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MULTIPLE-MIRROR TELESCOPE OBSERVATIONS OF THE TWIN QSOs 0957+561 A, B

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ABSTRACT

We present spectroscopic observations of the twin QSOs 0957+561 A, B obtained with the multiple-mirror telescope. The spectral similarities of the two objects reported by Walsh, Carswell, and Weymann are confirmed and strengthened. In particular, the absorption-line redshifts are found to differ by 7 ± 15 km s^{-1}. We examine hypotheses conventionally used to account for the origin of QSO absorption-line systems and have difficulty explaining such close agreement in the redshifts. The possibility that a gravitational lens is responsible for forming two images of a single QSO is discussed.

Subject headings: galaxies: redshifts — quasars

I. INTRODUCTION

The announcement of the discovery of the "twin" QSOs 0957+561 A, B and a description of some of their remarkable properties have recently been published by Walsh, Carswell, and Weymann (1979, hereafter WCW). These properties include the following: (*a*) The emission-line redshifts of C IV λ1549 from the two objects are the same to within the errors of measurement as are those of C III] λ1909, though the C IV and C III redshifts differ. (*b*) The equivalent widths of the C IV lines in A and B agree to within the errors of measurement, as do those of C III and O IV. (*c*) A strong, low-ionization absorption-line system with slightly lower redshift than the emission-line system occurs in both QSOs, but is stronger in A than in B. The two absorption-line redshifts are the same to within the errors of measurement.

Other emission features are present but were either very weak or fell outside the region of the high signal-to-noise ratio and were not measured. In particular, WCW could not accurately compare the Mg II emission lines.

In addition, although the highest resolution (2 Å) spectra on which the absorption-line discussion was based allow relative velocities of lines in the spectrum of the same object to be measured with substantially greater precision than WCW's quoted 75 km s^{-1} uncertainty, their external errors limit the precision with which velocity differences between lines in different spectra can be determined.

Accordingly, the observations described below were undertaken to compare the properties of the Mg II emission lines and to measure more accurately whatever velocity differences exist between the absorption-line systems.

II. OBSERVATIONS

Observations were obtained on the nights of 1979 April 20–22 UT using the Mount Hopkins 60 inch (1.5 m) telescope's moderate resolution spectrograph and photon counting Reticon detector (Davis and Latham 1979) on the multiple-mirror telescope (MMT). These are among the first scientific results obtained with the MMT, which has an equivalent aperture of 4.5 m. Because the MMT active optics have not yet been implemented, the six secondaries were co-aligned manually for the present observations. The entrance slit was 0.5 × 1.0 mm, corresponding to 1″.8 × 3″.6 at the MMT focal plane. The spectrograph produces a reciprocal dispersion of 42 Å mm^{-1}, and this slit projects to 4 Å at the spectrograph focal plane.

Five exposures were obtained of each QSO, totaling 100 and 120 minute integrations for A and B, respectively. Each QSO was observed alternately in each of the two spectrograph channels (star, sky) to reduce

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any systematic effects, and comparison lamp exposures were taken every 15 minutes during observations. Incandescent lamp exposures were taken for several hours after each night's observing to be used to remove fixed pattern noise (Davis and Latham 1979), and an exposure of the spectrophotometric standard EG-67 (Oke 1974) was used to convert the observations to flux units.

The wavelength as a function of pixel number was fitted with a fifth-order polynomial for each exposure, and the spectra were interpolated onto a linear wavelength scale before they were added. The software for these operations is part of the operating system for the spectrograph (Tonry and Davis 1979), so that many of them can be carried out in real time at the telescope.

III. RESULTS

Figure 1 shows the sum of the spectra of each QSO, and Table 1 summarizes the wavelengths and equivalent widths of both the emission and the absorption lines. The redshifts are geocentric, air-to-air, and the equivalent widths are in the observer's frame. The emission-line redshifts were determined simply by finding the wavelength of the line of symmetry about the central peaks. Alternatively, by fitting a fifth-order polynomial to the Mg II emission features after excising the absorption lines, we arrived at a separate measurement of the emission redshifts, with resulting velocity difference $\Delta v_{\rm em}$ (A − B) = -50 ± 50 (p.e.) km s^{-1}. The equivalent widths of the two emission lines were determined by smoothing the profiles by eye and fitting the continuum with a straight line.

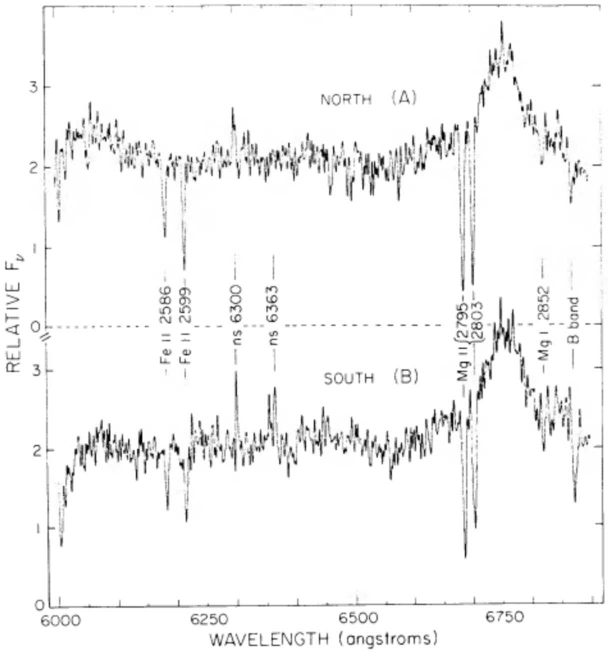

FIG. 1.—Spectra of the two QSOs 0957+561 A, B obtained with the Mount Hopkins photon-counting spectrograph attached to the multiple-mirror telescope. The resolution is 4 Å FWHM. The roll-off below 6050 Å is an instrumental artifact.

The absorption-line wavelengths were found by a software algorithm which locates the center of the line, and the equivalent widths were measured by hand. Omitting the Mg I redshift, which is poorly determined, we find that the mean redshifts are 1.3913 and 1.3912 for A and B, respectively. This corresponds to a velocity difference $\Delta v_{\rm abs}$ (A − B) = 12 km s^{-1}.

A separate cross-correlation analysis was performed on the absorption spectrum using the methods described by Tonry and Davis (1979). The correlation analysis was performed between 6100 Å and 6760 Å and was dominated by the Fe II and Mg II lines. Continuum and noise contributions were first removed by subtracting a fourth-order polynomial and then band-pass filtering the remainder. The cross-correlation peak yielded $\Delta v_{\rm abs}$ (A − B) = 7 ± 15 (p.e.) km s^{-1}.

IV. DISCUSSION

These results further emphasize the remarkable spectroscopic similarity of both the emission- and absorption-line features noted by WCW. These similarities are discussed in detail below.

a) All equivalent widths and redshifts of the emission-line features agree to within the errors of measurement. In this regard, Baldwin and Netzer (1978) determined the C III/C IV equivalent width ratio in a sample of 12 high-redshift QSOs to be 0.59 ± 0.45. From WCW's data on 0957+561 A, B the same ratio is found to be 0.79 ± 0.13. Additional very accurate measurements of this ratio in other QSOs would serve to establish the statistical significance of this result, but it appears that A and B are much more similar to each other than a pair selected at random from Baldwin and Netzer's data.

b) There appear to be real differences in the redshifts

TABLE 1

REDSHIFTS AND EQUIVALENT WIDTHS IN 0957+561A, B

	0957+561 A			0957+561 B		
IDENTIFICATION	$\lambda_{\rm air}$	Redshift	W_λ (Å)	$\lambda_{\rm air}$	Redshift	W_λ (Å)
Mg II 2797.9 (em)........	6753	1.4136	85 ± 12	6753	1.4136	76 ± 12
Mg I 2852.1 (abs)........	6820.4:	1.3913:	...	6819.5:	1.3910:	...
Mg II 2802.7 (abs).......	6701.6	1.3911	5.2	6702.2	1.3913	4.8
Mg II 2797.5 (abs).......	6684.6	1.3913	4.8	6684.7	1.3913	5.0
Fe II 2599.4 (abs)........	6216.0	1.3913	2.8	6214.8	1.3909	2.4
Fe II 2585.9 (abs)........	6184.1	1.3915	2.4	6183.6	1.3913	1.8

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of the C IV, C III, and Mg II emission lines within the same object, and it is of interest that these differences are the same for the two objects. Measurements of such differences in a larger sample of QSOs would be worthwhile.

c) The absorption-line equivalent widths appear to confirm the results of WCW that the absorption lines are stronger in A than in B. However, we note that the lines appear to be strongly saturated, and until data of substantially higher resolution are obtained, a curve-of-growth analysis is not meaningful. In particular, it is not clear that the column density of gas in the line of sight to A necessarily exceeds that to B.

d) The much more stringent limit ($\sim$15 km s^{-1}) set by the present data on the velocity difference between the absorption-line systems in the two spectra makes any explanation very difficult which postulates the existence of two distinct QSOs. In particular, ejection of the cloud by one object seen in projection against the other now requires the shell to be $\gtrsim$585 kpc from the ejecting QSO. Similarly, any explanation of the absorption involving clouds associated with either an intervening galaxy or a cluster of galaxies requires no differential motion in the line of sight exceeding $\sim$15 km s^{-1} across a distance of $\sim$68 kpc.

The alternative explanation involving a gravitational lens significantly eases the difficulties described above, since two lines of sight diverging from the continuum source at an angle of $\sim 6''$ would pass through the absorbing cloud at a separation of only 10 pc, if the absorbing cloud were 300 kpc from the source. Such a distance is reasonable if the cloud is associated with a galaxy in the same cluster as the QSO (Weymann *et al.* 1979). Even if the cloud is associated with cosmologically intervening material, the separation is only of order 1 kpc.

V. SUGGESTIONS FOR FURTHER OBSERVATIONS

Whether or not the images are formed by a gravitational lens, a number of additional observations suggest themselves. Some of these were discussed by WCW, but we list them for completeness. The first three assume that the lens hypothesis is correct.

1. Double images should appear at all wavelengths, provided the source at these wavelengths is at least as compact as that giving rise to the optical emission lines. Observations in the radio and X-ray regions are in progress by several groups, and single images would render the lens hypothesis untenable.

2. Since the two QSOs are quite similar in brightness, the deflecting mass should lie almost halfway between them in the plane of the sky. (For a detailed discussion of the theory of gravitational lenses in a cosmological context, see Press and Gunn 1973, hereafter PG, whose treatment we adopt.) If the deflector is luminous it might be detectable on deep plates of the region. At present, we can say only that no image is present having m_R brighter than about 22 mag, but several groups are obtaining and reducing data which reach substantially fainter limits than this.

This is already an interesting limit, if the deflector is a galaxy. Consider a (truncated) isothermal sphere characterized by line-of-sight velocity dispersion σ and central density ρ_c. From a straightforward development of the theory presented in PG for the case where the images have comparable brightness, the angular separation of the images can be expressed as

$$\Theta''_{\text{sep}} = 3''.2\left[\frac{\sigma\ (\text{km s}^{-1})}{300}\right]^2 \eta \times \left[(1+Z)_{\text{def}}\left(1-\frac{\lambda_{\text{def}}}{\lambda_{\text{source}}}\right)\right], \qquad (1)$$

where λ_{source} is the affine parameter of the source and λ_{def} the affine parameter of the deflector having redshift Z_{def}. The relation between the affine parameter and the redshift is especially simple for the $q_0 = 0$ and $q_0 = \frac{1}{2}$ cosmological models and is given by

$$\lambda = (1/n)\{1 - [1/(1+Z)]^n\}\ , \qquad (2)$$

where $n = 2$ for $q_0 = 0$ and $n = 2.5$ for $q_0 = \frac{1}{2}$. The parameter η allows for the effect of mass external to the impact parameter b. Provided the sphere extends to a distance $\gtrsim 2b$ and provided $b \gg r_0 = \sigma/(4\pi G\rho_c)^{1/2}$, $\eta \approx 1.5$. Of course, if the deflector has a complex nonspherical structure, the situation is more complicated.

The factor in the second set of brackets in equation (1) decreases monotonically from 1 to 0 as the deflector is moved from very small redshifts out to the redshift of the source. For $z_{\text{source}} = 1.4$ and $z_{\text{def}} = 0.7$ and a $q_0 = 0$ model, for example, it is equal to 0.355. The observed separation ($5''.7$) would then require $\sigma = 550$ km s^{-1}, which is substantially larger than any observed value in a galaxy. Even allowing for the fact that the luminous material in galaxies may be embedded in a nonluminous or very low luminosity component having a substantially larger value of σ than the luminous component (Whitmore, Kirshner, and Schechter 1979), reasonable values of σ can be obtained only if the deflector is moved to quite small redshifts ($z_{\text{def}} \lesssim 0.2$), in which case a giant elliptical galaxy should easily be seen on even moderately deep direct images.

3. There is a lag in the time of any variations of the two images resulting from the geometrical difference in their path lengths and from the different gravitational potential experienced by photons traveling those paths (see, e.g., Cooke and Kantowski 1975, eqs. [12] and [20]; Sanitt 1976, eqs. [1] and [12] of the Appendix). At the present time we can estimate only that it is of the order of months. A measurement of the value of such a lag could provide quantitative information about the nature of the deflecting mass. Thus photometric monitoring of the two images for several years at all wavelengths would be of great interest.

Regardless of whether the lens hypothesis proves correct, the following two observations should be undertaken.

1. Observations at very high signal-to-noise ratio covering the visible region will reveal just how identical the emission-line properties really are.

2. High-resolution ($\gtrsim 10^4$) spectroscopy of both the optical and 21 cm absorption lines should be able to detect a velocity difference between the two systems. It may also allow partial resolution of the velocity structure within each system, so that a meaningful curve-of-growth analysis can be carried out.

Early observations with the MMT required the assistance of a large number of people associated both directly and indirectly with the project. Bas van't Sant and Bill Wyatt spent many days moving spectrograph, computer, and associated hardware from the Mount Hopkins 60 inch telescope to the MMT, debugging them once installed, and returning them to the 60 inch at the end of the run. David Latham assembled a new image tube package for the spectrograph's TV guider on very short notice when the old one failed 5 days before the run. Mike Reed, J. T. Williams, and their staffs cooperated in every way under trying conditions. In particular, Steve McArthur and Wes Potts, the telescope operators on the nights these observations were made, were most helpful and patient in the midst of the chaos.

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