candidates: 112 (48%) of the objects are classified as Type 1 AGN (Sy1/QSO), 38 (16%) are Type 2 AGN (Sy2/LINER), and the remaining 36% are a mixture of weak emission line galaxies, high latitude carbon stars and L-dwarfs. The 2MASS AGN are plotted in the color-magnitude diagram in Figure 1a.

3. Redshift distribution

The 2MASS red AGN span a redshift range of $0.03 \leq z \leq 2.37$, as illustrated in Figure 1b. However, this search finds predominantly low redshift objects; the median redshift of the sample is 0.25, and only two AGN are found at $z > 0.7$. While the two highest redshift objects are quite interesting (the redshift 1.8 source is a double, non-lensed QSO with $5''$ separation [Nelson et al. 2000] and the $z=2.37$ source is a BAL QSO), they are exceptional. Our color-selection

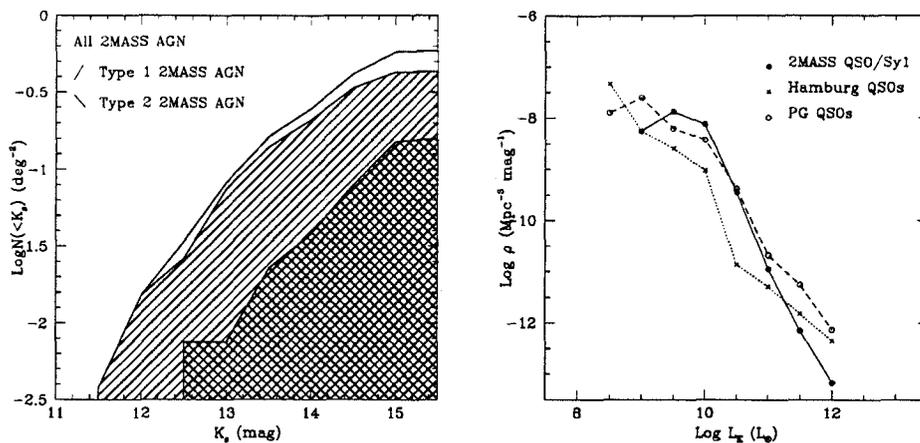


Figure 2. (left) Cumulative source counts for 2MASS AGN. (right) K_s -band luminosity function for 2MASS Type 1 AGN (solid circles), PG QSOs (open circles) and Hamburg QSOs (crosses).

technique is biased to finding low redshift objects because of the K-correction (e.g. Hyland & Allen 1982). The predicted $J - K_s$ color is plotted versus redshift for the radio-quiet QSO template of Elvis et al. (1994) in Figure 1b. The optically-selected Hamburg and Hamburg/ESO QSOs (Engels et al. 1998; Reimers, Kohler & Wisotzki 1996) shown in this figure confirm the general trend and illustrate the typical scatter for an ensemble of objects. The predicted color of “normal” QSOs shifts to the blue rapidly out to $z \sim 0.5$. The increase in predicted and observed QSO color near $z \sim 2$ occurs because $H\alpha$ enters the K_s bandpass. Although 2MASS has the sensitivity to detect QSOs out to redshift 3, they are rare in our color-selected sample. However, the key point is that 2MASS is revealing large numbers of previously unknown red AGN in the local universe, indicating that the intrinsic spread in $J - K_s$ colors of AGN is at least a factor of two larger than previously believed. The detection of a significant population of nearby, red AGN confirms the findings of the far-IR and radio surveys.

4. Surface Density and Luminosity Function

In Figure 2a is shown the cumulative surface density of the 2MASS red AGN as a function of observed K_s magnitude. The ratio of Type 2/Type 1 AGN increases towards fainter K_s magnitude. The curvature of the plot confirms that this color-based search on a flux-limited sample becomes increasingly incomplete fainter than $K_s \leq 13$ mag. Despite the incompleteness, assuming that the 65% AGN detection rate (Type 1 & 2) can be extrapolated to the entire 2MASS sample, then these results imply that there are $\sim 0.5 \text{ deg}^{-2}$ red AGN brighter than $\sim 1 \text{ mJy}$ at K_s (≤ 14.5 mag). This density holds interesting implications for future near- and mid-IR surveys. For example, a deep $3.5 \mu\text{m}$ SIRT/IRAC survey to a sensitivity of $2 \mu\text{Jy}$ should detect $\sim 29,000$ red AGN deg^{-2} , assuming no evolution and euclidean geometry.

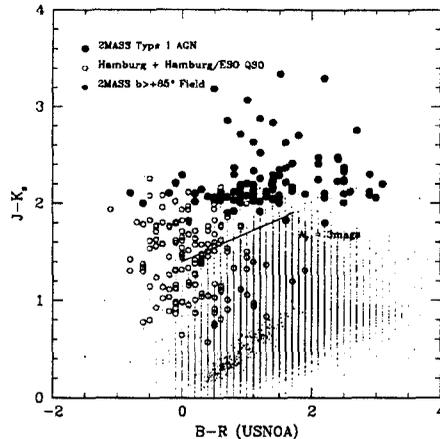


Figure 3. 2MASS $J - K_s$ color plotted versus B-R color from USNO-A catalog for 2MASS Type 1 AGN (solid circles), Hamburg and Hamburg/ESO QSOs (open circles), and for $\geq 35,000$ 2MASS sources within 5° of the north galactic pole (small points). A reddening vector corresponding to $A_V=3\text{mag}$ is shown. It will be difficult to distinguish AGN candidates with $J - K_s \leq 2.0$ from general field stars based on near-IR and optical colors alone.

The extrapolated surface density of 2MASS-selected red AGN is comparable to that of optically-selected QSOs at $B \leq 17.5$ mag (e.g. Kohler et al. 1997). This is further illustrated in Figure 2b that shows the $\Sigma 1/V_{max} K_s$ luminosity functions of PG, Hamburg and 2MASS red Type 1 AGN. The space densities are similar at intermediate luminosities, but the number of Type 1 red AGN becomes systematically smaller for $L_K > 10^{11} L_\odot$. This favors an obscuration scenario, since extinction produces both redder colors and diminished emission even at near-IR wavelengths (for low redshifts).

5. Detection at other Wavelengths

The 2MASS red AGN are not generally detected in large-scale X-ray and far infrared surveys, and thus are not the same type of objects revealed in AGN surveys at those wavelengths. Only 10% have positionally associated counterparts in the ROSAT All-Sky Survey. Approximately 20% of the 2MASS objects have far-infrared emission detectable by IRAS. Therefore, 2MASS is not finding analogs to the “IR-loud” QSOs found by Low et al (1988), or ultraluminous IR galaxies that exhibit large ratios of L_{ir}/L_{opt} . However, the 2MASS AGN detected by IRAS show L_{ir}/L_{opt} ratios intermediate between optically-selected QSOs and hyperluminous galaxies (e.g. Cutri et al. 1995).

Approximately half (52%) of the 2MASS red AGN in the area covered by the FIRST survey (Becker et al. 1995) have 1.4GHz radio counterparts within $5''$. The relative sensitivities of FIRST and 2MASS indicate that many of the objects have intermediate radio-loudness ($R \sim 1$), consistent with the class of new QSOs being found with the FIRST-based searches (White et al. 2000). Correlation between 2MASS and FIRST is one possible way to find the more

distant red AGN against which our color-selection is biased (Becker et al. 2000, this conference).

6. Optical and IR colors

In addition to being red in $J - K_s$, the 2MASS red AGN have systematically redder optical continua than optically-selected QSOs, as illustrated in Figure 3. Can a simple extinction model account for the relative colors of the IR-selected AGN? A reddening vector corresponding to $A_V=3$ mag has been drawn from the approximate midpoint of the Hamburg QSO distribution in Figure 3. If the 2MASS red AGN are simply extinguished versions of the optical QSOs, then there should be a large number of AGN with $B - R > 1$, but bluer $J - K_s$ colors, $1.5 \leq J - K_s \leq 2.0$ not sampled in this search. Distinguishing such objects from field sources using IR and optical colors alone will be difficult, as noted by Francis, Whiting & Webster 1999.

7. Polarization

Rather than relying on a statistical analysis to account for the red colors of the 2MASS AGN, polarization measurements can probe the emission mechanisms in individual objects. Smith et al. (2000b) have begun a polarization survey of the 2MASS red AGN. Eleven of 90 AGN observed to date have broad-band optical polarizations $P > 3\%$. For comparison, none of the PG QSOs have $P > 3\%$ (Berriman et al. 1990). The polarized fraction of the 2MASS AGN is comparable to the IRAS-discovered AGN (Hines et al. 1995). The degree of polarization in 2MASS red AGN correlates with $B - K_s$ color in that all of the highly polarized objects have $B - K_s > 4.3$ mag. However, not all of the reddest objects are highly polarized. Galactic starlight likely dilutes the polarized emission in these objects, so the measured degrees of polarization are probably lower limits.

Spectropolarimetry has been obtained for two of the most highly polarized 2MASS red AGN by Smith et al. (2000a). Both objects show strong broad lines and *blue* optical continua in the polarized light spectra, indicating that we are observing the broad line regions in scattered light in these objects. Thus, we conclude that at least for these two objects, obscuration by dust affects the optical continua and spectra, and likely contributes to the observed red broadband colors.

8. Summary

A simple color-based search of the 2MASS database is revealing large numbers of previously unknown, predominantly low redshift AGN. Three times more Type 1 AGN than Type 2 AGN are found, but the fraction of Type 2 objects may increase to fainter flux limits. Extrapolating the early AGN identification rate to the entire sample suggests that 2MASS will find $> 10,000$ new red AGN in the $|b| > 30^\circ$ sky, $> 7,000$ of which will be Type 1.

The space density of 2MASS Type 1 red AGN is comparable to that found in optical/UV QSO surveys at intermediate luminosities. There appear to be

systematically fewer red AGN for $L_K > 10^{11} L_\odot$, although this search is increasingly incomplete at fainter K_s levels and for increasingly red colors.

2MASS red AGN exhibit the highest polarized fraction of any AGN sample other than BL Lacs and OVV's. Spectropolarimetry of two red AGN reveals obscured broad emission line regions.

The redshift and color distributions, source counts, and polarization properties of the 2MASS red AGN sample all suggest that it is the partially obscured red "tail" of the general AGN population. This obscured population may comprise a significant fraction of the sources detected in future very deep near- and mid-IR surveys.

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