

INFRARED SPECTROPHOTOMETRY OF THE MOST LUMINOUS QUASAR S5 0014 + 81¹

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ABSTRACT

Spectrophotometric and broad-band infrared observations are reported for the most luminous quasar: S5 0014 + 81. $H\beta$ and the [O III] $\lambda\lambda 4959 + 5007$ emission lines are detected at a redshift of 3.41, in agreement with the optically determined redshift. S5 0014 + 81 is the first object at such high redshift in which $H\beta$ and [O III] have been measured separately, showing rest frame equivalent widths of 37 and 31 Å, respectively. The relatively high $Ly\alpha/H\beta$ ratio of 10.5 may be shaped by radiative transfer processes with little or no internal reddening. At the high-luminosity end represented by this quasar, a narrow-line region seems to be well established; the [O III] lines still seem to act as luminosity indicators over six and one-half orders of magnitude.

Subject headings: cosmology — infrared: spectra — quasars — spectrophotometry

I. INTRODUCTION

In a previous *Letter* Kühr *et al.* (1983, hereafter Paper I) reported optical, spectroscopic, and polarimetric observations of the flat spectrum radio source S5 0014 + 81 from the MPIfR 5 GHz S5 survey (Kühr *et al.* 1981). This source is of special interest as (a) it is almost certainly the most luminous quasar yet detected, (b) it has a redshift of $z = 3.41$ and a rich Lyman “forest” of absorption systems, (c) with an apparent brightness of $m_v = 16.5$ mag it is especially suitable for more detailed studies, and (d) at a redshift of 3.41 the $H\beta$ and [O III] $\lambda\lambda 4959, 5007$ lines are shifted into the atmospheric window at 2.2 μm . The study of these emission lines is important for understanding the properties of the emission-line regions of quasars and for applications in cosmology. The latter is based on the fact that the [O III]/ $H\beta$ ratio in QSOs and active galactic nuclei might be used as a standard candle, a redshift-independent measure for absolute luminosities (e.g., Yee 1980; Steiner 1981).

In this *Letter* we wish to report on near-infrared observations of S5 0014 + 81 taken at the Multiple Mirror Telescope (MMT) which revealed a 3000 Å feature (“bump”) and apparently faint $H\beta$ and [O III] $\lambda\lambda 4959, 5007$ emission lines. We will discuss some implications of the observed line strength of $H\beta$, and the line ratios $Ly\alpha/H\beta$ and [O III]/ $H\beta$.

Throughout the paper $q_0 = 0$ and $H_0 = 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are assumed.

II. OBSERVATIONS

Near-infrared photometric and spectrophotometric observations of S5 0014 + 81 were obtained using an infrared photometer on the 4.5 m MMT. The photometric measurements were made on the nights of 1982 October 29/30, November 3/4

and 4/5, and 1984 February 11/12 in the J , H , and K bands (1.25, 1.65, and 2.2 μm) through a 9" aperture with a chop of 12" in elevation. The measurements were transformed into flux densities using the standard system described in Elias *et al.* (1982) and are accurate to better than 0.03 mag in each color.

The spectrophotometric observations employed a circular variable filter (CVF) with a resolution $\lambda/\Delta\lambda = 100$. As an accurate redshift was not known at the time, the spectral region scanned was between 2.03 and 2.26 μm , ensuring the coverage of the $H\beta$ and [O III] lines for redshifts between 3.35 and 3.45. The aperture and chop spacings were the same as for the photometric measurements. S5 0014 + 81 was scanned on six nights: 1982 October 29/30 and 30/31, November 3/4 and 4/5, and 1983 January 24/25 and 28/29. The spacing between adjacent points was set to be one-half the nominal resolution of the CVF. In the reduction process the averaged scans were compared on a point-by-point basis with those measured for the nearby, bright star, HR 158. The ratios were then calibrated by scaling to the K band flux density for HR 158. The flux density for S5 0014 + 81 averaged over the entire scan agrees, within the errors, with the broad-band K flux for the quasar.

III. RESULTS

The results of the photometric measurements in the J , H , and K bands are given in Table 1, which shows magnitudes and corresponding flux densities together with their calculated uncertainties. The spectrophotometric results, to be described below, show that $H\beta$ and [O III] emission enhances the K band flux by about 5%. Assuming that Mg II $\lambda 2798$ and Fe II emission increase the J band flux by about 5%, too, and correcting for a galactic reddening value of $E(B - V) = 0.24$ (Burstein and Heiles 1982) using the reddening curve of Rieke and Lebofsky (1984), we derive corrected flux densities for the infrared continuum which are also given in Table 1. The latter

¹Research reported here is based on observations obtained with the Multiple Mirror Telescope Observatory (MMTO), a joint facility of the Smithsonian Institution and the University of Arizona.

TABLE 1
PHOTOMETRIC OBSERVATIONS OF S5 0014+81

Filter	λ_{eff} (μm)	Mag	S (mJy)	S_{corr} (mJy)
J	1.25	14.84 ± 0.03	2.05 ± 0.06	2.48 ± 0.08
H	1.65	14.29 ± 0.03	2.08 ± 0.06	2.35 ± 0.08
K	2.22	13.68 ± 0.03	2.29 ± 0.06	2.47 ± 0.08

values are used to calculate the overall spectral index: $\alpha_K^J = 0.02 \pm 0.12$; this flat spectrum together with the steep spectrum observed in the visible indicates the existence of a strong $\lambda 3000$ Å “bump” seen in many QSOs and Seyfert galaxies (e.g., Grandi 1982).

The observational results from our spectrophotometric measurements are given in Table 2 and shown in Figure 1. The spectrum displays what appear to be two emission features at 2.15 and 2.21 μm . If we assume these to be $H\beta$ and [O III] $\lambda 5007$ lines, the redshift of the object would be $z = 3.41 \pm 0.01$. This agrees with the optically determined redshift and confirms the identification of the lines.

We have used a nonlinear least squares fitting routine to estimate the line strengths for $H\beta$ and the two [O III] lines and to estimate the continuum placement. The continuum has been assumed to be a power law of the form $S_\nu \propto \nu^{-0.3}$; the spectral index has been determined from the H and K broad-band measurements. Note that an unweighted least squares fit to the points designated by an asterisk in Table 2 yields a slope of -0.4 . In the fitting routine, the two points at 2.028 and 2.076 μm were not used, as they fall on the positions of telluric CO_2 features.

We have assumed that the lines can be described by Gaussian profiles. Because the [O III] lines are unresolved, the FWHM of the profiles were chosen to be $\Delta\lambda/\lambda = 0.013$, corresponding to the instrumental width at 2.2 μm (1.1%) plus

TABLE 2
SPECTROPHOTOMETRY OF S5 0014+81

Channel	λ (μm)	S (mJy)
1	2.028	1.23 ± 0.34
2*	2.040	1.80 ± 0.30
3*	2.052	1.85 ± 0.36
4*	2.064	2.05 ± 0.36
5	2.076	1.51 ± 0.22
6*	2.088	1.65 ± 0.20
7*	2.100	1.84 ± 0.19
8*	2.112	1.84 ± 0.20
9*	2.124	2.06 ± 0.02
10	2.136	2.46 ± 0.20
11	2.148	2.53 ± 0.20
12	2.160	2.36 ± 0.20
13	2.172	2.29 ± 0.21
14	2.184	2.29 ± 0.21
15	2.196	2.19 ± 0.21
16	2.208	2.56 ± 0.22
17	2.220	2.34 ± 0.22
18*	2.232	2.05 ± 0.22
19*	2.244	2.02 ± 0.22
20*	2.255	1.72 ± 0.23

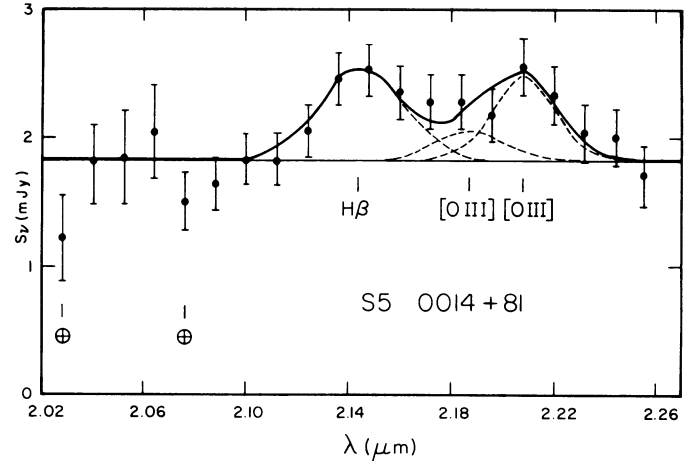


FIG. 1.—Fluxed spectrophotometric measurements of $H\beta$ and [O III] $\lambda\lambda 4959, 5007$ with the CVF, uncorrected for galactic reddening. Shown are also the expected redshifted positions of the lines (Paper I), and least squares fits to the data (dashed lines). The total derived spectrum is represented by a heavy solid line.

an uncertainty of 0.2% owing to possible instability in the positioning of the CVF over the six observing sessions. The $\lambda 4959$ line was assumed to be one-third the strength of $\lambda 5007$. In the fitting routine, the free parameters were therefore the level of the power-law continuum, the width and height of the $H\beta$ profile, and the height of the [O III] lines.

The fit is shown in Figure 1. The light solid line shows the underlying continuum, while the dashed lines show the profiles of the three lines. The heavy solid line represents the total derived spectrum.

The fit yields a reduced $\chi_\nu^2 = 0.35$, which is more than acceptable; however, such a low value for χ_ν^2 also means that the acceptable range for the parameters is large. For $H\beta$ we derive an observed line flux of 1.96×10^{-14} ergs cm^{-2} s^{-1} and a FWHM of $\Delta\lambda/\lambda = 0.0185$, corresponding to a velocity width of about 5600 km s^{-1} ; this is somewhat less than that found for $\text{Ly}\alpha$ in the optical. The total observed line strength for the [O III] lines is found to be 1.56×10^{-14} ergs cm^{-2} s^{-1} . We estimate that the uncertainties in the strengths of both the $H\beta$ and the [O III] lines do not exceed 20%, and indeed the uncertainty in the strength of $H\beta$ provided by the fitting routine (where error estimates are available for both the width and height of the line) is 12.5%.

The fluxes derived correspond to enormous line luminosities. Using the aforementioned values for H_0 and q_0 and correcting for galactic reddening (Burstein and Heiles 1982; Rieke and Lebofsky 1984), we find $F_{H\beta} = 6.4 \times 10^{45}$ ergs s^{-1} and $F_{[\text{O III}]} = 5.2 \times 10^{45}$ ergs s^{-1} . The equivalent widths for $H\beta$ and the [O III] lines are 37 Å and 31 Å, respectively, in the rest frame. In the following, only reddening corrected values are used.

IV. DISCUSSION

a) The Redshift

The redshift of $z = 3.41 \pm 0.01$ calculated from the observed positions of the $H\beta$ and [O III] $\lambda\lambda 4959, 5007$ lines

confirms the value of 3.41 ± 0.01 derived from the C IV $\lambda 1549$ and C III] $\lambda 1909$ lines (Paper I).

b) Variability

The infrared photometry extends over more than a year; during this time no flux variations were detected within the observational accuracy of about 5%.

c) The H β Line Luminosity

Studies in QSOs, broad-line galaxies, and narrow-line galaxies have generally shown a strong correlation between luminosities in H α and H β versus the nonthermal continuum with a slope close to unity in a $\log L_{\text{H}\alpha, \text{H}\beta} / \log L_{\text{NT}}$ diagram (e.g., Weedman 1976; Yee 1980; Shuder 1981). In order to see whether this still holds for a much more luminous object than previously studied, we can compare our observational result with that found by Yee (1980) for 105 QSOs, radio galaxies, and Seyfert galaxies. We assume that the observed continuum flux in S5 0014+81 is totally nonthermal and derive a continuum luminosity over a 3000–9500 Å bandpass in the rest frame of the QSO by using our corrected infrared measurements between 1.2 and 2.2 μm and an estimated spectral slope of -0.7 between 2.2 and 4.2 μm (the slope of -0.7 arises from a simple interpolation of continuum measurements at 3 mm and our broad-band flux at K band). This yields $L_{\text{NT}} = (1.50 \pm 0.11) \times 10^{48} \text{ ergs s}^{-1}$.

According to Yee (1980) the quantity $D_{\text{H}\beta}$, defined as

$$D_{\text{H}\beta} = \log L_{\text{NT}} - \log L_{\text{H}\beta},$$

averages to $D_{\text{H}\beta} = 1.77 \pm 0.24$ for the total sample and 1.89 ± 0.24 for the QSOs alone; the value derived from S5 0014+81 is $D_{\text{H}\beta} = 2.37 \pm 0.09$. Relative to the nonthermal continuum H β in S5 0014+81 is thus fainter by a factor of 4.0 in comparison with lower luminosity QSOs. Since the equivalent width of Ly α is also small (23 Å in the rest frame), as are values of C IV (6.2 Å) and C III] (6 Å), it is likely that the covering factor for the broad-line region in S5 0014+81 is less than in typical QSOs of lower luminosity. Lawrence and Elvis (1982) have discussed the apparent decrease in the covering factor of the broad-line region with increasing luminosity indicated by the X-ray absorption; S5 0014+81 may represent the continuation of this effect at high luminosity.

d) The Ly α to H β Ratio

We derive a ratio of the line strength of Ly α (see Paper I) to that of H β of 10.5 ± 2.3 . Although the ratio expected from normal recombination theory is bigger by a factor of about 3, our line ratio is surprisingly high compared with typical values of about 6 found in lower luminosity QSOs (Puetter *et al.* 1981). It also exceeds values predicted by the radiative transfer models of Kwan and Krolik (1979) and Canfield and Puetter (1981). If the latter models are indicative of the physical conditions in the broad-line region of S5 0014+81 it follows that very little or no internal reddening can take place.

e) The [O III] to H β Ratio—A Luminosity Indicator?

The spectral resolution and signal-to-noise of our observations permit us to deconvolve the [O III] lines from H β . We

can thus study the relationship between [O III]/H β and continuum luminosity, discussed by several authors, at the extreme luminosity represented by S5 0014+81.

Yee (1980) found that for a large number of QSOs and galaxies with active nuclei, the [O III] $\lambda\lambda 4959 + 5007$ luminosity does not scale exactly with the nonthermal luminosity as does the H β luminosity; a formal regression fit yielded a slope of 0.8 ± 0.2 (in a more recent study by Yee [1984] the significance of this result was improved by using H β luminosities instead of nonthermal luminosities). This suggests the potential of the [O III]/H β value as a luminosity indicator. Subsequently, Steiner (1981) tightened the correlation by restricting it to objects with Fe II emission and concluded that it could be used to determine the cosmological parameter q_0 .

Conversely Rudy (1984) has investigated the correlation as a function of luminosity and finds that while it is strong for the type 1 Seyfert galaxies (which constitute the majority of Steiner's class A objects), it weakens considerably for the more luminous QSOs, the objects which can be observed at the greatest distances and thus are the more useful in deriving q_0 .

A strong motivation for us to carry out the measurements presented in this paper was to assess the usefulness of the relationship between [O III]/H β and luminosity to cosmology by observing a high-redshift object.

In regard to the analysis of Steiner, our ground-based observations cannot determine whether S5 0014+81 shows any Fe II multiplets in its spectrum; however, the radio properties and the existence of the 3000 Å “bump” resemble those of the class A objects. We calculate the ratio of the fluxes of the [O III] lines and H β to be $\log r([\text{O III}]/\text{H}\beta) = -0.09 \pm 0.12$. Extrapolating Steiner's (1981) data, however, yields a predicted value of $\log r([\text{O III}]/\text{H}\beta) = -1.3$. This places our derived line ratio up by a factor of 16 over the predicted ratio. As the weakness of H β luminosity in S5 0014+81 cannot account for the total difference, we conclude that the [O III] lines are unusually strong and thus do not support the correlation toward higher H β luminosities.

The [O III]/H β ratio measured for S5 0014+81 is significantly higher than predicted by extrapolating Yee's (1984) data. This is due principally to the weak H β line. The ratio [O III] versus nonthermal continuum, however, supports Yee's (1980) correlation. Thus our measurements suggest that the [O III] $\lambda\lambda 4959 + 5007$ lines may still be useful as an indicator of absolute luminosity.

In summary, it appears that in S5 0014+81 all emission lines normally associated with the broad-line region have small equivalent widths. One straightforward explanation would be a decrease of the covering factor of the broad-line region with increasing luminosity.² The detection of the surprisingly strong forbidden [O III] $\lambda\lambda 4959, 5007$ lines indicates that the narrow-line region persists at the very highest luminosities.

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²As radiative transfer effects, however, seem to influence the observed line ratios, we cannot rule out that they may also alter the intensity ratios of the broad emission lines relative to the continuum.

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