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NEAR-INFRARED PHOTOMETRY OF TWO $z>4$ QUASARS

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ABSTRACT

Near-infrared *J, H,* and *K* measurements have been obtained of the continua of the quasar with the currently highest known redshift, Q0051 − 279 ($z = 4.43$), and a second very high-redshift quasar, Q0101 − 304 ($z = 4.07$). It is found that the rest-frame optical/ultraviolet continuum of Q0051 − 279 is considerably steeper than that seen in most lower-redshift quasars. In addition, for this quasar there is evidence for substantial excess emission at roughly 2300 Å, which is not easily explained by known quasar emission features.

I. INTRODUCTION

New search techniques have recently resulted in the discovery of several quasars with redshifts $z>4$ (see Shaver 1987, and references therein). At such large redshifts, familiar features in the spectra of quasars appear at infrared wavelengths. For this reason, near-infrared observations of the quasars of highest known redshift are important to our understanding of such objects.

The discovery of Q0051 − 279 and Q0101 − 304 was reported by Warren *et al.* (1987a) from a search covering 30 sq. deg, using a broadband multicolor selection technique (Warren *et al.* 1987b). Based on the observed optical spectrum (rest wavelengths ~1000 − 1700 Å), Q0051 − 279 can be classified as a broad-absorption-line quasar (Warren *et al.* 1987a). In this paper, we present observed near-infrared broadband measurements to supplement the observed optical measurements of Warren *et al.* (1987a), in an effort to derive some basic properties of the intrinsic ultraviolet continua of these objects.

II. OBSERVATIONS AND DATA REDUCTION

The near-infrared measurements, shown in Table I, were made on 10 December 1987 with a solid-nitrogen-cooled InSb photovoltaic detector mounted at the $f/70$ Cassegrain focus of the Hale 5 m telescope at Palomar Observatory. The filters used correspond to the CIT photometric system for which the *J, H,* and *K* wavelengths are 1.27, 1.65, and 2.23 μm, respectively, and the corresponding filter bandwidths are $\Delta\lambda = 0.24$, 0.30, and 0.41 μm. These measurements correspond, respectively, to rest-frame wavelengths of 2340, 3040, and 4110 Å for Q0051 − 279, and 2500, 3250, and 4400 Å for Q0101 − 304. The beam diameter for all measurements was 5″. The statistical uncertainties are given in Table I, and the limit obtained for the *H* measurement of Q0101 − 304 represents 3σ above zero.

The measurements have not been corrected for possible contamination from emission lines. The only measurement for which the observed bandwidth included an emission line prominent in quasars was the 1.65 μm measurement of Q0051 − 279, which included Mg II. As this line is known to be strong in some sources, this measurement may be an overestimate of the continuum at that wavelength, but any error incurred is probably less than the uncertainties in the data.

III. RESULTS

In Fig. 1, the data are plotted as log (f_{ν_0}), where f_{ν_0} is the observed flux density at the rest frequency ν_0. All frequencies and wavelengths will refer to the rest frame of the source, unless otherwise stated. Included in Fig. 1 are the optical measurements from Warren *et al.* (1987a), which correspond to wavelengths of 660, 790, 1010, 1290, and 1660 Å for Q0051 − 279, and 710, 850, 1080, 1380, and 1780 Å for Q0101 − 304.

For Q0051 − 279, four of the five measurements at wavelengths longer than that of Lyα (1216 Å) conform to a single power law. The spectral index estimated from a least-squares fit to these four measurements is $\alpha_{\rm UV} = -1.2$ (where $f_\nu \propto \nu^\alpha$). The three highest frequency measurements, which are only limits, were not considered in the calculation of the power law, since they are all at wavelengths less than that of Lyα, and hence are diminished substantially due to intervening absorption systems (the "Lyα forest"; see, for example, Steidel and Sargent 1987, and references therein); this effect is apparent in the ultraviolet spectrum for this object (Warren *et al.* 1987a). Q0051 − 279 also shows prominent broad-absorption-line systems (primarily C IV and Si IV/O IV]; see Warren *et al.* 1987a) in the wavelength range corresponding to the 1290 Å measurement, suggesting that this measurement may be an underestimate of the continuum. No attempt has been made to correct for this effect, and hence a more accurate power law fit to the continuum may be somewhat flatter. However, since the 1660 Å measurement does not correspond with any broad-absorption-line systems (and should thus be a good representation of the continuum), the effect on $\alpha_{\rm UV}$ should be small.

IV. DISCUSSION

The ultraviolet continua of quasars are generally flatter than their corresponding infrared/optical continua (see

TABLE I. Measurements and derived quantities.

	Q0051-279	Q0101-304
J (mag)	18.09 ± 0.15	18.06 ± 0.26
H (mag)	17.84 ± 0.15	<17.77
K (mag)	16.80 ± 0.13	17.41 ± 0.50
$\alpha_{\rm UV}$	−1.2	−0.1, −0.9†
M_B	−26.2	
log[$L_{\rm IR}$]††	39.8	

† These are upper and lower limits, respectively.
†† $L_{\rm IR}$ is defined as the luminosity at 1 μm (see text); units are Watts.

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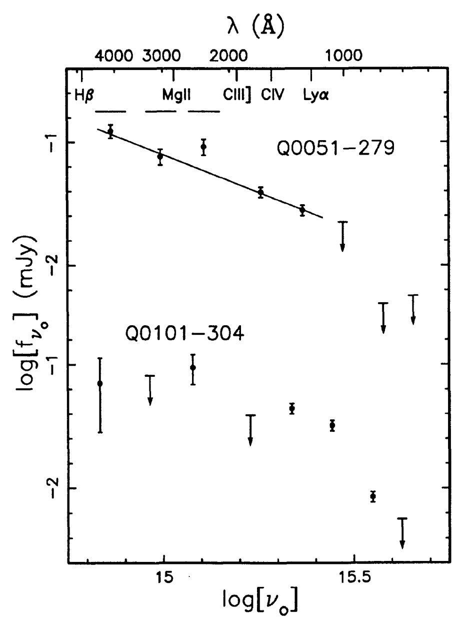

FIG. 1. Optical/ultraviolet rest-frame energy distributions of Q0051 − 279 and Q0101 − 304. The data at wavelengths shorter than 2000 Å are from Warren *et al.* (1987). The rest-frame bandpasses for the *J*, *H*, and *K* filters at $z = 4.43$ are indicated by the horizontal lines near the top of the figure. Selected emission lines prominent in quasars are also shown at their rest wavelengths. The solid line drawn through the data for Q0051 − 279 represents a least-squares fit to the data points at 1290, 1660, 3040, and 4110 Å (see text).

Weedman (1986) for a summary of quasar properties). This observation is sometimes represented by a single power law, extending from the infrared through the ultraviolet, coupled with an excess of ultraviolet emission, known as the "UV excess," the "blue bump," or, somewhat confusingly, the "3000 Å bump" (confusing, since this term is also used to describe a much narrower emission feature which is often seen in quasars; compare, for example, Malkan (1983) with Soifer *et al.* (1983)). In the discussion that follows, the reader should keep in mind that, due to the limited data available for Q0051 − 279 and Q0101 − 304, α_{UV} refers *only* to the ultraviolet wavelength range; no attempt has been made to associate this with any "UV excess" or any power law extending over a broader wavelength range.

The derived ultraviolet spectral index for Q0051 − 279, although not unique among quasars, suggests that a power law fit to the ultraviolet continuum is significantly steeper than that found for other high-redshift quasars. By comparison, Soifer *et al.* (1983) found $\langle \alpha_{UV} \rangle = -0.37 \pm 0.05$ for 18 quasars with redshifts $2.66 < z < 3.53$ (none of which had $\alpha_{UV} < -1$), as determined from broadband measurements over a wavelength range comparable to that used here. Also, Steidel and Sargent (1987) found $\langle \alpha_{UV} \rangle = -0.6$ for a sample of eight quasars with redshifts $z > 2.5$ (none of which had $\alpha_{UV} < -1$), from spectrographic measurements over a comparatively narrow wavelength range (between ~1200 and 2400 Å), and Neugebauer *et al.* (1987) found a median $\alpha_{UV} = -0.2$, with a full width at half-maximum of 0.8, for 105 quasars with redshifts $z \lesssim 2$ (only two of which had $\alpha < -1$), from broadband measurements over a comparatively large wavelength range (from ~2000–3000 Å to ~1 μm). The inclusion of a broad wavelength range in this last sample might be expected to yield spectral indices inappropriate for comparison to Q0051 − 279. However, examination of the data presented by Neugebauer *et al.* suggests that, for the 11 quasars with measurements at wavelengths as short as ~1200 Å, the spectral index calculated between 1200 and 4100 Å does not differ significantly from that determined from the broader wavelength range.

Using the derived value of α_{UV} and the cosmological parameters adopted for the current analysis,* it is found that $M_B \approx -26.2$ for Q0051 − 279. This value indicates a higher luminosity for this quasar than is found for most quasars, but also shows that Q0051 − 279 is definitely not the most luminous object known. By comparison, 21 of the 114 quasars in the Palomar Bright Quasar Survey have $M_B < -26.2$ (Schmidt and Green (1983), where their data have been adjusted to $H_0 = 75$ km s^{-1} Mpc^{-1}. See also Véron–Cetty and Véron (1987), for comparison to most quasars with known redshifts, but note that M_B for Q0051 − 279 should then be taken as ≈ -28.9 to adjust for the different H_0 and q_0 used by those authors).

An estimate of the infrared luminosity L_{IR}, for comparison to the analysis of Neugebauer *et al.* (1987), has been obtained by calculating the quantity $L_{IR} \equiv 4\pi d^2 \nu_0 f_{\nu_0}$, where f_{ν_0} corresponds to the flux density extrapolated to the rest wavelength of 1 μm using the derived ultraviolet power law, and d is the luminosity distance. The resulting L_{IR} is given in Table I, and falls in the top 5% of the quasars studied by Neugebauer *et al.* Since quasar continua often change abruptly in going from ultraviolet to infrared wavelengths (note the discussion at the beginning of this section), the uncertainty in L_{IR} is clearly large. However, any error incurred by an extrapolation of α_{UV} beyond its applicable wavelength range would be expected to be such as to underestimate L_{IR}, since quasar ultraviolet spectral indices are generally the same or flatter than the corresponding infrared index. Thus, the estimate of an unusually large L_{IR} for Q0051 − 279 is reasonable.

A striking feature derived from the data for Q0051 − 279 is the apparent excess emission seen at 2340 Å. The excess in the broadband, relative to the interpolated power law continuum, represents 40% of the total continuum flux density. This does not appear to be associated with the excess emission often seen in quasar continua near a rest wavelength of 3000 Å, and attributable to a confluence of Fe II emission lines (the alternative definition of the "3000 Å bump"; see previous discussion). The redshift of this quasar fortuitously places a rest wavelength of 3000 Å at an observed wavelength of 1.63 μm, near the center of the *H* filter bandpass, so that the good agreement of the observed *H* measurement with an ultraviolet power law indicates that, within the uncertainties of the measurements, there is no evidence for any significant excess emission at a rest wavelength of 3000 Å. Since the 1660 Å measurement also agrees well with an ultraviolet power law distribution, the observed feature would have to peak between roughly 2000 and 2500 Å, and contribute significantly over a total wavelength range $\lesssim$ 1000 Å.

Contamination from unusually strong emission lines does not seem to be a reasonable explanation for the 2340 Å excess. The *J* filter bandpass extends from 2120 to 2560 Å, and

*The Hubble parameter H_0 and the deceleration parameter q_0 have been taken as 75 km s^{-1} Mpc^{-1} and 0.5, respectively.

there are no known significant quasar emission lines within this wavelength range. The nearest line at longer wavelengths is Mg II, which, at 2798 Å, would require a width (in velocity) of more than 40 000 km s^{-1} to even contribute to the J filter measurement, and in any case would contribute more significantly to the H filter measurement, which extends from 2760 to 3315 Å. The nearest line at shorter wavelengths, C III] (λ 1909 Å), would require a width in excess of 60 000 km s^{-1} to be detected in the J filter. Such extreme velocities for the broadline region of this quasar can be ruled out observationally by the ultraviolet spectrum, which indicates broadline velocities of ~15 000 km s^{-1} (Warren *et al.* 1987a).

Another emission mechanism which contributes at the appropriate wavelengths is the two-photon Lyα process. However, it is difficult to imagine this process being responsible for such a large effect. The data thus suggest the presence of an emission feature that is not easily explained by the usual methods invoked to describe quasar energy distributions.

It is interesting to consider whether a similar feature has been seen in other quasars. An examination by the authors of 24 of the quasars studied by Neugebauer *et al.* (1987), eight quasars studied by Steidel and Sargent (1987), and another seven quasars ($1.0 \leqslant z \leqslant 2.2$) studied by Bechtold *et al.* (1984), all of which have extensive optical/ultraviolet measurements covering the necessary wavelength range (1700–3000 Å), shows no unambiguous evidence for any 2000–2500 Å feature with a strength comparable to that seen in Q0051 − 279.

For Q0101 − 304, a quantitative analysis of the shape of the energy distribution is not possible since there have been only three detections at wavelengths longer than Lyα, two of which have quite large uncertainties. However, the measurements can be used to constrain the spectral index of any underlying power law. A spectral index consistent with the measurements at 1380 and 4400 Å (and hence falling within the error bars in Fig. 1), as well as the limit at 3250 Å, must satisfy $-0.8 < \alpha_{UV} < -0.1$.

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REFERENCES

Bechtold, J., Green, R. F., Weymann, R. J., Schmidt, M., Estabrook, F. B., Sherman, R. D., Wahlquist, H. D., and Heckman, T. M. (1984). Astrophys. J. **281**, 76.

Malkan, M. A. (1983). Astrophys. J. **268**, 582.

Neugebauer, G., Green, R. F., Matthews, K., Schmidt, M., Soifer, B. T., and Bennett, J. (1987). Astrophys. J. Suppl. **63**, 615.

Schmidt, M., and Green, R. F. (1983). Astrophys. J. **269**, 352.

Shaver, P. (1987). Nature **330**, 426.

Soifer, B. T., Neugebauer, G., Oke, J. B., Matthews, K., and Lacy, J. H. (1983). Astrophys. J. **265**, 18.

Steidel, C. C., and Sargent, W. L. W. (1987). Astrophys. J. **313**, 171.

Véron-Cetty, M. P., and Véron, P. (1987). *A Catalogue of Quasars And Active Nuclei*, 3rd ed. (European Southern Observatory, Munich).

Warren, S. J., Hewett, P. C., Osmer, P. S., and Irwin, M. J. (1987a). Nature **330**, 453.

Warren, S. J., Hewett, P. C., Irwin, M. J., McMahon, R. G., Bridgeland, M. T., Bunclark, P. S., and Kibblewhite, E. J. (1987b). Nature **325**, 131.

Weedman, D. W. (1986). *Quasar Astronomy* (Cambridge University, Cambridge).