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A $3 \times 10^9\ M_\odot$ BLACK HOLE IN THE QUASAR SDSS J1148+5251 AT $z = 6.41$

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ABSTRACT

We present near-infrared *H*- and *K*-band spectra of the $z = 6.41$ quasar SDSS J114816.64+525150.3. The spectrum reveals a broad Mg II λ2799 emission line with an FWHM of 6000 km s^{-1}. From the peak wavelength of this emission line, we obtain a more accurate redshift than is possible from the published optical spectrum and determine a redshift of $z = 6.41 \pm 0.01$. If the true peak of the Lyα emission is at the same redshift, then a large fraction of the flux blueward of the peak is absorbed. The equivalent width of the Mg II emission line is similar to that of lower redshift quasars, suggesting that the UV continuum is not dominated by a beamed component. Making basic assumptions about the line-emitting gas, we derive a mass estimate of $3 \times 10^9\ M_\odot$ for the central black hole in this quasar. The very high luminosity of the quasar shows that it is accreting at the maximal allowable rate for a black hole of this mass, adopting the Eddington limit criterion.

Subject headings: galaxies: formation — quasars: emission lines — quasars: individual (SDSS J114816.64+525150.3)

1. INTRODUCTION

The vast energy requirements of the most luminous quasars can be met by a model invoking the extraction of gravitational potential energy from matter falling toward a supermassive ($\sim 10^9\ M_\odot$) black hole. The correlation between black hole mass and galaxy mass observed in the local universe strongly suggests that the most luminous quasars will reside in the most massive galaxies in the most massive dark matter halos. The luminous quasars at redshifts $z > 6$ found in the Sloan Digital Sky Survey (SDSS) therefore pinpoint the earliest massive objects to form (Fan et al. 2001, 2003).

The recent discovery of SDSS J114816.64+525150.3 (hereafter SDSS J1148+5251) at a redshift of $z = 6.43$ by Fan et al. (2003) makes it the most distant known quasar, observed only 840 million years after the beginning of the universe (cosmological parameters of $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ are assumed throughout). The very high luminosity of this quasar ($M_{1450} = -27.8$) suggests that it contains a black hole mass of at least several billion solar masses.

We have obtained near-infrared spectroscopy of SDSS J1148+5251 in order to search for the Mg II emission line (with a rest wavelength of 2799 Å) redshifted into the *K* band. This line is particularly useful since it is usually found close to the systemic redshift, unlike higher ionization lines such as C IV that typically show large blueshifts of $\sim$1000 km s^{-1} (Richards et al. 2002). The redshift for this quasar given by Fan et al. was based on the position of a heavily absorbed Lyα line and the onset of the Lyman break and is therefore quite uncertain. An accurate redshift is important for determining the strength of the proximity effect and for molecular line searches. Additionally, it has recently been shown that the width of the Mg II emission line can be used to derive the mass of a quasar's central black hole in the same way that the Hβ line has traditionally been used (McLure & Jarvis 2002).

We describe the spectroscopic observations and measurements made from them in § 2. The importance of the new redshift determination is discussed in § 3. We determine an estimate for the mass of the black hole in § 4. Our conclusions are presented in § 5.

2. NEAR-INFRARED SPECTROSCOPY

2.1. *Observations*

We observed SDSS J1148+5251 with the United Kingdom Infra-Red Telescope (UKIRT) equipped with the UKIRT Imager Spectrometer (UIST) on 2003 January 10. UIST is a 1–5 μm imager-spectrometer with a 1024 × 1024 InSb array. Conditions were photometric, with seeing at the *K* band approximately 0″.6. The *HK* grism was employed with a 0″.48 wide slit giving continuous wavelength coverage from 1.4 to 2.5 μm with a resolving power of $\sim$500. The pixels have size 10.9 Å spectrally and 0″.12 spatially. The target was nodded along the slit a distance of 12″ in between exposures to enable accurate sky subtraction. The total integration time of the observation was 6480 s.

The data frames were flat-fielded, and then adjacent pairs were subtracted from each other in order to subtract the sky emission and produce positive and negative spectra of the target. These data were combined, and any pixels deviating from the mean at the 3 σ level were excluded since this indicates contamination by cosmic rays. The residual background level was subtracted from the combined image. The positive and negative quasar spectra were extracted from this image using apertures of 1″.0 and combined.

Flux calibration and atmospheric extinction corrections were made by dividing the spectrum by that of a star of spectral type F6 that was observed immediately preceding the quasar. An accurate wavelength calibration was made by comparison with an argon arc lamp. This solution was then checked against the positions of about 20 sky emission lines, giving an rms uncertainty in the wavelength calibration of 1 Å. The absolute flux scale of the spectrum was set by comparison with the magnitude measured in a snapshot *K*-band image. The image gave $K = 16.86 \pm 0.05$, consistent with the $K' = 16.91$ quoted by Fan et al. (2003).

2.2. *Emission-Line Fitting*

The spectrum of SDSS J1148+5251 is shown in Figure 1. It shows a broad emission line at approximately the position expected for redshifted Mg II. To determine the wavelength and width of the Mg II emission line, a line-fitting process was applied that involves the determination of the underlying continuum and Fe II emission surrounding the Mg II line. Due to the blending of the Mg II line emission and the Fe II features in the 2700–2900 Å region, the fitting of the continuum and Fe II emission is confined to two bands on either side of the Mg II line (with rest frames of 2250–2700 Å and 2900–3100 Å, respectively).

The Fe II emission in this spectral region is modeled using an Fe II template based on an archival *Hubble Space Telescope* Faint Object Spectrograph spectrum of the narrow-line Seyfert galaxy I Zw 1, which is notable for its extremely strong Fe II emission. Due to the fact that the Fe II emission in I Zw 1 is relatively narrow (FWHM ~ 900 km s^{-1}), this template can be smoothed in order to match the much broader Fe II features typical of powerful quasars. The fitting of the Fe II emission template and active galactic nucleus (AGN) continuum are performed simultaneously, with the amplitude and FWHM of the Fe II iron template left as free parameters. The AGN continuum is modeled as a power law that is normalized with the continuum magnitude (at a rest frame of 1280 Å) of $AB_{1280} = 19.10$ given by Fan et al. (2003). The spectral index of the power law is a free parameter, and the fitting produces a value of $\alpha = 0.2$ (defining $f_\nu \propto \nu^{-\alpha}$, where f_ν is the flux density at frequency ν). This continuum slope is typical of quasars (e.g., Vanden Berk et al. 2001). The goodness of fit for the Fe II+continuum fit is determined from a χ^2 test using the noise array from the observation.

Once the minimum χ^2 fit has been determined, the best-fitting combination of continuum and Fe II emission is then subtracted from the spectrum, leaving the isolated Mg II emission line in the 2700–2900 Å region. The Mg II emission line itself is then modeled using two identical Gaussians that represent the line doublet λλ2796, 2802. During the fitting of the line profile, the amplitude, FWHM, and central wavelength of the Gaussians are treated as free parameters, while the doublet separation is held fixed at its laboratory value. The best fit to the Mg II emission was determined with a χ^2 test. Although more complex deconvolutions of the line profile are obviously possible, due to the signal-to-noise ratio constraints of the spectrum, the above procedure was adopted because it was able to effectively describe the Mg II line profile with the minimum level of complexity.

We also performed an alternative fitting procedure in which the continuum was fixed at two points with low expected Fe II emission and then the Mg II and Fe II features fitted simultaneously. The results from this independent fitting method are consistent with those using the former method. The ratio of Fe II to Mg II emission lines in high-redshift quasars is a powerful diagnostic of early element production inside supernovae (Yoshii, Tsujimoto, & Kawara 1998). Unfortunately, we do not have a sufficient signal-to-noise ratio to place meaningful constraints on this ratio using either of our two fitting methods.

The best-fit Mg II line doublet in SDSS J1148+5251 is at a redshift of $z = 6.41 \pm 0.01$. The deconvolved FWHM of each component of the doublet is 6000^{+1100}_{-600} km s^{-1}. The rest-

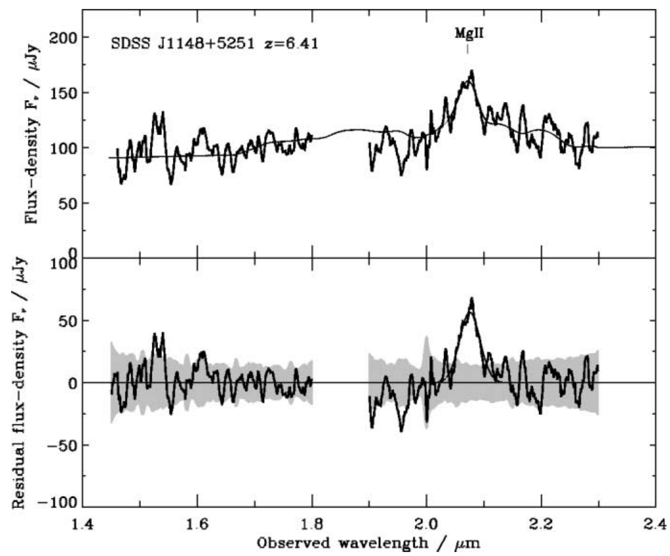

FIG. 1.—*Upper panel:* UIST *H*- and *K*-band spectrum of SDSS J1148+5251 (*thick line*; smoothed with a 7 pixel boxcar). The location of the broad Mg II emission line is marked. The smooth curve shows the best fit comprising a power-law continuum ($\alpha = 0.2$), a broadened Fe II template, and a broad Mg II line. *Lower panel:* Residual spectrum after subtraction of the power-law continuum and Fe II template (*thick line*). The best fit to the broad Mg II doublet (FWHM = 6000 km s^{-1}) is also shown here (*thin line*). The shaded region shows the $\pm 1\ \sigma$ noise level of the observation.

frame equivalent width of the Mg II line is 35 Å. The typical equivalent width of Mg II lines in lower redshift SDSS quasars is 32 Å (Vanden Berk et al. 2001). The fact that the equivalent width of Mg II in SDSS J1148+5251 is similar to that of other quasars indicates that the UV continuum emission from this quasar is not strongly beamed. Fan et al. (2003) noted that the Lyα equivalent widths of this and other $z \sim 6$ quasars are smaller than lower redshift quasars. Pentericci et al. (2002) observed the C IV line in the $z = 6.28$ quasar SDSS J1030+0524 and also found an equivalent width typical of lower redshift quasars. These results suggest that the low Lyα equivalent widths are primarily due to Lyα absorption and not to a fundamental difference between the emission properties of these quasars.

3. AN ACCURATE REDSHIFT DETERMINATION

The redshift of $z = 6.43 \pm 0.05$ for this quasar given in Fan et al. (2003) is based on the position of the heavily absorbed Lyα line and the onset of the Lyman break. The lack of distinguishable N V emission or any other lines in the optical spectrum means that a more accurate redshift could not be obtained. In our spectrum, we are able to measure the location of the Mg II line and hence obtain a more accurate redshift for this quasar. We find a redshift of $z = 6.41 \pm 0.01$. The Mg II line is particularly useful for redshift estimation compared with, for example, C IV, which could be observed in the *J* band. The low-ionization Mg II line is usually found close to the systemic redshift, whereas the high-ionization C IV line often shows blueshifts of several thousand kilometers per second (Richards et al. 2002). Another important fact is that there is no systematic velocity offset for the Lyα and Mg II lines in a large sample of SDSS quasars (Vanden Berk et al. 2001), so we can predict the intrinsic, unabsorbed Lyα line peak.

Accurate redshifts for the most distant quasars are important for several reasons. The rest-frame UV spectra of $z \sim 6$ quasars show a deficit of flux shortward of Lyα because of absorption by neutral hydrogen in the intergalactic medium (IGM; Fan et al. 2001; Becker et al. 2001). These observations have led to the possibility that we are now witnessing the epoch of reionization. While accurate quasar redshifts are not essential for determining the ionization state of the universe as a function of redshift, they are very important when dealing with the state of the IGM close to the quasar.

Assuming that the IGM in general is neutral at the redshift of the quasar, the strong ionizing field of the quasar will ionize a local region around the quasar, allowing Lyα photons to be transmitted. This *proximity effect* has been observed as a lack of absorption lines in the spectra of quasars close to the peak of Lyα (Bajtlik, Duncan, & Ostriker 1988). Cen & Haiman (2000) show that the size of this ionized region and the transmitted flux blueward of the peak of Lyα depend on the number of ionizing photons that have been emitted from the quasar, i.e., the product of its lifetime and luminosity. Haiman & Cen (2002) apply this to the spectrum of the $z = 6.28$ quasar SDSS J1030+0524 to show that it is not strongly gravitationally lensed and to derive a lower limit on how long the quasar has been active. Such an analysis depends critically on knowing where the peak of the Lyα line should be in the spectrum.

The spectrum of SDSS J1148+5251 presented by Fan et al. (2003) also shows zero flux at Lyα redshifts of 5.7–6.33, suggestive of a neutral universe. However, there is some flux apparent on the blue wing of Lyα that is likely due to the proximity effect. The marked location of Lyα at $z = 6.43$ given by Fan et al. is at the peak of the Lyα emission. However, adopting the new redshift of $z = 6.41$ for the quasar shifts the location of Lyα to 9010 Å, which is coincident with a steep decline in flux to less than half of the peak value. Hence, the revised redshift indicates a substantially more neutral IGM close to the quasar. The amount and extent of transmitted flux on the blue side of Lyα are similar to that in SDSS J1030+0524, and the conclusions about this quasar made by Haiman & Cen (2002) and Pentericci et al. (2002) probably apply equally to SDSS J1148+5251.

The evolutionary state of the host galaxies of high-redshift quasars can be probed by (sub)millimeter observations of dust and molecular gas. Particularly important tracers are the emission lines from transitions of CO molecules and carbon atoms (Blain et al. 2000). However, current millimeter receivers have a fairly small bandwidth corresponding to ~2000 km s^{-1}. Hence, systemic redshifts must be known to an accuracy of ~0.01 to ensure that the emission line will fall within the frequency range of the observation. Our observations of SDSS J1148+5251 provide a redshift of sufficient accuracy for millimeter line searches.

4. ESTIMATING THE BLACK HOLE MASS

Reverberation mapping studies of low-redshift quasars have been successfully employed to estimate the masses of their black holes (Netzer & Peterson 1997). This method determines the radial distance of the broad-line–emitting region (BLR) from the nucleus ($R_{\rm BLR}$), by observing the time lag (~1 yr) between variations in the UV/optical continuum and the line strength. Combining this distance with the velocity of the emission-line gas ($V_{\rm BLR}$, which is closely related to the observed FWHM of the line) gives a virial estimate of the black hole mass ($M_{\rm bh} = G^{-1}R_{\rm BLR}V^2_{\rm BLR}$). This estimate assumes that the dynamics of the gas is dominated by gravitational forces (see Peterson & Wandel 2000 for a discussion). These reverberation studies have revealed a correlation between the continuum luminosity and the radius of the BLR that can be used to estimate black hole masses when only the line FWHM and luminosity are available (Kaspi et al. 2000).

Traditionally, the Hβ emission line has been used for this work since it is readily observable in the optical spectra of low-redshift quasars where the reverberation mapping calibration of luminosity and BLR has been derived. Recently, McLure & Jarvis (2002) have cross-calibrated this relationship from the Hβ line to the Mg II line using a sample of AGNs with reverberation mapping measures of $R_{\rm BLR}$, so that black hole mass estimates can be derived to higher redshifts. They note that the Mg II line (which has an ionization potential close to that of Hβ) is a much better choice than higher ionization lines like C IV whose dynamics may be strongly influenced by outflows. McLure & Jarvis derived a calibration between $R_{\rm BLR}$ and L_{3000} (the monochromatic luminosity at 3000 Å) and performed a fit to the Hβ and Mg II FWHMs, finding a linear relationship with virtually identical normalization. The resulting black hole mass estimator has the form

$$\frac{M_{\rm bh}}{M_\odot} = 3.37 \left(\frac{\lambda L_{3000}}{10^{37}\ {\rm W}}\right)^{0.47} \left[\frac{\rm FWHM(Mg\ II)}{\rm km\ s^{-1}}\right]^2 . \qquad (1)$$

Our spectrum covers the rest wavelength region of 3000 Å, and we have determined the Mg II FWHM. Therefore, we can apply this formula to derive an estimate of the black hole mass in SDSS J1148+5251. Using $\lambda L_{3000} = 6.2 \times 10^{39}$ W and FWHM(Mg II) $= 6000$ km s^{-1}, we get $M_{\rm bh} = 3 \times 10^9\ M_\odot$. Assuming that $z \sim 6$ quasars are not fundamentally different from low-redshift quasars (evidence supporting this is that their spectra are similar), the accuracy of this black hole mass estimator with respect to those from reverberation mapping is a factor of 2.5 (1 σ).

This is an extremely massive black hole to be in existence such a short time (840 Myr) after the beginning of the universe. Assuming that this black hole is residing in a proportionately massive halo (~$10^{13}\ M_\odot$), then standard theories of structure formation predict that this is one of the rarest, most massive halos to have collapsed by this time (e.g., Haiman & Loeb 2001; Fan et al. 2001). There are two caveats to the derived black hole mass. Since the estimator depends on $L^{0.47}_{3000}$, if we have overestimated the intrinsic, isotropic luminosity, we will have overestimated the black hole mass. If the luminosity function of $z \sim 6$ quasars has a steep slope, then there are expectations that a significant fraction of the SDSS $z \sim 6$ quasars will have their luminosities enhanced by either gravitational lensing or beaming (Turner 1991; Wyithe & Loeb 2002a). Fan et al. (2003) discussed K'-band images of the three new $z \sim 6$ quasars and found that none of them show evidence of gravitational lensing. Our spectrum shows that the equivalent width of the Mg II line is typical of quasars, which suggests that the continuum luminosity is not strongly enhanced by beaming. Therefore, the available evidence suggests that there is minimal amplification of the intrinsic quasar luminosity.

It is interesting to consider the maximum luminosity that can be attained by an accreting black hole of this mass. This is usually considered to be the Eddington limit at which the outward radiation pressure equals the inward gravitational attraction. The Eddington limit for a black hole of mass $3 \times 10^9\ M_\odot$ is 4×10^{40} W. Using a bolometric correction of 7 to get the bolometric luminosity from λL_{3000} (Wandel, Peterson, & Malkan 1999), we determine a bolometric luminosity for SDSS J1148+5251 of $L = 4 \times 10^{40}$ W. Therefore, we find that the black hole in this quasar is radiating the maximal amount possible. This supports the often made assumption when relating quasar luminosities to black hole and halo masses that the highest redshift quasars are accreting at the Eddington limit (e.g., Fan et al. 2001; Wyithe & Loeb 2002b). It is not too surprising to find that SDSS J1148+5251 has the minimum-size black hole given its luminosity. As mentioned above, the short cosmic time available for the growth of supermassive black holes by this redshift means black holes with such masses will only have arisen within rare collapsed peaks. In such conditions, there is likely to be a plentiful gas supply to fuel the quasar, and the black hole is expected to be accreting close to its Eddington limit.

5. CONCLUSIONS

We have presented *H* and *K* spectra of the quasar SDSS J1148+5251, which currently has the highest known redshift. We clearly detect the broad Mg II emission line. Fitting the location of this emission line, we derive a redshift of $z = 6.41 \pm 0.01$. The equivalent width of this line is similar to that of lower redshift SDSS quasars, suggesting that the optical continuum is not strongly beamed. We obtain a virial estimate of the black hole mass of $M_{bh} = 3 \times 10^9\ M_\odot$. The quasar is radiating at the Eddington luminosity, in line with the expectation that it is easier to fuel a supermassive black hole than create one at such an early epoch. Similar observations of other $z > 6$ quasars would reveal whether or not they are all radiating at the Eddington luminosity.

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