NOAO Observing Proposal *CNTAC proposal* **Panel:** *For office use.*
Date: March 31, 2001 **Category:** Active Galaxies

Determining the Fraction of Dust-Reddened Quasars Using 2MASS

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
I propose continued spectroscopy of K_s magnitude limited samples of quasar candidates from the Two Micron All Sky Survey (2MASS). $B-J$ and $J-K_s$ colors are used to select $K_s < 13.5$ and $K_s < 14.5$ candidates from ∼3000 deg^2 of 2MASS data visible in the austral winter. The selection criteria are insensitive to dust reddening. Thus this sample should help provide an answer to the question of what fraction of the quasar population has been missed in optically selected surveys due to dust reddening. Additionally, this bright sample will be more sensitive than previous optical ones to dusty transition objects between ultraluminous IR galaxies and quasars, dusty young quasars, quasars with strong broad and associated absorption, and quasars with dusty intervening absorption line systems. These samples complement those selected from ∼2500 deg^2 visible in the austral summer, and will ensure that objects are available for detailed followup all year long.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-1.5m	CSPEC + L1K	6	dark	Aug - Jan	Aug - Jan
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines).*

September 8-18 not usable due to travel; October 3-12 not usable due to LCO observing

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

Our understanding of many aspects of Active Galactic Nuclei (AGN) is still rudimentary. The observed emission from AGN is thought to be powered by the release of gravitational potential energy from matter falling into supermassive black holes, but the details of this process and their effects on the observed spectra of AGN are not understood. Part of our ignorance may be due to selection effects: most high-luminosity AGN (quasars) have been selected using rest-frame UV-optical colors. Thus dust extinction has almost certainly masked part of the quasar population from detection, and quasars found by their UV-optical colors are likely less dusty than the typical quasar. Webster et al. (1995) found that a sample of radio-selected, mostly radio-loud quasars (RLQs) had B–K colors extending to much redder values than found in optically-selected samples. Because quasar number counts rise steeply toward fainter magnitudes, any population of red radio-quiet quasars (RQQs) would be greatly underrepresented in optical surveys. Webster et al. estimated that the true quasar space density could be up to a factor of five higher than previously estimated.

The Two-Micron All-Sky Survey (2MASS, Skrutskie et al. 1997) has now made it feasible to select near-IR (NIR) magnitude-limited quasar samples, greatly reducing the bias against dust-reddened objects. (Hard X-ray selection also overcomes this bias, but NIR selection is currently possible over much larger areas, and thus samples more luminous, more easily studied quasars.) For efficient selection of quasar candidates from magnitude-limited surveys, even in the NIR, additional color selection criteria are needed. Barkhouse & Hall (2001) correlated the quasar catalog of Veron-Cetty & Veron (2000) with the public 2MASS point source catalog, and found that efficient quasar selection is possible using $B-J$ and $J-K_s$ colors (Figure 1 & Experimental Design), with $R-J$ providing additional discrimination against stars. This criterion recovers 90-95% of known quasars, including the Webster et al. radio-selected quasars, and is insensitive to dust reddening. The criterion is similar to that of Warren et al. (2000; cf. Sabbey et al. 2001), and much more complete than that of Cutri et al. (2000), who used simply $J-K_s \geq 2$. Nonetheless, Smith et al. (2000a) find RQQs with B–K_s colors as red as those of the Webster et al. RLQs among the Cutri et al. northern 2MASS AGN, suggesting that more complete $B-J/J-K_s$ selected AGN samples will be very efficient at finding large numbers of reddened AGN, such as the two from Smith et. al. 2000b.

As shown in Figure 1, a sample of 111 $K_s < 13.5$ quasar candidates extracted from 2500$\square^\circ$ of 2MASS data using this criterion includes a population of candidate reddened quasars with $J-K_s > 1.25$ and $B-K_s > 4$. A similarly sized $K_s < 14.5$ sample can be constructed from a smaller area (careful selection is needed that close to the 2MASS completeness limit). With this combined $K_s < 13.5$ and $K_s < 14.5$ sample we will address many key issues in AGN research, including:

- Do optical surveys miss a significant portion of the population of quasars with broad and associated absorption, as suggested by studies of radio-selected quasars (Becker et al. 2000)?
- How do the properties of NIR-selected quasars differ from UV/optically selected ones of similar M_K and z? e.g. Baldwin effect, line profiles, ratios and extinction, FeII emission, polarization, host galaxy luminosities and morphologies, correlations with radio and X-ray properties, etc.
- NIR-selected quasar samples will enable surveys for intervening absorption-line systems to be conducted without pre-selecting for rest-frame UV-bright quasars, which may be biasing our view of gas at high z (e.g. are dusty, metal-rich damped Lyα systems missed due to this pre-selection?).
- Helfand et al. (2000) find that FIRST radio selected quasars are dominated by radio-intermediate quasars, not RLQs or RQQs. NIR quasar selection will establish if there is a continuum or a dichotomy of IR properties between UV-bright quasars and buried quasars in ultraluminous IR galaxies (Wills & Hines 1997). NIR selected quasars are likely dustier than the average quasar and may preferentially be transition objects between ultraluminous IR galaxies and quasars, dust-enshrouded young quasars, or other "Rosetta Stones" for understanding the AGN phenomenon.

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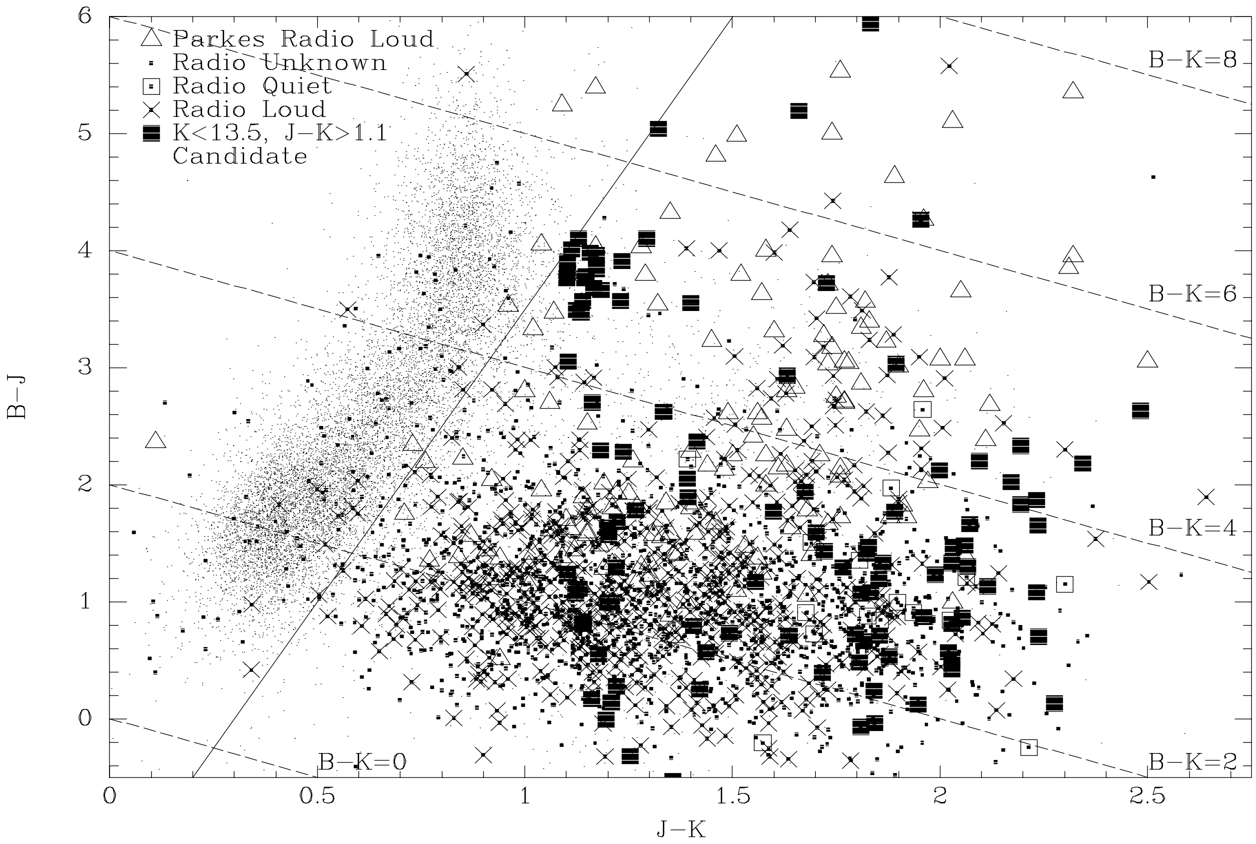

Figure 1: From Barkhouse & Hall (2001): $B-J$ vs. $J-K_s$ color-color diagram for all 2277 2MASS counterparts of quasars from Veron-Cetty & Veron (2000; VV00). The small dots are approximately 14,000 2MASS point sources located within 5′ of the 1802 VV00 quasars with no 2MASS counterpart within 4″. They illustrate the colors of the stellar locus as well as other objects (quasars and compact galaxies) seen at moderate to high galactic latitude. The small filled squares are the 2277 VV00 quasars with 2MASS counterparts within 4″. Known radio-quiet quasars are denoted by overplotted boxes, and known radio-loud quasars are denoted by overplotted crosses. Dashed lines show lines of constant $B-K_s$ color. Radio-loud quasars outnumber radio-quiet or radio-unknown quasars for $B-K_s \gtrsim 3.5$, whereas the opposite is true for $B-K_s \lesssim 3.5$. This heterogenous sample of RLQs from VV00 has a range of colors similar to the well-defined Parkes sample (open triangles; Webster et al. 1995; Francis, Whiting & Webster 2000). The solid line shows the selection criteria adopted in Barkhouse & Hall (2001) to separate stars from quasar candidates. **The large filled squares show the application of this criterion to the 2MASS database.** This sample consists of 111 $K_s < 13.5$ quasar candidates selected from ∼2500□° visible from CTIO. This initial search of 2MASS has required $J-K_s > 1.1$ and $R > 13$ in addition to the selection criteria shown. Adding an $R-J/J-K_s$ selection criteria avoids 90% of the contamination seen at $J-K_s \sim 1.15, B-J \sim 3.8$. **Even at bright K_s magnitudes, there is a population of candidate reddened quasars** with $J-K_s > 1.25$ and $B-K_s > 4$, and **preliminary spectroscopy shows that ∼65% of these are quasars**, along with ∼65% of all other candidates as well. In fainter K_s-selected samples this red population should increase slightly in prominence relative to the classical quasar population at $1 < B-K_s < 4$.

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. List all telescopes on which you have applied for or been granted time for observations related to this project. For each, indicate the nature of the observations, and describe the importance of the observations proposed here in the context of the entire program. (limit text to one page)*

Quasar Selection from Optical and Near-Infrared Colors: Warren, Hewett & Foltz (2000; hereafter WHF) proposed a criterion for selecting K_s-band flux-limited samples of quasars from the $V-J$ vs. $J-K_s$ color-color diagram. Barkhouse & Hall (2001) adopted this method to use the USNO-A B magnitudes included in the 2MASS database (Figure 1). The bulk of quasars from Veron-Cetty & Veron (2000; hereafter VV00) which are also detected by 2MASS have blue $B-J$ colors, but there is a tail at $J-K_s \sim 1.75$ and $B-J \geq 2$ of candidate reddened quasars, predominantly RLQs (crosses; see figure caption for complete guide to symbols). Note that most of these quasars do not have $J-K_s > 2$ and so would not be selected by Cutri et al. (2000). The lines of constant $B-K_s$ color (a convenient estimator of reddening for quasars at $z \lesssim 3.3$) show that red $J-K_s$ color does not correlate strongly with red $B-K_s$ color either. We cannot rule out strong selection effects against quasars with red $B-J$ and $J-K_s$ in the mostly optically-selected samples that comprise VV00. However, we have also plotted in Figure 1 a subsample of radio-selected quasars from the completely identified Parkes Half-Jansky sample (open triangles; Webster et al. 1995; Francis, Whiting & Webster 2000). There is no strong correlation between $J-K_s$ and $B-J$ or $B-K_s$ for these objects either. Selecting objects red in $J-K_s$ would not appear to be an efficient way of selecting objects red in $B-K_s$.

With RLQs, there is no guarantee that red $B-K_s$ colors are due to dust rather than synchrotron emission with a short wavelength cutoff in the rest-frame optical (Serjeant & Rawlings 1997; Francis, Whiting & Webster 2000), but with RQQs the latter effect will be much weaker and any confirmed population of RQQs with red $B-K_s$ will almost certainly be reddened by dust.

We have constructed selection criteria similar to the $V-J/J-K_s$ criterion of WHF to illustrate the separation of quasars from stars in the $B-J/J-K_s$ color-color diagram (solid line in Figure 1). Only 124 of 2277 2MASS counterparts to VV00 quasars (5.4%) have colors that do not meet the $B-J/J-K_s$ selection criteria; some of these are probably chance coincidences with stars. And as WHF point out, reddening moves quasars approximately parallel to these selection criteria and to the bluer portion of the stellar locus in this diagram, resulting in good sensitivity to both reddened and unreddened quasars.

The large filled squares in Figure 1 show a first attempt at applying this criterion to the 2MASS database. This sample consists of 111 $K_s < 13.5$ quasar candidates selected from $\sim$2500$\square^\circ$ visible from CTIO in 2001-A; a slightly larger area of $\sim$3000$\square^\circ$ is visible in 2001-B. The sample plotted is limited to $J-K_s > 1.1$, but spectra are also of course obtained for objects with $J-K_s < 1.1$ which fulfill the selection criteria. The $B-J/J-K_s$ selection criteria suffers some contamination from the stellar locus at $J-K_s \sim 1.15, B-J \sim 3.8$, but application of an additional $R-J$ criterion eliminates 90% of this contamination. This $K_s < 13.5$ sample includes a population of candidate reddened quasars with $J-K_s > 1.25$ and $B-K_s > 4$. Preliminary spectroscopic results (several dozen objects) from this semester's ongoing 1.5m run indicate that at least 2/3 of the candidates are AGN, including candidates with $J-K_s > 1.25$ and $B-K_s > 4$. In fainter K_s-selected samples this red population should increase slightly in prominence relative to the classical quasar population at $1 < B-K_s < 4$. A similarly sized $K_s < 14.5$ sample has been constructed from a smaller area; somewhat more careful selection is needed at such magnitudes in 2MASS to avoid being swamped by outliers from the stellar locus. Spectroscopy of another similarly sized $K_s < 14$ sample with counterparts in the Sloan Digital Sky Survey is scheduled for April 2001 at ESO.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the Principal Investigator during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal.*

$\boxed{\star}$ • **Hall**; 6 nights 2001A for spectroscopy of 2MASS-selected AGN candidates; run ongoing, AGN selection criteria about 65% efficient

• **Hall**, Barrientos, Gladders, Yee, Sawicki, De Robertis; 2 nights 2001A for J followup of candidate brown dwarfs & z>5.5 quasars from Red-Sequence Cluster Survey; 2 quasar and 6 T dwarf candidates from 1 night of data reduced so far

• **Hall**, Green, Kennefick, Osmer, Smith: 1 night Mar. 1999 w/HYDRA+CTIO4m for Big Faint Quasar Survey spectroscopy; 1 project & 1 backup Deep Multicolor Survey field observed, but key targets missed due to instrument software errors; data reduced, results now in online DMS database

• **Hall**, Ellingson, Carlberg, Yee, Lin & Marzke; 3 nights Feb. 1999 (2.5 usable) and 1 night June 1999 with ONIS on KPNO 2.1m for near-IR survey of CNOC1 cluster fields as a quasi-independent Ω_M measurement; data being analyzed, paper in preparation

• **Hall**, Green, Kennefick, Osmer, Smith: 8 nights (5 usable) Spring 1997 & 1998 w/BTC+CTIO4m for multicolor imaging for Big Faint Quasar Survey; processing pipelines up and running; data and catalog papers in preparation

• Yee, Barrientos, Gladders, Ellingson, **Hall**, Infante, Kodama; 13 nights 1999B - 2001A w/CTIO4m + MOSAIC for southern Red-Sequence Cluster Survey imaging; 7/10 useful nights to date; 3 upcoming in Apr. 2001; 27 deg^2 imaged; run 1 reduced to catalogs; runs 2-4 being processed

• Kennefick, Falco, Green, **Hall**, Osmer, Smith, Monier, Conti; 8 nights Fall 1999 - Fall 2000 for longslit spectra of candidate z>5 quasars & gravitational lenses from a 40 deg^2 BVIZ survey; two z$\sim$4.75 quasars found despite typically poor seeing & weather; paper in preparation

Why CTIO? *(For CTIO proposals only.) Explain why access to the southern hemisphere is needed to achieve your scientific goals.*

The all-sky coverage of 2MASS enables K_s-selected AGN samples to be assembled in both hemispheres. A relatively small investment of 1.5m time will yield a very scientifically interesting sample even without further followup, but the growing number of 4-m and 8-m telescopes in the southern hemisphere will also benefit from having samples of bright objects for detailed study.

Observing Run Details for Run 1: CT-1.5m/CSPEC + L1K

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

We will use grating 32 (300 l/mm, 6750Å blaze, 8.6Å FWHM resolution, 3450Å coverage) with the OG570 blocking filter. A 2.6″ wide slit (worst case scenario) means that our extraction aperture will be at most 2.6″x2.6″ in size. We assume a sky brightness of 21 magnitudes per arcsec^2 in R. Our goal is SNR=20 per 8.6Å resolution element at 6500Å, where the spectrograph throughput is highest. This will be sufficient both for identification and for detailed study of the spectral properties of any quasars found. We will need 2 minutes' exposure per object to achieve this at R=16, 5 minutes at R=17, 12 minutes at R=18, and 40 minutes at R=19. based on scaling of observed counts with the KPNO 2.1m GoldCam spectrograph provided on the KPNO webpage. This estimate agrees with experience using GoldCam and other KPNO and CTIO spectrographs.

A $K_s < 13.5$ sample has $13 < R < 18$, with typical $R = 16$. About 10 hours of exposure will be required for a sample of ∼100 objects. A $K_s < 14.5$ sample has typical $R = 17$, so a similarly sized sample of ∼100 $K_s < 14.5$ objects will require about 36 hours. For a total of 46 hours of exposure, accounting for overheads, 6 nights will be required.

Instrument Configuration

Filters: OG570	Slit:	Fiber cable:
Grating/grism: 32	Multislit:	Corrector:
Order: 1	$\lambda_{\rm start}$: 5750	Collimator:
Cross disperser:	$\lambda_{\rm end}$: 9200	Atmos. disp. corr.:

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.4.