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SPECTROPHOTOMETRY OF QUASI-STELLAR OBJECTS AT OPTICAL AND INFRARED WAVELENGTHS: PG 0026+129 AND 3C 273

R. C. PUETTER,* HARDING E. SMITH,* B. T. SOIFER,* AND S. P. WILLNER*
Department of Physics, University of California, San Diego

AND

J. L. PIPHER*
Department of Physics and Astronomy, University of Rochester
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ABSTRACT

Near-infrared and optical spectrophotometry has been obtained for the low-redshift QSOs PG 0026+129 and 3C 273. Both objects show relatively strong Pα emission in the 2.3 μm atmospheric window as well as steep Balmer decrements in the optical. These results confirm the suggestion that Case B recombination-line ratios reddened by normal dust cannot explain the hydrogen line spectra of these objects. Possible mechanisms for producing the steep Balmer decrements and strong Pα features are discussed.

Subject headings: line formation — quasars — spectrophotometry

I. INTRODUCTION

The approximate equality between the energy available in the (extrapolated) nonthermal ultraviolet continuum in quasi-stellar objects and that observed in the emission lines suggests that photoionization is the primary energy source for QSO emission-line regions. However, several recent investigations have suggested that simple photoionization/recombination models are unable to explain the line ratios observed in QSOs. Baldwin (1977) has formed a composite QSO spectrum by summing the rest frame spectra of objects at a variety of different redshifts. His composite spectrum suggests that the ratio Lα/Hβ is about 3 as opposed to the much larger value (Lα/H$\beta \gtrsim 22$) derived for Case B recombination (Osterbrock 1974). More recently, Davidsen, Hartig, and Fastie (1977) from rocket UV observations of 3C 273, and Hyland, Becklin, and Neugebauer (1978) and Puetter, Smith, and Willner (1978) from near-infrared spectrophotometry of PKS 0237−23 and B2 1225+317, respectively, find a ratio $I(\mathrm{L}\alpha)/I(\mathrm{H}\alpha) \approx 1$–2. Baldwin (1977) has argued that this anomalous ratio must be due to enhancement of the Balmer lines rather than destruction of Lα photons, since the number of observed Lα photons emitted roughly equals the number of available Lyman-continuum photons. Moreover, normal reddening does not appear plausible, since the "λ2200 Å" dust-absorption feature generally is not seen. In addition, observations of Pα in 3C 273 by Grasdalen (1976) suggest that reddening cannot explain the steep Balmer decrement in that object.

In order to expand the available spectrophotometry of QSOs to a longer baseline and in particular to investigate the problems discussed above, we have begun a program of near-inrared and optical spectrophotometry of bright quasi-stellar objects. Atmospheric transmission and instrumental sensitivity necessarily restrict our sample to QSOs with $V \lesssim 17.5$ which have important spectral features redshifted into the 1.65 and 2.3 μm atmospheric windows. In this *Letter* we report observations of the Pα–Balmer-line intensities of the QSOs PG 0026+129 and 3C 273. PG 0026+129 is a bright ($V = 14.8$) QSO discovered by Green (1976) by color-excess techniques. The redshift of PG 0026+129 ($z = 0.1469$ from our observations) is sufficient to shift Pα ($\lambda_0 = 18751$ Å) into the 2.3 μm window. There is no previously published spectrophotometry of PG 0026+129 at either optical or near-infrared wavelengths. The history of 3C 273 is well chronicled. Previous spectrophotometric studies of 3C 273 include that of Baldwin (1975*a*, *b*) at optical wavelengths and that of Grasdalen (1976) in the near-infrared.

II. OBSERVATIONS

a) Infrared Observations

Near-infrared narrow-band spectrophotometry and broad-band photometry of PG 0026+129 were obtained on 1978 October 28 and November 29 (UT) at Lick and Kitt Peak observatories. The Lick observations were made by using the UCSD 2–4 μm InSb filter wheel spectrometer ($\Delta\lambda/\lambda \approx 2\%$) on the 3 m Shane telescope. The KPNO InSb *Blaukorte* 1–5 μm spectrometer ($\Delta\lambda/\lambda \approx 2\%$) was used in October on the 4 m Mayall telescope. The observing apertures used for these observations were approximately 7″ in diameter. The Lick and KPNO data, shown in Figure 1, represent approximately 1 hour and 4½ hours of integration time, respectively. The strong Pα emission is clearly detected, falling at the wavelength predicted by the redshift obtained from our optical observations. We derive an intensity for Pα of $I(\mathrm{P}\alpha) = (3.2 \pm 0.7) \times 10^{-13}$ ergs cm^{-2} s^{-1} in the QSO rest frame.

* Visiting Astronomer at Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

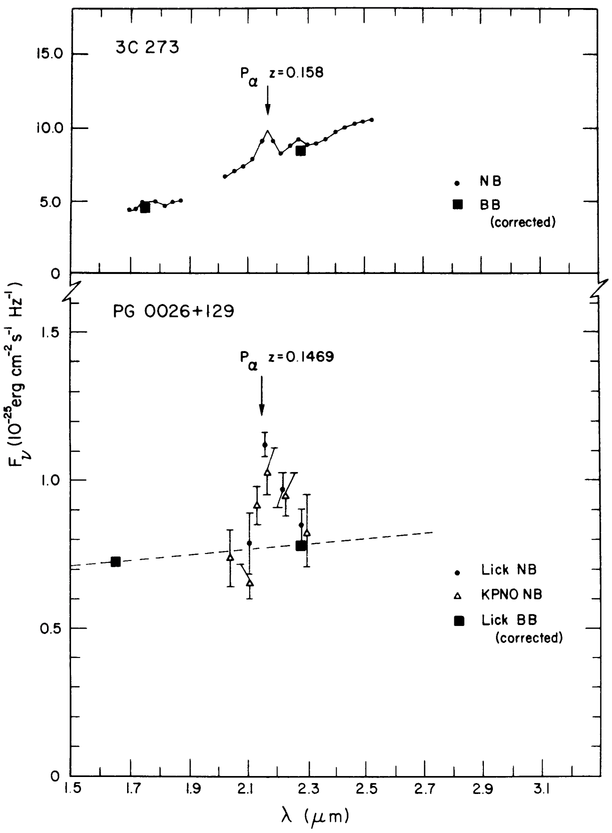

FIG. 1.—Near-infrared narrow-band and broad-band measures of PG 0026+129 and 3C 273. The expected position of Pα emission is indicated. The 2.28 μm broad-band measurement has been corrected for the line flux; thus it represents the continuum level. The dashed line indicates the continuum adopted to calculate the line intensity.

Observations of 3C 273 were obtained on 1978 Apri 28 (UT) at Kitt Peak National Observatory by using the UCSD 2–4 μm InSb spectrometer on the 4 m Mayall telescope. The observing aperture employed for these observations was 7″ in diameter. The data displayed in Figure 1 represent 1 hour of integration time. We derive an integrated intensity of $I(\mathrm{P}\alpha) = (7.8 \pm 1.6) \times 10^{-13}$ ergs cm^{-2}s^{-1} in the rest frame, in reasonable agreement with that found by Grasdalen (1976). We consider the major uncertainty in these results to be the determination of the continuum level.

b) Optical Observations

The optical observations of PG 0026+129 were obtained in 1978 October 10 and 11 and November 14 (UT) by using the Robinson-Wampler image-dissector scanner (IDS) on the Shane telescope. Our summed scans are shown in Figure 2. Observations were obtained with both 2″.8 and 6″ angular apertures on each night in an attempt to provide both maximum spectral resolution and absolute spectrophotometry. Seeing on each night was about 1″; nonetheless, the fluxes derived from the large-aperture observations were approximately 10% larger than those from the 2″.8 aperture observations. In Table 1 we list the relative line intensities from our data normalized to our large-aperture Hβ intensities. The major source of uncertainty for most features is the placement of the continuum. As can be seen in Figure 2, the emission-line spectrum of PG 0026+129 is exceedingly rich with only a very few, narrow continuum intervals. The Balmer-line intensities, the principal feature of interest for this work, were determined both by integrating numerically over the line profiles, and by fitting the Hβ profile (excluding [O III] λλ4959,5007) to the profiles of Hγ, Hδ, and Hϵ. The Hβ profile scaled in intensity and velocity width

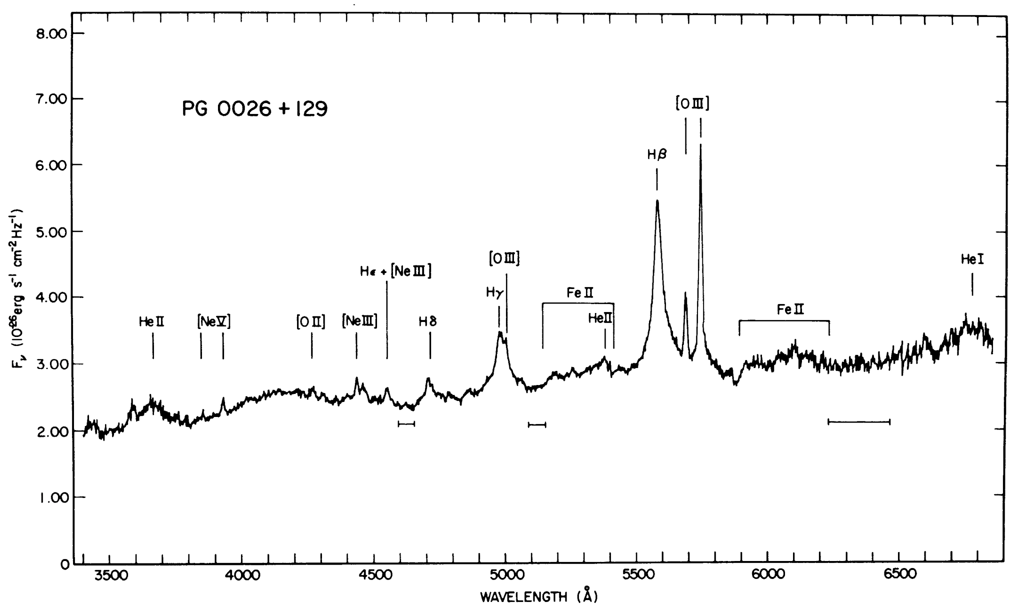

FIG. 2.—Lick Observatory IDS observations of PG 0026+129; the emission features are marked. Spectral intervals considered to be continuum are indicated below the spectrum.

TABLE 1

REST FRAME* LINE INTENSITIES FOR PG 0026+129

Line	λ (Å)	I_λ (10^{-13} ergs cm^{-2} s^{-1})	$I_\lambda/I(\text{H}\beta)$	W_λ (Å)
Pα	18751	3.2	1.4	380
He I	5876	0.7:	0.3:	25:
Fe II	5190, 5320	0.6	0.25	15
[O III]	4959–5007	1.3	0.56	35
Hβ	4861	2.2	1.00	60
Fe II He II	4570 4686	0.9	0.40	23
[O III]	4363	0.2	0.1	5
Hγ	4340	0.8	0.34	17
Hδ	4101	0.3	0.14	6
[Ne III] Hε	3968 3970	0.09	0.04	2
[Ne III]	3869	0.13	0.06	2
[O II]	3727	0.05	0.02	<1
[Ne V]	3426	0.06	0.03	1
[Ne V]	3346	0.02	0.01	<1
He II	3203	0.9	0.4	13
Mg II	2800	2.0:	0.9:	40:

NOTE.—Colons indicate measures of lower quality (because they fall near the end of a particular scan).

* All line intensities and equivalent widths have been shifted to the QSO rest frame; thus I_λ Rest $= I_\lambda$ Obs $(1+z)^2$ and W_λ Rest $= W_\lambda$ Obs$/(1+z)$.

TABLE 2

THE REST FRAME HYDROGEN LINE SPECTRUM OF 3C 273

Line	λ (Å)	I_λ (10^{-12} ergs cm^{-2} s^{-1})	$I_\lambda/I(\text{H}\beta)$	W_λ (Å)
Pα	18751	0.8	0.33	135
Hα	6563	12.5*	5.2*	473*
Hβ	4861	2.4*	1.0*	61*
Hγ	4340	0.9*	0.39*	20*
Hδ	4101	0.5*	0.21*	10*
Lα	1216	16.4†	6.8†	60†

* We have adopted Baldwin's (1975*b*) equivalent widths and relative line intensities normalized to the absolute Hβ intensity given by Wampler and Oke (1967).

† A. Davidsen, private communication.

appears to be a good fit to all three other lines. The two methods were in good agreement and suggest a relative error of about 10% in the ratio of Hγ/Hβ and one slightly larger for Hδ/Hβ. [Ne III] λ3968 contributes up to 50% of the intensity of the Hε/[Ne III] blend; thus Table 1 gives an upper limit to the Hε/Hβ ratio. The uncertainties in the other line intensity ratios are estimated to be 10% for the stronger lines up to 50% for the weaker features. Systematic calibration errors in the absolute line intensities are also believed to be of the order of 10%.

The spectrum of PG 0026+129 is unusual in that it shows relatively strong emission from the permitted Fe II multiplets near 4570, 5190, and 5320 Å. These features are seen in the optical spectra of relatively few low-redshift QSOs (Phillips 1978*a*). Whether excitation of these lines is fluorescent or collisional is at present uncertain (Phillips 1978*b*). The spectrum of PG 0026+129 also shows a broad hump in the UV from the atmospheric cutoff to about 3900 Å (rest). Because this "hump" occurs just as the broad Balmer lines begin to converge, we interpret this hump as due to the Balmer continuum, in concurrence with the suggestion of Baldwin (1975*b*).

The definitive optical study of the spectrum of 3C 273 is that of Baldwin (1975*a*,*b*). In order to allow for variability, we obtained optical observations of 3C 273 on 1978 March, about 1 month before our infrared observations. Our line intensities are in relatively good agreement with Baldwin's higher-quality measures; thus we adopt the measures of Baldwin (1975*b*) in comparing the optical/infrared line intensities. The Lα intensity measured by Davidsen, Hartig, and Fastie (1977) has been revised slightly upward (Davidsen, private communication). We list the hydrogen line intensity ratios for 3C 273 in Table 2.

III. DISCUSSION

The presence of dust in or around the line-emitting region has been one attractive explanation for the emission-line intensities in QSOs. Selective destruction of trapped Lα on dust grains embedded within the permitted-line region might explain the anomalously low Lα/Hα ratio (London 1978). Also, the steep Balmer decrements in QSOs might be explained by dust reddening of lines emitted in the normal recombination ratios. Our results for PG 0026+129 and 3C 273, however, strongly support the suggestion of Grasdalen (1976) that reddening by dust cannot be responsible for the Pα/Hβ ratios and the steep Balmer decrements in these two QSOs. For Case B line ratios, the dust extinction would have to have the wavelength dependence shown in Figure 3. While small amounts of reddening, $E_{B-V} = 0.42$ and ~ 0, respectively, might account for the Pα/Hβ ratio, the steep Balmer decrements in both QSOs require much larger values. For PG 0026+129 the observed Balmer decrement steepens with increasing series number faster than predicted by the Whitford curve (independent of the adopted value of R). Our intensity ratios for PG 0026+129 would require $E_{B-V} = 0.72$ for Hγ/Hβ, 1.0 for Hδ/Hβ, and $E_{B-V} \gtrsim 2$ for Hε/Hβ. For 3C 273, however, the data require a minimum in the extinction at Hα.

For the reasons discussed above, it seems likely that mechanisms other than dust absorption are responsible for producing the observed hydrogen line ratios. Zirin (1978) has commented on the similarity of the Lα/Hα ratios in the solar chromosphere, solar flares, and QSOs. He suggests that large optical depths may lead to thermalization of the lines to the local electron temperature. An electron temperature of 15,000–20,000 K will produce Lα/Hα ratios similar to those observed. The higher members of the Balmer series must not thermalize, however, because the steep Balmer decrements imply considerably lower temperatures ($T_e \sim 2500$ K for 3C 273 and PG 0026+129).

Krolik and McKee (1978) have made the most detailed investigations to date of the hydrogen line spectrum in QSO emission-line regions. They consider a large number of physical processes and use an escape probability formalism to calculate the effects of radiative transfer. In their models, a very large optical depth in the Balmer lines, $\tau_{\mathrm{H}\alpha} \sim 200$–$300$ ($\tau_{\mathrm{L}\alpha} \gtrsim 3 \times 10^5$), will provide both a steep Balmer decrement and a relatively large Pα/Hβ ratio. This results from the preferential conversion of higher lines of the Balmer series into a lower Balmer line plus lines of higher series. However, at the electron densities of interest ($N_e \lesssim 10^{10}$ cm^{-3} so that [C III] λ1909 is not collisionally de-excited), their models continue to produce very large Lα/Hα ratios (typically 10). In order to explain the emission-line spectrum of 3C 273, Krolik and McKee suggest both large optical depth and an electron density high enough to collisionally excite the Balmer and Paschen lines while collisionally de-exciting Lα. None of their calculations, however, accurately reproduce the observed ratios in either 3C 273 or PG 0026+129.

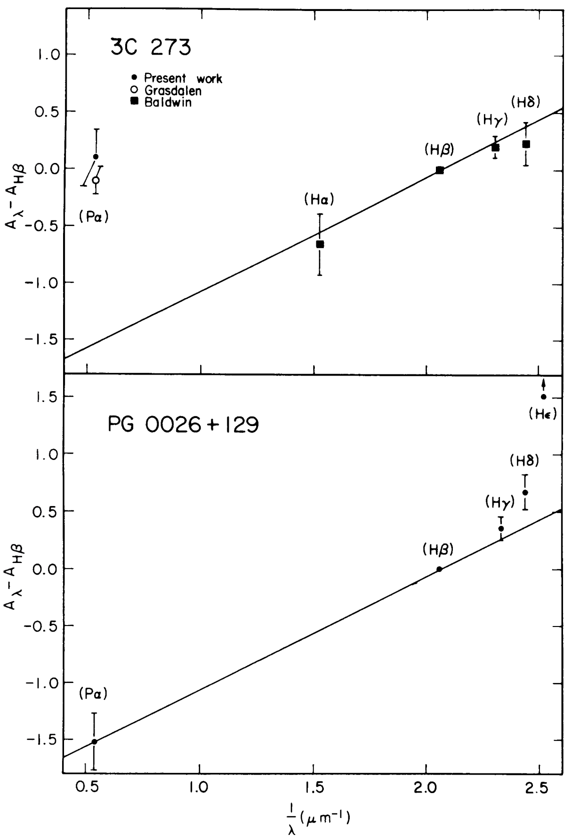

FIG. 3.—The selective extinction as a function of wavelength inferred from PG 0026+129 and 3C 273 for Case B recombination-line ratios reddened by dust. A 1/λ extinction law (corresponding to $E_{B-V} = 0.42$) is plotted for comparison.

These results point to the necessity for a more detailed treatment of the radiative transfer. As pointed out by Krolik and McKee, an escape probability formalism breaks down for very large optical depths ($\tau_{\mathrm{L}\alpha} \gtrsim 10^4$). This is because the radiation field, which is a function of optical depth, affects the level populations and thus the photon creation and destruction rates. In any case, the physical conditions are considerably different from those found in galactic H II regions, which have been the basis for previous emission-line models. The consequences of a detailed treatment of the radiative transfer in QSO emission-line regions are currently being investigated.

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J. L. PIPHER: Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

R. C. PUETTER, HARDING E. SMITH, and S. P. WILLNER: Department of Physics, C-011, University of California, San Diego, La Jolla, CA 92093

B. T. SOIFER: Department of Physics, Downes Lab, California Institute of Technology, Pasadena, CA 92093