High Resolution Spectroscopy of 'Red' Flat-Spectrum Radio-Quasars

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Motivation:

While it has long been known that dust is important in the physics of AGN, only recently are surveys starting to reveal populations where dust plays an increasingly important role. One particular (and ongoing) study is that of Webster *et al.* (1995) who found a large fraction of quasars with anomalously red optical/UV continua from optical follow-up of a sample of bright ($\gtrsim$0.5Jy) flat-spectrum radio sources (Drinkwater *et al.* 1997). Spectroscopic follow-up at ~ 15Å resolution has shown that a majority have optical/UV (rest frame) continuum slopes $\alpha \gtrsim 2$ ($f_\nu \propto \nu^{-\alpha}$), much redder than those of normal (optically-selected) quasars, where typically $\alpha \simeq 0.3$. Equivalently, if extrapolated into the UV, their ratio of ionising photon flux to B-band flux is smaller by factors > 100 than those of normal quasars.

Webster *et al.* (1995) proposed that the red continuum slopes were due to extinction by dust. In fact, detailed studies at near-IR to X-ray wavelengths by Masci *et al.* (1999) strongly support extinction by optically-thin diffuse dust with $\langle A_V \rangle \simeq 2$ mag somewhere in the quasar environment. 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 exact location of the dust remains uncertain. There are two obvious possibilities: The quasar host galaxy, or one of the classical line-emitting regions composed of clouds of gas.

The broad line region (BLR) at $\lesssim$1pc from the central engine is unlikely to contain dust, as grains there are expected to rapidly sublime (Laor & Draine 1993). The more extended narrow line-emitting region (NLR) at $10 - 1000$ pc **with cloud velocities ~50-500 km s^{-1}** is physically plausible for dust and indeed, evidence for dust is strongly suggested by numerous observational studies of AGN (Netzer & Laor 1993 and references therein). One interpretation is that the ionised gas is simply an extension of the smaller scale NLR. Dust in the quasar host galaxy is a possibility, and can be justified indirectly if the data from this project argues against a significant amount of NLR internal dust. Most evidence for dust in the NLR comes from studies of locally bright AGN where typically $A_V \lesssim 0.2$ mag, and most cases show little or no evidence for a reddenend optical/UV continuum (eg. Wills *et al.* 1993). This project however will focus on the narrow-line spectra of quasars known apriori to have excessively red continua.

Our main goal is is to constrain the distribution of NLR internal dust using line diagnostics similar to those applied in previous studies. Since narrow-line emmission is thought to be produced in clouds of gas embedded in a hot intercloud medium (Netzer 1990), we would like to distinguish between two possibilities: **Is the dust largely confined within individual clouds, or is it dispersed between clouds in the intercloud medium?** At high resolution, the narrow-lines of AGN often show asymmetric profiles, the majority being blueward asymmetric with excess flux on the blue side. This is observed in both low luminosity, nearby AGN and high luminosity, high redshift quasars (Boroson & Green 1992), and is interpreted by invoking the effects of extinction and the radial motion of gas clouds (eg. De Robertis & Shaw 1990). The asymmetries can be equally explained by either of the following: with extinction *between* radially *outflowing* clouds or extinction confined *within* individual *infalling* clouds. From an analysis of high resolution narrow-line spectra for a number of nearby Seyfert galaxies, De Robertis & Shaw (1990) attempted to distinguish between these possibilities by comparing the degree of line asymmetry as a function of ionization potential and critical gas density. In other words, as a function of distance from the central photoionizing source. Their results were consistent with a scenario in which extinction arises from dust embedded within *radially infalling clouds.*

The geometry and kinematics of gas clouds in flat-spectrum radio-loud quasars (FSRQs) is expected to be very different from that of radio-quiet quasars and seyferts discussed above. According to simple unified models for radio-loud AGN, FSRQs are believed to be those sources whose radio jets are directed more-or-less along the line-of-sight (or 'pole-on'), as compared to the more extended (or misaligned) steep-spectrum radio quasars (see Urry & Padovani 1995 for the strong supporting evidence). One would then expect to first order, an outflow geometry for the narrow line-emitting gas, primarily due to interaction and acceleration by outflowing plasma from the radio jet. This indeed is suggested by strong narrow lines with larger than normal velocity widths observed to coincide with linear radio structures in nearby AGN (eg. Pedler *et al.* 1985). Another ingredient of the unified model is the presence of an obscuring medium in the midplane such as a dusty torus extending to a few kpcs. For FSRQs, this axisymetric medium will be viewed face-on and immediately leads to one simple prediction: narrow-line emission from gas outflowing away from the observer on the far-side may suffer more extinction than that on the near-side leading to a net blueward assymetry in the emission lines. The strongest narrow forbidden line [OIII]λ5007, which is visible in our low-resolution spectra (Figure 1), will provide the definitive test.

If FSRQs do indeed have pole-on radio jets, then accelerated outflowing gas would imply a relative velocity shift between the peaks of emission lines corresponding to different levels of ionisation, ie. between lines formed at different distances from the photoionizing continuum source. This was reported in a large number of radio-quiet quasars by

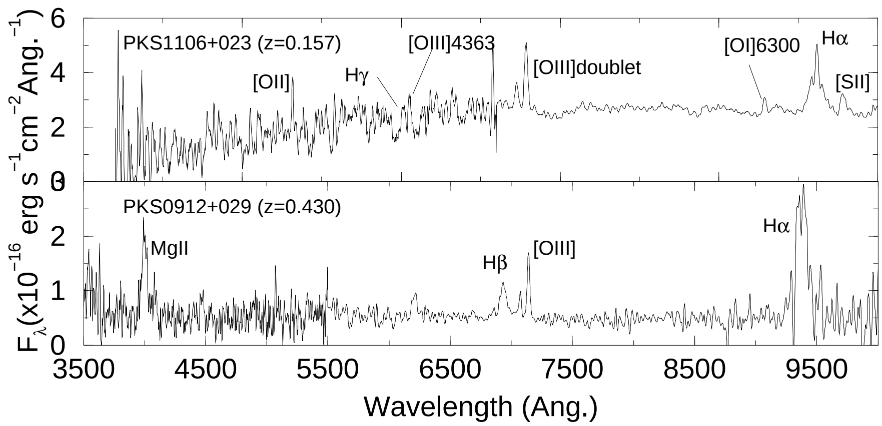

Figure 1: *Observed frame spectra of the two quasars we propose to observe. Spectra were taken with the RGO on the Anglo-Australian Telescope (Drinkwater et al. 1997) and have resolution* ~ 15Å *with signal-to-noise ratio* ~ 10. *Continua are well described by 'red' power-laws with* $\alpha \simeq 2.5$ *(PKS1106+023) and* $\alpha \simeq 2$ *(PKS0912+029), where* $F_\nu \propto \nu^{-\alpha}$ *or equivalently* $F_\lambda \propto \lambda^{\alpha-2}$.

Tytler & Fan (1992). These velocity shifts should be maximal in FSRQs if the unified model is correct.

The questions we wish to address are therefore the following:

1. What is the distribution of dust in the narrow line region of FSRQs? Is it located in clouds, diffusely distributed in between, or both?
2. Will the observed optical/UV continuum reddening be consistent with the degree of line-profile asymmetries and/or extinction derived from line-ratios?
3. What is the kinematic geometry of NLR clouds in FSRQs? Will it be an outflow as suggested by the simple orientation dependent unified model? Do the hypothesised radio-jets significantly modify the line emission as compared to radio-quiet AGN?

Additional Science:

A measurement of the complete narrow-line spectrum over a wide wavelength range in the same object will shed light on several important issues. Comparisons with the predicted spectrum emitted by photoionized gas will help constrain the line generation mechanism. Is the gas primarily photoionized by the central continuum source, or does collisional ionization in radio-jet induced shocks play a more important role? A study of the emission-line equivalent widths will in particular determine the importance of beamed continuum radiation from a possible relativistic jet. A number of other physical properties of the NLR could also be constrained: densities, temperatures, covering and filling factors, and spatial extents. Are these the same as measured in the extensively studied radio-quiet AGN class? What are the implications for unified schemes? These latter questions may require sufficiently large source statistics and will be considered in more detail in a future project. Before any of these are explored however, we must first understand the effects of dust on line-emission.

This Project:

We are requesting time to obtain spectra of moderately high resolution ($\lesssim$2Å) for two relatively low redshift 'optically reddened' quasars: PKS1106+023 ($z \simeq 0.157$) and PKS0912+029 ($z \simeq 0.430$). Both sources have accurately known positions measured from long-baseline radio interferometry.

The sources were carefully selected in redshift to enable good coverage of *rest* wavelengths 3400-6800Å, known apriori to contain forbidden lines spanning a broad range in ionization parameter and critical density. Most of these are undetected in our rather noisy, low-resolution spectra of Figure 1, except however for [OII]λ3727 and [OIII]λ5007. We expect to detect the high ionisation (but relatively weak) species [Ne V]λ3426, He IIλ4686 and low ionisation species [O I]λ6300, [S II]λ6731. These lines will provide good sampling of gas at a range of distances from the photoionizing continuum source. The region at rest wavelengths $\lambda \lesssim 3500$Å is avoided since the presence of numerous broad-permitted lines will introduce large uncertainties in the deblending of narrow lines.

This is a new project that uses the Palomar 200 inch. Depending on the results of this proposal, we envisage proposing for time during the next 3-4 observing semesters to obtain more reliable source statistics.

Instrumental Set-up and Plan:

We propose to use the Double Spectrograph to achieve a moderately high spectral resolution $\lesssim 2$Å (or $\lesssim 90\mathrm{km\,s^{-1}}$) in the rest frame to measure line profiles accurately and minimise instrumental effects.

An outline of the strategy and requirements are as follows:

(1). We plan to use a *single* slit of width $1''$ (provided the seeing will be good) and length $128''$. This choice of slit will allow for instrumentally limited wavelength resolution. It should also provide enough spatial coverage for good sky subtraction and enable any extended line-emission to be spatially resolved.

(2). The 1200 line mm^{-1} grating in first order (with 4700Å blaze) using the blue camera (to cover $\lesssim$7000Å), and, the 600 line mm^{-1} grating in first order (with 9500Å blaze) using the red camera (to cover $\gtrsim$7000Å) will best suit our requirements.

(3). We will be interested in the *observed* ranges $\lambda \simeq 3930-7850$Å (PKS1106+023), $\lambda \simeq 4700-9700$Å (PKS0912+029). The blue set-up (with CCD#14) will result in a dispersion $\simeq 0.87$Å/pixel and give a total coverage $\simeq 890$Å on the chip. The red set-up (with CCD#21) will give $\simeq 1.31$Å/pixel and a coverage $\simeq 1335$Å. We will combine both the red and blue sides to obtain spectra at each of five different, slightly overlapping regions to cover our ranges.

(4). Motivated by previous studies (eg. De Robertis & Shaw 1990), we will require a signal-to-noise ratio of ~ 30/pixel in continuum for accurate profile analysis of the weakest lines. The quasars PKS1106+023 and PKS0912+029 have B-band magnitudes $\simeq 18$ and $\simeq 18.7$ respectively. We have estimated integration times using the spectrum of a $B = 9.92$ mag star provided by Eric Bloamhof (private communication) which achieves $S/N \sim 290$/pixel in 30 sec for a resolution 3.36Å/pixel. Read-noise is negligible and measurements will primarily be sky-noise limited for the quasars. We envisage needing $\simeq$ 40min and $\simeq$ 1hr, *per spectrum* for the above sources respectively. Since we require five separate spectra for the two quasars, and also adding a 40% margin for overheads, we anticipate a total of $\simeq 4.5$ and 7 hr for each respectively. We therefore request time for 2 nights.

(5). Our sources are well positioned in right ascension to complete the project in a minimum number of *two* nights during a March to April observing period.

(6). We will observe in 1800 sec blocks in order to avoid significant contamination by cosmic rays. Each integration will also have the source slightly dithered along the slit.

(7). In the case of poor observing conditions, we will still aim at acquiring a signal-to-noise ratio of ~ 30, but only on a few spectral regions instead of the full wavelength ranges planned above.

Although I have not personally used the Double Spectrograph myself, I will be assisted by Glenn Morrison, who has substantial experience with the instrument. It must be emphasised that due to the faintness of our sources, the 200 inch telescope is the most appropriate (and only) instrument we have access to carry out this project.

Relevant Past Publications

1999. *A New Complete Sample of Sub-millijansky Radio Sources: Detection of an Optically Faint Population*, F.J. Masci, J.J. Condon, C.J. Lonsdale, T.A. Barlow, G.E. Morrison, C. Xu, D.L. Shupe, O. Pevunova, F. Fang., ApJ., In Press. This project made use of the COSMIC imager during Janurary 1999.

1999. *Spectroscopy of Microjansky Radio Sources.* This project made use of the COSMIC spectrograph during 7 nights in July 1999 and data is currently being analysed.

1999. *Red Parkes Quasars: Evidence for Soft X–ray absorption*, F.J. Masci, M.J. Drinkwater, R.L. Webster, ApJ., 510, 703. This project has used the RGO/FORS spectrograph on the 4-m Anglo Australian Telescope.

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