Red Quasars in the Las Campanas Infrared Survey

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Summary

We propose to search for red quasars in the Las Campanas Infrared (LCIR) Deep Survey. Selection in the near-infrared will be relatively unbiased by the presence of dust and allow a determination of whether there exists a significant population of dust-absorbed quasars that have missed detection in the optical. Such a study will complement existing radio-quasar surveys, extending the search to the radio-quiet quasar population.

We will use a near-IR (and possibly optical) color-color selection technique to isolate candidates. These will then be classified according to optical/near-IR appearence prior to spectroscopic follow-up. Our method will preferentially select red quasars at $z \gtrsim 2$ with a few to several magnitudes optical extinction. We expect to detect of order 100 red quasars or more within the survey area to $K_s \simeq 21$ mag and proposed sensitivities in other bands. Due to the rarity of quasars in general, the unique area and depth of the LCIR survey is the best combination yet with which to undertake such a project.

Introduction

The majority of quasar surveys have been based on optical multicolor techniques which assume a UV excess. Even a small amount of dust, anywhere along the line-of-sight will dramatically decrease the observed optical/UV flux leading to a selection bias. Samples selected at longer wavelengths however will be less prone to extinction. An optical/near-IR imaging study of a complete sample of flat-spectrum radio-loud selected quasars (Webster *et al*. 1995) has revealed that a large fraction ($\gtrsim$60%) are unusually red in $B-K$ color. A broad and flat distribution with $2 \leq B-K \leq 10$ as compared to $B-K \sim 2.3$ for an optically-selected sample was found.

From a detailed study of their optical spectroscopic and X-ray continuum properties, Webster *et al*. 1995 and Masci *et al*. 1999 proposed that the red radio-quasars were due to extinction by dust. The data suggested an 'optically-thin' (and possibly hot) diffuse dust component of typically $\langle A_V \rangle \simeq 2$ mag, similar to that invoked for diffuse HII regions in the local ISM. This amount of extinction is considerably smaller than that invoked for obscuring molecular tori in AGN. It is however, fully consistent with unified models for radio-loud AGN since our line-of-sight to the central AGN in flat-spectrum radio quasars is not expected to intercept a torus. The authors claimed that if *radio-quiet* quasars (which form $\gtrsim$80% of QSOs detected optically) had similar amounts of dust extinction, then traditional optical surveys may have missed up to 60% of QSOs to a given flux limit.

There remains however one obstacle with interpreting the anomalous colors of red radio-quasars. The evidence for extinction is not strong and there is still some controversy as to the physical mechanism for the extreme reddening observed in their optical–to–near-IR colors. The competing theory is that their emission is "intrinsically red", possibly from an enhancement of non-thermal emission associated with the relativistic radio jet (Serjeant & Rawlings 1996). If this were true, then the reddening observed will not be representative of *radio-quiets* which lack the non-thermal (red) emission components contaminating *radio-louds*. The incompletess in existing optical surveys will then not be as severe as claimed by Webster *et al*. (1995). Thus, a direct detection of a similarly reddened radio-quiet population is essential to assess the importance of dust-reddening on the QSO population.

A hidden population of quasars will shed light on the origin of the integrated cosmic X-ray and IR-backgrounds and on the nature of the faint sub-millimeter population detected by SCUBA (Smail *et al*. 1998). Indeed, a much larger contribution by quasars to the cosmic IR-background would help alleviate the discrepancies between the star-formation (and metal production) rates derived from various methods (Blain *et al*. 1998). Current modelling predicts that the fraction of far-IR/sub-mm background and faint sub-mm source counts contributed by AGN is about 10-20% (Almaini, Lawrence & Boyle 1999). Such estimates however remain controversial, depending sensitively on the assumed luminosity function, its evolution and the spectral energy distribution of the obscured population.

Is there any evidence for a large population of dusty radio-quiet QSOs? Only recently are studies at hard X-ray wavelengths starting to reveal a potential new population, with colors somewhat redder than average (eg. Georgantopoulos *et al.* 1997). These surveys however cover areas of only a few arcminutes and the statistics are very low. Nonetheless, there is strong indirect evidence that obscured quasars outnumber normal optically detected quasars by factors of 3-4 from current models of the X-ray background (eg. Comastri *et al.* 1995). Direct confirmation of this result will require identification of the contributing sources using an unbiased selection method.

Near-IR emission from quasars is believed to be associated with hot dust originating close to the central engine and thus may be heavily absorbed by large columns of dust and gas. This will particularly apply to the type-II AGN class where an optically thick molecular torus (motivated by the popular unified model) blocks our view to the central engine. Consequently, near-IR selection is likely to be heavily biased against such sources. Our selection will therefore favor type-I AGN (with face-on tori) or lines-of-sight relatively transparent in the near-IR. Such a population will then represent the "tip of the iceberg" of a potentially large population of obscured AGN, bridging the gap between the dusty highly luminous far-IR sources (eg. ULIGS) and optically-bright quasars. Full confirmation of their nature will soon be possible with the next generation of X-ray and Far/Mid-IR satellite missions.

Expectations

Our aim is to identify the radio-quiet analogues of 'red' radio-loud quasars discovered by Webster *et al.* (1995). Such quasars are expected to suffer up to six magnitudes of extinction in the optical and are well suited for selection in the near-IR. Extinction in the K-band (2.2μm) is approximately 6% of that in B (0.44μm) and thus, an extinction of $A_B = 6$ mag ($A_V \simeq 4.5$ mag) will correspond to $A_K = 0.4$ mag. With an intrinsic $B-K \sim 2.3$ for unreddened (optically-selected) quasars (Francis 1996), we will be able to detect red radio-quiet quasars with colors of up to $B-K \sim 8$ (or equivalently $V-K \sim 6.5$, $R-K \sim 5.5$, $J-K \sim 2.9$ and $H-K \sim 1.5$). The proposed sensitivities of the LCIR survey to $J \simeq 22.9$, $H \simeq 21.7$, $K \simeq 21.1$ and also optical follow-up to $V \simeq 28.2$, $R \simeq 26.5$ will be well suited to measure such red colors for the faintest of sources. These colors are almost the reddest observed in the radio-selected sample discussed above. Furthermore, the LCIR survey sensitivity of $K_s = 21.1$ will enable a typical QSO with $M^*_K \simeq -27.5$ to be detected to redshift $z \simeq 7$. (assuming $B-K = 2.5$, $M^*_B \simeq -25$, a power-law K-correction and $q_0 = 0.5$; Pei 1995)

We use a simple model to predict the numbers of QSOs (both red and unreddened) expected to $K_s = 21.1$ within a square degree - the survey area. First, for optically-selected samples, the cumulative surface density of QSOs at $z < 2.2$ is $N_{obs}(B < 22.5) \approx 129\,\mathrm{deg}^{-2}$, while for $z > 2.2$ it is $N_{obs}(B < 22.5) \approx 31\,\mathrm{deg}^{-2}$ (Hartwick & Shade 1990). The redshift $z \approx 2.2$ is where the comoving space density of QSOs is observed to peak. To the observed redshift limit of existing surveys ($z \simeq 5$), we therefore have $N_{obs}(B < 22.5, z < 5) \approx 160\,\mathrm{deg}^{-2}$. The "true" number of QSOs expected if there were no dust extinction bias can be estimated by assuming for simplicity a power-law luminosity function $\Phi \propto L^{-\beta}$, where $\beta \simeq 0.95$ at the faint end. With this assumption, the true number of QSOs to some flux limit in terms of that actually observed can be shown to be: $N_{true} \simeq \exp[\beta\tau_B(obs)]N_{obs}$, where $\tau_B(obs)$ is the observed frame B-band extinction. Adopting the minimal value $\tau_B = 1.5$ (as compared to $\langle\tau_B\rangle \simeq 2.3$ for the red radio-quasars), we have $N_{true}(B < 22.5) \simeq 660\,\mathrm{deg}^{-2}$. Converting this to the K-band by applying a color correction and also correcting for the non-negligible extinction at K ($\tau_K \simeq 0.06\tau_B$), we have

$$N_{obs}(K_s < 21.1, z < 5) \gtrsim 600\,\mathrm{deg}^{-2}. \tag{1}$$

This represents the total surface density of both unreddened and reddened QSOs expected in the survey. The surface density of *just reddened* QSOs with $\tau_B = 1.5$ (or $R-K_s \sim 2.8$, $V-K_s \sim 3.4$) will approximately equal that of sources which fall below the flux limit of an optically-selected sample.

This is given by $N_{red} \approx N_{true} - N_{obs}$, and thus using the above estimates,

$$N_{red}(\tau_B \gtrsim 1.5, K_s < 21.1, z < 5) \gtrsim 500\,\mathrm{deg}^{-2}. \qquad (2)$$

For the separate redshift ranges: $z < 2.2$ and $z > 2.2$ respectively, we have:

$$N_{red}(\tau_B \gtrsim 1.5, K_s < 21.1, z < 2.2) \gtrsim 400\,\mathrm{deg}^{-2}, \qquad (3)$$

$$N_{red}(\tau_B \gtrsim 1.5, K_s < 21.1, z > 2.2) \gtrsim 100\,\mathrm{deg}^{-2}. \qquad (4)$$

Previous $K-$band surveys report a total source count $\approx 10^4\,\mathrm{deg}^{-2}$ to $K \simeq 21$ (all stars, galaxies, QSOs etc; eg. Soifer *et al.* 1994) and thus, we expect a red quasar-fraction of at least 1% in the LCIR survey. Note that these values are lower limits due to our assumption of first, a "flat" slope for the luminosity function (ie. the faint end value) and second, the "low" *observed frame* value $\tau_B(obs) = 1.5$. This optical depth will be considerably larger for the high z sources since the short rest wavelengths observed in our fixed bandpass will suffer relatively more extinction.

Selection Strategy

A near-IR color-color criterion will be used to provide a first cut at selecting red quasar candidates. As shown by Spinoglio *et al.* (1995) and Beichman *et al.* (1998), the range of near-IR colors for almost all normal stars and galaxies is relatively narrow. The colors of exotic objects such as quasars, low luminosity AGN and ultraluminous IRAS galaxies are found to be occupy distinctive regions of near-IR color-color space. A near-IR color selection technique is currently being used to identify quasars in the 2 Micron All Sky Survey (2MASS) (Roc Cutri, private communication). Initial results and an outline of the strategy was discussed by Beichman *et al.* (1998). The main advantage of the LCIR survey over 2MASS is its relatively faint flux limit $K_s = 21.1$ mag, as compared to $K_s = 14.5$ for 2MASS. The LCIR survey will detect sources more than six magnitudes fainter at a given redshift, increasing the surface density by two orders of magnitude, or for a typical luminosity, probe redshifts $z \gtrsim 4$.

Figure 1 shows a $J-K_s$ versus $H-K_s$ color diagram for various classes of object and predictions using composite model SEDs. The locus of normal stars (mostly M and K dwarfs) is taken from Beichman *et al.* (1998) and that of normal galaxies (mostly starbursts) from Spinoglio *et al.* (1995). The long dashed curve in Figure 1 represents the observed frame colors of a model galaxy formed in a 1 Gyr burst at $z = 5$ (using stellar synthesis models of Bruzual & Charlot 1993). Such a model may apply to a typical elliptical or the spheroidal components of disk galaxies. The solid curve shows the median track of an unreddened quasar, computed using a composite SED determined from an optically-selected quasar sample (the LBQS; Francis *et al.* 1991). The dotted curve uses this same composite but is reddened with an extinction $A_V = 1.5$ mag in the rest frame.

While evolved (red) early-type galaxies within $z \simeq 1-2$ are the main target of the LCIR survey, quasars reddened with moderate amounts of extinction are predicted to be well separated from their locus at these redshifts. A simple first cut in Figure 1 can be made with $J - K_s > 2.5$ and $H - K_S > 1.3$ which will preferentially select red quasars at $z \gtrsim 2$. Scatter about the red-quasar locus in Figure 1 will not be significant since intrinsic dispersions $\lesssim 0.3$ mag (Francis *et al.* 1991) and photometric uncertainties $\lesssim 0.2$ mag are expected. Depending on the quality and depth of the optical follow-up photometry, candidates can also be selected on an optical-IR color-color diagram as shown in Figure 2. Again, the region which is likely to avoid "red" early-type systems at $z \simeq 1-2$ (dashed line) is $J - K_s > 2.5$ and $V - z' > 4$, where selection for $z \gtrsim 2$ candidates will be optimised.

Once a list of candidates is selected, they will then be classified according to near-IR or optical appearance. To maxmimise the likelihood of quasar identification, only unresolved candidates will be retained. Extended elliptical morpologies of $\sim$ 20kpc size should be clearly resolved to $z \sim 2.5$ as $\gtrsim 3''$ sources. Even allowing for a worst possible seeing of $\sim 2''$, it should be straightforward to select quasar candidates using a point-source/galaxy classification algorithmn.

As outlined in the LCIR survey proposal, the initial 340 square arcminutes of the survey will be covered in each of J, H and K_s, with a decision to possibly discontinue imaging in H for the

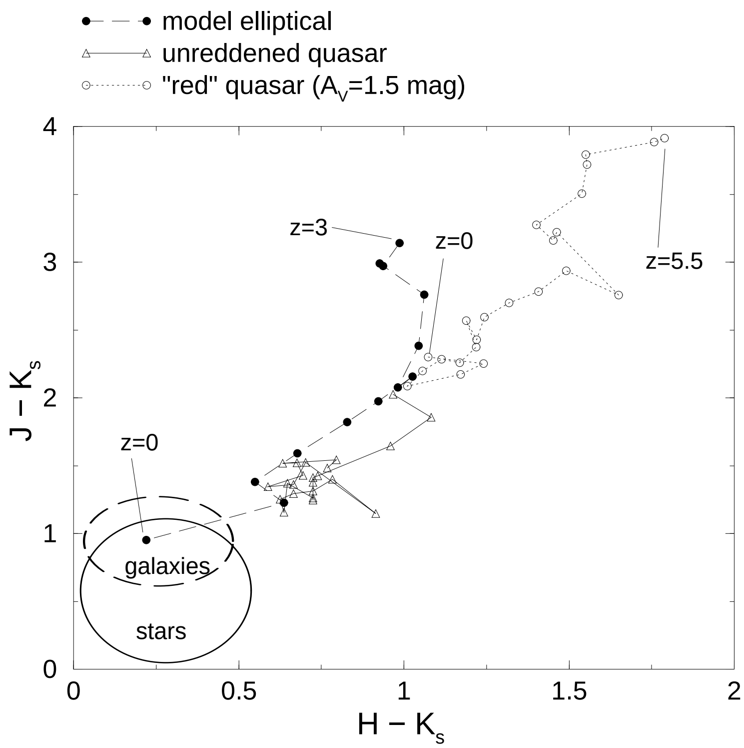

Figure 1: $J-K_s$ versus $H-K_s$ color diagram showing regions occupied by most normal and starburst galaxies (dashed ellipse; Spinoglio *et al.* 1995) and M and K stars (solid ellipse; Beichman *et al.* 1998). Long dashed curve: Synthetic colors of a model (early-type) galaxy at $z=0-3$ formed in a 1Gyr burst at $z=5$. Solid curve: Predicted median track of an *unreddened* quasar at $z=0-5.5$ using a composite SED of optically-selected quasars. Dotted curve: Prediction using the same composite SED, but *reddened* in the rest frame with $A_V=1.5$ mag.

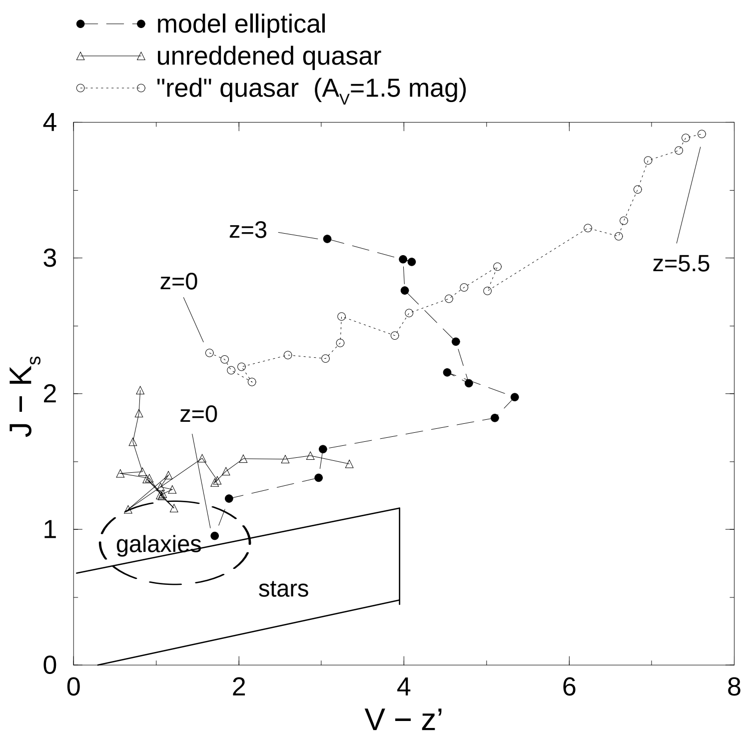

Figure 2: $J-K_s$ versus $V-z'$ where the z'-band is centered at 9130Å. Labelling is same as in above figure.

remainder of the survey. Although our near-IR color-color selection technique (Figure 1) is most optimised when using J, H and K_s, the exclusion of H will not significantly affect the selection strategy. It is found that very similar techniques can be applied if $J - K_s$ versus $I - K_s$ or $z' - K_s$ (not shown) is used instead. Thus, the minimal filter set will initially be J,H,K_s and then depending on sensitivity, making the switch to either z',J,K_s or I,J,K_s.

To summarise, we will use near-IR and optical color-color selection criteria to select red quasar candidates at high redshift. Objects will then be classified according to optical/near-IR appearence. Our technique will be most efficient for sources at $z \gtrsim 2$, where red quasars are likely to be well separated from other red extragalactic objects. Over 100 red quasars (Eq.4) should be detected at these redshifts. Once a sample of candidates is defined, they will then be followed-up with optical spectroscopy on either *Keck*, or if they are too faint optically (as we may expect), with near-IR spectroscopy on possibly Magellan.

Possible Overlapping Surveys

There also exist some completed deep surveys at other wavelengths, which, if combined with the LCIR survey, can provide additional well-defined quasar selection criteria and also a wealth of information on galaxy evolution in general. Near-IR follow-up of deep radio observations in particular can be used to asses the importance of dust extinction at those wavelengths. These surveys are purely suggestive and are by no means a requirement for this proposal.

There are two deep (southern) radio surveys which should be mentioned. The first is a deep survey at 20cm to an rms sensitivity $\simeq 10\mu$Jy centered on the Hubble Deep Field-South (http://www.atnf.csiro.au/~rnorris/hdf-s). The survey covers one square degree. Smaller regions within this area are also being imaged at higher radio frequencies. Another large area radio survey, but not going as deep is the "Phoenix Deep Survey" (Hopkins *et al.* 1998; http://www.atnf.csiro.au/~ahopkins/thesis). This covers an area of about three square degrees with an rms sensitivity $\simeq 45\mu$Jy, except for the central one square degree which was imaged to $\simeq 25\mu$Jy. Data from both surveys is now public.

The European Large Area ISO Survey (ELAIS) has a southern region of area $\simeq 4\,\mathrm{deg}^2$ imaged at 15μm to 2mJy (5σ) and at 90μm to ~ 60mJy (5σ) using ISO-CAM and ISO-PHOT respectively. Deep radio imaging of the entire region to 200μJy is also available. See Oliver *et al.* *et al.* (1999) or http://athena.ph.ic.ac.uk/.

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