The Discovery of a Low Redshift, Red Quasar in the 2MASS Prototype Survey

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1. Abstract

A prototype camera designed to test the observing and data reduction techniques for the 2 Micron All Sky Survey (2MASS) has been used to search for extremely red objects. Selection criteria based on the combination of near-IR and visible light observations help separate the vast majority of ordinary stars from more exotic objects. Visible spectroscopic observations for objects selected using these criteria in an area of just a few tenths of a sq. deg. has resulted in the discovery of a quasar with a redshift of 0.147. The number of quasars expected at K_s in the 2MASS survey based on typical quasar colors and on the surface density of optically selected samples is ~ 0.17 (sq. deg.)$^{-1}$. The 2MASS survey will result in a sample of quasars relatively unbiased by the presence of dust and will allow a reliable determination of whether there is a significant population of quasars with internal dust absorption.

Subject headings: Quasars: general — Infrared radiation

2. Introduction

The goals and characteristics of the 2 Micron All Sky Survey (2MASS) are described in Kleinmann *et al.* (1994) and Skrutskie *et al.* (1997). A survey using prototype hardware and software is described in a companion paper (Beichman *et al.* 1997). This brief note describes the use of combined optical and near-IR measurements to identify interesting sources among the large number of objects that 2MASS will find. Optical follow-up observations described herein show that one object in the 2MASS prototype data is a quasar. We discuss the potential for near-IR surveys to remove uncertainties about the quasar population due to the presence of dust.

3. Classification of Objects via their Colors

The basic data for point sources from the prototype 2MASS data consist of source positions and magnitudes for the three near-IR infrared bands (J, H, K_s). As described in Beichman *et al.* 1997, the infrared source data were combined with digitized POSS data from the Automated Plate Measuring (APM) project (Evans and Irwin 1995). Since the vast majority of the more than 100,000,000 point sources will be M and K stars whose statistical properties will be important to those interested in galactic structure, but whose individual nature will be of compelling interest to almost nobody, it is important to find techniques to identify astrophysically interesting sources.

The range of near-IR colors for most astronomical objects is relatively narrow, typically $0.0 < J - H < 1$ mag and $-0.1 < H - K < 0.8$ mag for almost all normal stars and almost all normal galaxies made up of normal stars. Figure 1 shows a near-IR color-color diagram for a sample of objects at high galactic latitude from the prototype 2MASS survey. Also plotted are colors of different classes of objects, including Young Stellar Objects, AGNs and ultra-luminous IR galaxies detected by IRAS. While the most extreme objects can be distinguished from the large number of normal stars, the separation is not as clear as one would like, particularly at faint levels (SNR<10) where >10% photometry will be the norm.

Figure 2 shows an optical-IR (Opt-IR) color-color diagram (R-K,H-K) for these same classes of objects. There is an immediate separation between red stars and more exotic extra-galactic or galactic objects (Kirkpatrick, Beichman, and Skrutskie, 1996). In particular, notice how the brown dwarf GL 229B (Nakajima *et al.* 1996; Matthews *et al.* 1996) becomes dramatically apparent in the Opt-IR diagram. In recognition of the importance of optical information to the utility of the 2MASS survey, the survey processing will match the IR objects with source lists made from scanned plates. The present plan is to use US Naval Observatory scans of the POSS-I plates and eventually POSS-II data when

those become available in digital form.

4. Optical Follow-up of Red 2MASS Sources

In order to investigate some of the reddest objects in the dataset, we selected sources with the following characteristics from the 1992-1994 database: $|b| > 30°$; coverage at J, H and K_s; detections at H and K_s; H-$K_s > 0.7$; K < 14.5; and $\alpha < 6^h$ or $\alpha > 18^h$ to be observable on an observing run in October 1995. Two fields comprising a total of 0.2 sq. deg. (Table 1) fitted these criteria. The requirement of three band coverage proved to be the most restrictive criterion. Seven sources meeting these criteria are listed in Table 2. A classification based on optical or near-IR appearance, or on optical spectra (below) is given for six of the seven objects. Examination of the POSS images shows that about half of the objects appear to be slightly extended galaxies $\sim 5 - 10''$ in size. The prototype processing software for point sources is not reliable for the photometry of extended sources, so the magnitudes and colors of such sources must be regarded as uncertain.

Optical follow-up observations for three objects were made on 1995 October 28 (UT) with the Kast Spectrograph on the Lick Observatory 3 m Shane Telescope, under conditions of 1'' seeing but non-photometric (1-2 mag of cirrus) conditions. Simultaneous "g" and "r" band images were obtained over a 2' field surrounding the 2MASS source and spectra obtained over the wavelength region $\lambda\lambda 3500 - 5500$ at 3 Å resolution (blue arm) and $\lambda\lambda 5500 - 10000$ at 5 Å resolution (red arm). The spectra were reduced in standard manner using the NOAO IRAF data analysis package. Strong telluric absorption features (O_2, H_2O, etc.) have been removed by dividing the relevant spectral intervals by the normalized spectrum of a standard star. Absolute flux densities are indeterminate, and the uncertainty in relative flux densities is of order 5% longward of 4000 Å assuming that the cirrus extinction is gray outside specific spectral features.

4.1. A z=0.15 Quasar in a 2 μm Sky Survey

The spectra of two of the objects are unremarkable. One is of a late type star; the other is of an z =0.09 emission line galaxy. The most notable result of these observations is the detection of the first 2MASS selected QSO, 2MASP0313264+050016, at $z = 0.147$. The spectrum (shown in Figure 3) is similar to the spectra of high luminosity, high density QSOs (e.g. 3C273) with Balmer features identifiable to $H\zeta$ and $HeI\lambda5876$ clearly present. The $[OIII]$ nebular features are weak, as in the spectrum of 3C 273 (Baldwin 1975), and lie on a pedestal of $FeII$ emission. The Balmer features yield a (rest) velocity width of order 2500 km s^{-1}, modest by AGN standards.

The POSS shows a faint nebulosity 15″ SE of the QSO which our images confirm to be a spiral galaxy. The spectrograph slit was rotated so that it fell across both the QSO and the galaxy. The galaxy shows relatively blue continuum with [OIII] and NaD lines indicating z=0.147, the same as the QSO.

The spectral energy distribution of the 2MASS object (Table 3 and Figure 4) is peculiar. The near-IR (J, H, K$_s$) and optical (R and B) regions taken separately are within the range seen for PG quasars, quite red in the near-IR and somewhat blue in the visual (Neugebauer et $al.$ 1987; Elvis et $al.$ 1994). When the complete O-IR range is examined, 2MASP031326 stands out as different from most quasars. The optical to the near-IR color is very red, as shown by examination of Figure 11a of Elvis et $al.$ (1994), which shows quasar continua normalized to 1.25 μm. In this figure, 2MASP031326 lies at the extreme end of the distribution (>90% percentile) of quasar energy distributions. One explanation for the apparent redness of the source that cannot be ruled out is that the quasar was fainter during the epoch of the POSS plates than during the 2MASS observations (1992, December 7 at J; 1992, October 17 at H; and 1992, October 16 at K$_s$). Figure 4 shows a model for emission from a typical quasar (Elvis et $al.$ 1994) reddened by dust screens

producing various amounts of extinction. While the uncertainties on the visible data are large, the R-B color appears to be too blue to be consistent with extinction larger than $A_V \sim 1$ mag).

The luminosity per logarithmic frequency interval, $\nu L\nu$, of 2MASP0313264 taken at J, corresponding to $\lambda_{rest} \sim 1$ μm is at the low end of the range observed by Neugebauer *et al.* 1987, $5.8 \times 10^{10}\,L_\odot$ (for $H_0 = 50$ km s^{-1} and q_0=0.5).

4.2. Is There a Missing Population of Near-IR Quasars?

The existence of high luminosity 60 μm sources with $A_V \sim$ 10-100 mag of internal extinction and a space density comparable to or in excess of UV-selected quasars (Sanders and Mirabel 1996 and references therein) suggests a possible continuum of sources between UV-excess objects with little or no extinction and the extremely dusty IRAS sources. Such objects might be found in a near-IR survey where the effects of extinction are greatly reduced.

On the basis of the detection of just one previously unknown quasar found in the near-IR it is dangerous to speculate on the existence of a whole population of quasars that may have heretofore escaped detection. However, it is appropriate to examine the power of different surveys in finding quasars with different amounts of dust. There is remarkably little evidence for any dust in *optically selected* objects. Laor and Draine (1993) set a limit of $E(B - V) < 0.03$ mag or $A_V \lesssim 0.1$ mag (cf. Tripp *et al.* 1994) in a sample of known optical quasars. The lack of dust may be due to a selection effect, since optically selected objects must be almost dust-free to be detected in optical/blue surveys. Webster *et al.* 1995 argued on the basis of the B-K colors of *radio- selected* quasars that existing samples of UV-excess objects represents only 10-20% of the true population of quasars; the rest are

hidden by extinction. Boyle and diMatteo (1995) argue that the optical-to-X-ray flux ratios of an *X-ray selected* sample of quasars were consistent with an $A_B < 2$ mag.

We examine the importance of extinction in optical-near-IR surveys as follows. First, we represent the spectrum of a quasar by the composite spectrum (e.g. Elvis *et al.* 1994) as modified by extinction given by A_λ (e.g. Draine and Lee, 1984; Tripp *et al.* 1994). We follow Tripp *et al.* 1994 in adopting the Small Magellanic Cloud form of A_λ (Prévot *et al.* 1984) which shows no 2200 Å bump. Then, counting the number of quasars of each luminosity, $M(B)$, observable out to a maximum distance z_{max} (e.g. Weinberg 1972) gives the surface density of quasars for a combination of wavelength, limiting flux density, and quasar extinction. The quasar luminosity function, $\Phi(M_B, z)$, is represented by a double power-law (Boyle 1991; Hewett, Foltz, and Chafee, 1993) using the numerical values from (Boyle 1991).

$$\Phi(M_B, z)dM_B dz = \Phi^* \left[10^{0.4[M_B - M_B(z)](1+\alpha)} + 10^{0.4[M_B - M_B(z)](1+\beta)} \right]^{-1} dM_B dz \qquad (1)$$

where the pure luminosity evolution is accounted for by

$$M_B(z) = M_B^* - 2.5k_L log(1 + z) \ , z < z_{evol} \qquad (2)$$

$$M_B(z) = M_B(z_{max}) \quad , z > z_{evol}$$

and $\Phi^* = 6.5 \times 10^2 \, mag^{-1} \, Gpc^{-3}$, $\alpha = -3.9$, $\beta = -1.5$, $M_B^* = -22.5$, $k_L = 3.45$, $z_{evol} = 1.9$.

The number of quasars per sq. deg. observable down to a limiting flux density, $f_\nu(min)$ is given by

$$N(f_\nu(min)) = \int_{M_B(min)}^{M_B(max)} dM_B \int_0^{z_{max}} dz \frac{dV}{dz} \Phi(M_B, z) \tag{3}$$

where $M_B(min) = -23$ mag, $M_B(max) = -28$ mag, and z_{max} is the highest redshift at which a quasar of absolute B magnitude, M_B, seen through A_λ magnitudes of extinction can be detected in a survey at λ with sensitivity $f_\nu(min)$. We truncate the luminosity function at $z = 5$. The co-moving volume element per sq. deg. on the sky is given by (e.g., Pei 1995)

$$\frac{dV}{dz} = 8.2 \times 10^{-3} h^{-3} (1+z)^{-3} (1+2q_o z)^{-1/2} d_L^2 \, deg^{-2} \, Gpc^3 \tag{4}$$

where $h = H_0/100$ km s^{-1} and the luminosity distance, d_L, in units of c/H_0 is given by

$$d_L = q_o^{-2} \left[1 - q_o + q_o z + (q_o - 1)(1 + 2q_o z)^{1/2} \right] \tag{5}$$

A cosmology with $H_0 = 50$ km s^{-1} and $q_0 = 0.5$ has been adopted.

Figure 5 shows the surface density of quasars with extinctions varying from $A_V = 1$ to 10 mag (Table 4) for a B=16.2 mag survey (e.g. the PG Survey; Schmidt and Geeen 1983), for two Sloan Digital Sky Survey (SDSS; Kent 1994) bands, and for 2MASS at K_s. The figure shows that UV excess surveys are heavily biased against objects having even small amounts of dust, with $A_V = 1$ mag of dust decreasing the detectable B surface density by almost a factor of 10. Figure 5 also indicates that the mean redshift of 2MASS quasars will vary by a factor of two for $0 < A_V < 10$ mag whereas the mean redshift can vary by a factor of 10 at shorter wavelengths over the same range of extinction. Data from SDSS and 2MASS will be critical for making an *unbiased* determination of the true quasar population and for determining is there is a continuum between UV-excess objects and ultraluminous infrared objects.

The number of quasars expected at K_s in the 2MASS survey based on typical quasar colors and on the surface density of optically selected samples is ~ 0.17 (sq. deg.)$^{-1}$. Based on this expected density of objects, the formal probability of finding one quasar in a survey of just 0.2 sq. deg is only $\sim 3\%$ (95% confidence). If follow-up observations of a larger sample of 2MASS objects reveal that the surface density of quasars is greater than this predicted level then some mechanism, perhaps internal extinction, must be responsible for a red population of quasars not yet identified by other means.

5. Conclusions

The detection of a very red quasar in an examination of just a few tenths of a square degree suggests that there may be a population of quasars missed by previous surveys for UV excess objects. 2MASS and sensitive CCD surveys in the red such as the SDSS, in conjunction with spectroscopic follow-up, will enable unbiased surveys for quasars and determine whether or not these objects contain significant amounts of dust.

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