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THE SYSTEMIC REDSHIFT OF THE QUASAR 1331+170

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ABSTRACT

Infrared spectra covering the 1.6 and 2 μm regions of the quasar 1331+170, redshift $z = 2.09$, were obtained with the CGS4 spectrometer at the UK Infrared Telescope. These spectra show redshifted Hα, Hβ, and [O III] lines. The redshifts of the forbidden lines are similar to the low-ionization lines measured at optical wavelengths but are significantly higher than the high-ionization line redshift. Thus the low-ionization lines are likely to provide a reliable estimate for the systematic redshift in this object, and the high-ionization material is therefore flowing out from, or into, the quasar and is subject to some obscuration.
Subject headings: line profiles — quasars

1. INTRODUCTION

Work by Gaskell (1982) and Wilkes (1984) showed that there are systematic profile and velocity differences between the ultraviolet emission lines seen shifted to optical wavelengths in the spectra of high-redshift quasars. Subsequent detailed studies (Espey et al. 1989; Corbin 1990) have confirmed this finding. For example, Espey et al. measured line profiles for Lyα, C IV λ1549, C III] λ1909, Mg II λ2798, and Hα in a number of quasars. They showed that for their sample the high-ionization lines and Lyα have lower redshifts by around 1000 km s^{-1} compared to the low-ionization lines and Hα. A number of possible explanations for these velocity differences have been suggested. They generally involve bulk mass flows and internal obscuration in the quasar, but since the true redshifts of the quasars were not known, it has been difficult to choose between them. One obvious way forward is to measure the forbidden line redshifts. Since these are expected to arise in the extended emission regions, they should therefore provide a reasonably accurate value of the systemic redshift for the quasar.

There have been previous attempts to measure the forbidden lines in high-redshift quasars, but these have not been of sufficient accuracy to permit useful estimates of the redshift. Kühr et al. (1984) report the detection of the [O III] λλ4959, 5007 lines in the $z = 3.4$ quasar 0014+81, but in this case all lines have the same redshift to within the errors. Espey et al. (1989) attempted to measure the same lines in the quasar 1100−264, at a redshift of $z = 2.14$, in which there is a significant velocity shift between ionization levels, but they failed to attain sufficient signal-to-noise ratio in their spectrum to detect the lines.

We report here the measurement of Balmer line and [O III] emission shifted to infrared wavelengths in the spectrum of the quasar 1331+170 which has a redshift of 2.09. This quasar was first discovered as part of a radio source identification program (Baldwin, Wampler, & Gaskell 1973) and was chosen for this study because it is known to have a large velocity shift between low- and high-ionization lines (Espey et al. 1989). It thus provides a straightforward example of the profile differences between the various broad emission lines.

2. OBSERVATIONS

A spectrum of 1331+170 covering the H window was obtained using the Cooled Grating Spectrometer CGS4 (Mountain et al. 1990) during its first scheduled commissioning run on UKIRT on 1991 February 11, and subsequent spectra in both H and K were obtained in 1991 April. The detector for all observations was a SBRC 62×58 InSb array. Since the pixel size of 76 μm corresponds to 3″, to adequately sample the instrument profile, the detector was moved in the spectral direction between exposures. The first observation consisted of 24 object/sky pairs at three detector positions each with an exposure time of 20 s. The total integration time on the source was 24 minutes, with an equal time devoted to sky observations. For subsequent observations the object was switched between two defined positions along the slit, and the remainder of the slit was used to measure the sky. During all the H-band

TABLE 1

OBSERVATIONS

Date (1991)	Exposure (minutes)	Grating (lines mm^{-1})	Order	Wavelength Range (μm)	Substeps per Pixel	Resolution ($\lambda/\delta\lambda$)	Comments
Feb 11	24	75	1	1.41–1.82	3	200	Plus 24 minutes of sky observation
Apr 7	115	75	2	1.43–1.64	2	450	Efficiency low
Apr 21	27	75	1	1.95–2.34	3	~300	

exposures, the array was read out using a multiple nondestructive scheme (Chapman et al. 1990), resulting in an effective read noise of 30 electrons per exposure. This, combined with a dark current plus background seen by the array of less than 10 electrons per second per pixel, meant that all the observations were background noise–limited. Details of the observations are given in Table 1.

To extract the object spectrum, the sum of the object minus sky frames was formed, and then an optimal extraction performed using the method described by Horne (1986). The wavelength scales were determined from argon lamp exposures combined with the positions of sky emission lines present in the object exposures.

To determine the [O III] redshift $z = 2.095$ and line fluxes, we have used the fact that the [O III] λ5007:[O III] λ4959 flux ratio is 3:1 and fitted single Gaussian profiles to the lines in the Hβ/[O III] blend. The measured forbidden line widths are close to those of the comparison arc lines, so we are unable to comment on the intrinsic FWHM of the [O III] lines, apart from quoting an upper limit of around 1500 km s^{-1}. The other parameters for the emission lines are contained in Table 2.

The 2 μm spectrum shows strong broad Hα emission and no other discernible features (Fig. 1). An arc calibration was not taken for this spectrum, so the wavelengths were determined from the sky features. For this reason we are unable to determine the spectral resolution directly, but use the known spectrograph characteristics to give an estimate in Table 1. The redshift given in Table 2 is the result of a Gaussian fit to the line. Against the assumed continuum, the formal uncertainty in the velocity is ~100 km s^{-1}, but the result also depends on the

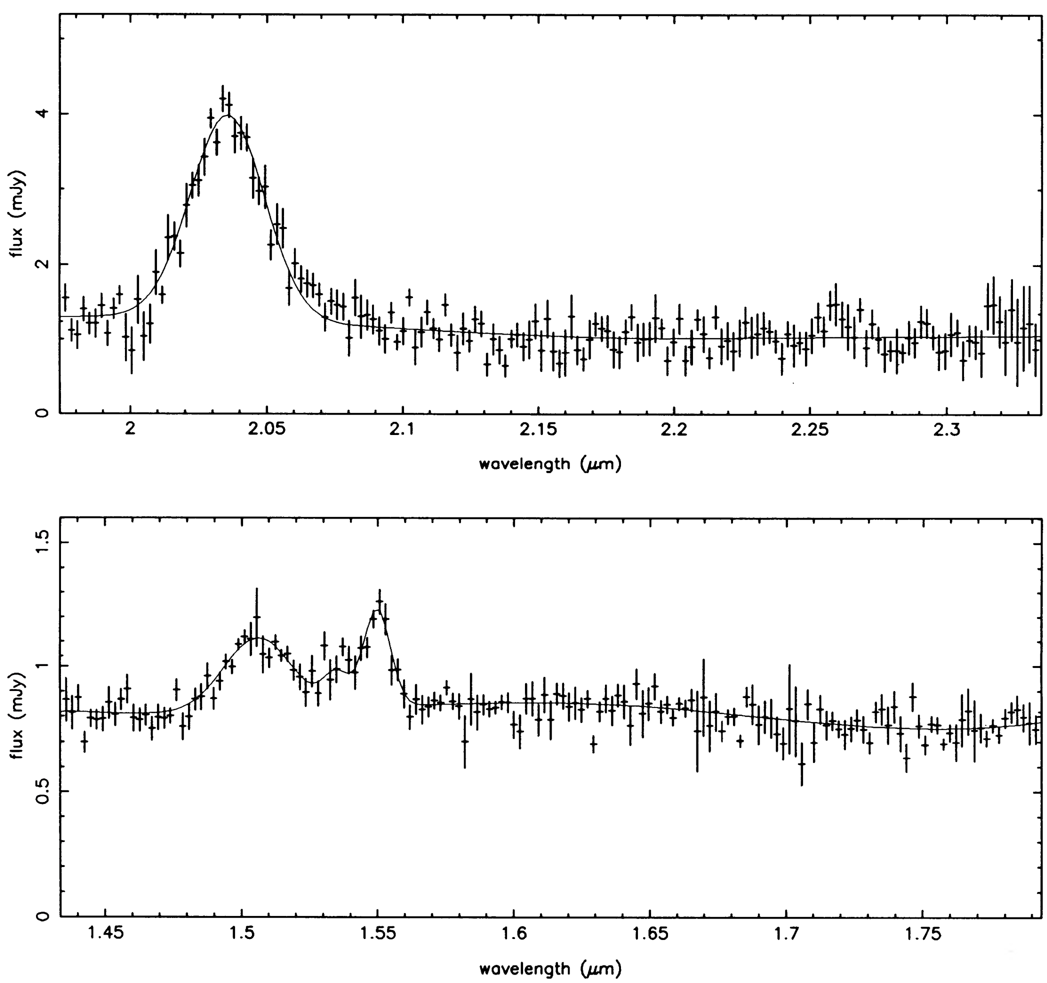

FIG. 1.—The CGS4 spectra of 1331+170. The vertical bars indicate the $\pm 1\ \sigma$ error range at each data value. Redshifted Hα is at 2.035 μm, Hβ at 1.505 μm, and [O III] λ5007 at 1.545 μm. The fainter continuous curves show the fitted profiles.

continuum placement and slope. Trials with different subsets of the data suggest that the typical uncertainty in the velocity measures is about 200–300 km s^{-1}.

3. DISCUSSION

The *H*-window spectrum shows the redshifted Hβ and [O III] λλ4959, 5007 emission lines at redshift $z = 2.095$ (Fig. 1), and an otherwise featureless continuum. The spectral resolution is sufficiently high that the lines should be clearly separated, but at the signal-to-noise ratio achieved the [O III] λ4959 line is poorly defined. We believe that the lines we have identified as [O III] are predominantly [O III] and not Fe II emission from multiplet 42 at wavelengths 4924 and 5018 Å (in contrast with 3C 273; Shuder 1984). This is because the feature is clearly narrower than Hβ and there is no sign of the other component of Fe II multiplet 42, Fe II λ5169. Also, Fe II emission is generally quite weak in this object—Fe II emission from multiplets 48 and 49 around 5300 Å is not seen in our spectra, and the spectra used by Espey et al. (1989) do not show particularly strong Fe II emission in the region below the Mg II λ2798 emission line.

The [O III] λλ4959 + 5077/Hβ intensity ratio is ∼0.75. This is similar to the ratio ∼0.85 found from CVF spectra of the quasar 0014 + 81 at a redshift of $z = 3.4$ (Kuhr et al. 1984) and is within the range found for lower redshift lower luminosity quasars (see, e.g., Baldwin 1975; Steiner 1981). If these values are typical of bright high-redshift quasars, then the low-redshift example, 3C 273, with [O III]/Hβ ∼ 0.12 (Shuder 1984), is therefore atypical of the class.

The CGS4 data presented here supplement the line profile measurements obtained by Espey et al. (1989) for Lyα–Mg II λ2798 and Hα. Espey et al. found that the high-ionization lines (and Lyα) are blueshifted with respect to the low-ionization lines (plus Hα) in 1331 + 170 and other high-redshift quasars. In the case of 1331 + 170, the velocity shift is about 1000 km s^{-1}, and the dilemma from the earlier study was to identify which lines should be used to determine the true redshift. Since the forbidden lines arise in extended regions beyond the broad-line region where the velocities are considerably lower, they should provide a means of determining the redshift without such ambiguities. Thus the redshift determined from [O III] λ5007, $z = 2.095$, is the true (systemic) redshift of 1331 + 170. This agrees well with the redshift of Mg II λ2798 and (less certainly) O I λ1305 from Espey et al., so the low-ionization lines have a mean redshift close to that of the quasar (see Table 2). The emission-line profiles are shown in Figure 2.

It is clear that these velocity differences require the presence of some form of bulk gas motions, which are different for the various lines concerned. The direction of the flow remains ambiguous. If the obscuration is external to the emission clouds (e.g., as for an accretion disk or distributed continuous absorption near the central continuum source), then the material responsible for the high-ionization emission lines must be flowing out from the quasar. Infall models with electron scattering (Kallman & Krolik 1986), or obscuring material associated with the emission clouds, could equally well explain the observational data.

Our conclusion that the high-ionization material is in bulk flow and suffering obscuration depends on the assumption that the system redshift is given by [O III]. A study of Seyfert galaxies by Whittle (1991) shows that the [O III] peak velocity is generally a good indicator of the systemic velocity, so our assumption appears reasonable. It is possible, however, that in

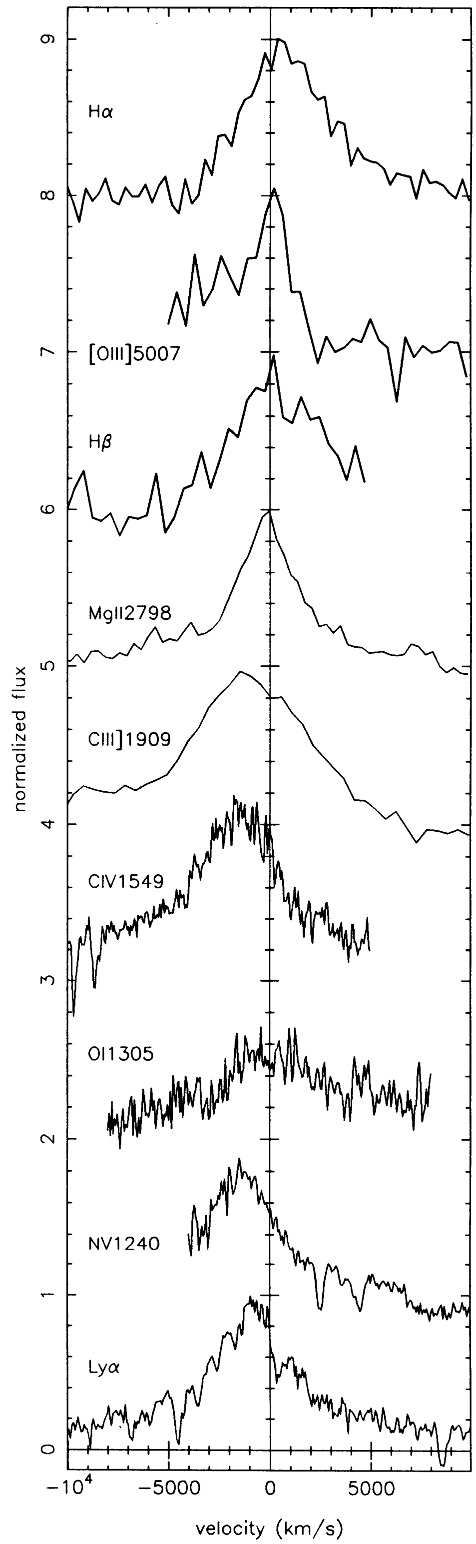

FIG. 2.—Profiles of the emission lines in 1331 + 170, reduced to a velocity scale relative to a redshift of $z = 2.095$. The Mg II λ2798 and shorter wavelength lines are from Epsey et al. (1989). The Lyα and N V λ1240 lines are blended in the original spectrum, so for the purposes of illustration they have been separated using the C IV λ1549 line as a template. The Lyα profile shown is the result of subtracting 0.9 × the C IV λ1549 line profile shifted to N V λ1240, and the N V λ1240 profile is the result of subtracting 1.8 × the C IV λ1549 shifted to Lyα.

TABLE 2

EMISSION-LINE PARAMETERS

Line	z	EW (Å) (rest)	FWHM (km s^{-1})	Velocity cf. [O III]	Observation Date(s)
Hα	2.101	250	4600	600	1991 Apr 21
[O III] λ5007	2.095	20	1100	...	1991 Feb 11 and Apr 7
[O III] λ4959	2.095	6	1100	...	1991 Feb 11 and Apr 7
Hβ	2.097	36	5700	250	1991 Feb 11 and Apr 7
Hα	2.103	140	3000	800	1987 Mar 16 and 1988 May 1
Mg II λ2798	2.094	16	3200	−100	1988 May 26
C III] λ1909	2.085	22	6600	−1000	1988 May 26
C IV λ1549	2.077	19	4500	−1800	1988 May 26
O I λ1305	2.095	4	3500	0	1988 May 26
N V λ1240	2.080	...	4500	−1500	1988 May 26
Lyα	2.083	...	4800	−1200	1988 May 26

an individual case the [O III] emission may arise from material which is itself in bulk motion as, for example, in the Seyfert galaxy Markarian 78 (de Robertis 1987).

The Hα line flux is $\sim 6.5 \times 10^{-17}$ W m^{-2}, and that of Hβ is 1.2×10^{-17} W m^{-2}, so the Hα/Hβ ratio is ~5.5. This value is uncertain, since the spectra were obtained through a 3" slit, so the photometric accuracy may not be very high. Indeed, the sections of continuum observed are flat and suggest that a constant continuum level ~1 mJy over the wavelength range might be appropriate. Using a normalization to make the continua levels match, the Balmer line ratio is ~4.2. Also, we have not allowed for the possible presence of [N II] λλ6548, 6584 emission as a contaminant of the Hα line. It is difficult to do this unambiguously, but a best fit using the [O III] parameters as templates suggests that about 33% of the feature could be due to forbidden [N II] and [S II]. Thus the Hα/Hβ flux ratio is likely to be lower than 5.5 and is probably between 3.7 and 5.5. This is within the range found for many lower redshift quasars and active galactic nuclei (e.g. Baldwin 1975; Rudy 1984; Baldwin et al. 1989).

Comparison of the Hα line in the 1991 CGS4 spectrum with that obtained using FIGS at the AAT in 1987 and 1988 reveals some interesting differences. The line equivalent width has increased since the earlier spectra by a factor of about 1.8. The absolute fluxes for these measurements are uncertain since the conditions were not necessarily photometric, but it appears that the continuum flux has decreased by a factor of 2 since the earlier observations. This could naturally account for the change in the Hα line equivalent width.

However, there is evidence that the Hα line has also varied, since there is a large discrepancy between the Hα line profile widths at the two epochs. The 1991 data give Hα FWHM 4500 km s^{-1}, while the 1987–1988 material yields 3000 km s^{-1}. It is hard to see how this difference could arise because of differences in the instrument resolution (~800 km s^{-1} for both the CGS4 and the FIGS data), or as a result of the wings of the line being lost in the continuum, so the most plausible explanation is an intrinsic variation in the Hα profile. Comparison of the optical data from 1987–1988 with those published by Baldwin et al. (1973) shows that any changes in the high-ionization line widths or equivalent widths over 15 yr have been small.

4. CONCLUSIONS

The Hα/Hβ flux ratio in 1331+170 has a value ~3.5–5.5, which is similar to that observed in low-redshift quasars. The Hβ line is broader than Hα; this is a common property of active galaxies and low-redshift quasars (Osterbrock & Shuder 1982), and these lines also have a slightly different redshift. The profile width of the Hα line seems to have increased significantly, and the continuum flux decreased, over a time scale ~1 yr in the quasar's frame, indicating a characteristic size for the Balmer line–emitting region $\lesssim$1 lt-yr.

We have detected [O III] λ5007 at a redshift of 2.095. Comparison with other lines in this object shows that the low-ionization lines have similar redshifts, while the high-ionization material appears to have a systematic velocity toward us with respect to the low-ionization material. If this is true for all quasars which show similar velocity shifts and assuming the forbidden lines are at the systemic redshift, then the high-resolution material must be in ordered motion and suffer some obscuration to explain the differential velocities.

Observations of the forbidden lines in a sample of objects are required to establish reliably which of the broad lines are good indicators of the systemic redshift. Using the new generation of infrared spectrographs, such as CGS4, these observations are now feasible for quasars with redshifts around 2.

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