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FURTHER VLB OBSERVATIONS OF THE REDSHIFTED H I ABSORPTION IN AO 0235+164

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ABSTRACT

VLB observations of the 932 MHz H I absorption line and continuum of the BL Lacertae object AO 0235+164 with projected baselines of $1.8 \times 10^7 \lambda$ have failed to reveal any transverse spatial differences between the emitting and absorbing regions. The apparent source size is probably not broadened by scattering in the absorbing region. A 3 rms upper limit of 0.12 km s^{-1} to the velocity change of the absorber between 1976 December and 1977 July was set. The corresponding acceleration of less than 1×10^{-3} cm s^{-2} indicates that the absorbing region is probably more than 3 kpc away from the continuum source.

Subject headings: BL Lacertae objects — interferometry — radio sources: general

I. INTRODUCTION

Recently we reported a VLB observation of the high-redshift, neutral-hydrogen absorption line at $z = 0.524$ in AO 0235+164 with a baseline of $7.9 \times 10^6\lambda$ (Wolfe *et al.* 1978). The source and absorber appeared totally unresolved. In order to learn more about the spatial structure of the emission and absorption regions, higher-resolution VLB observations have been made.

II. OBSERVATIONS

The three elements of the interferometer were the 305 m antenna of the National Astronomy and Ionosphere Center[3] near Arecibo, Puerto Rico, the 100 m antenna of the Max-Planck Institut für Radioastronomie near Effelsberg, West Germany, and the 43 m antenna of the National Radio Astronomy Observatory (NRAO)[4] at Green Bank, West Virginia. The relevant parameters for each telescope and the three baselines are given in Tables 1 and 2.

The observations were obtained 1977 July 13–14. All the data were recorded using the 1 MHz bandwidth of the NRAO Mark II VLBI terminals. The feed polarization was linear at all three sites. At Arecibo, the *E*-vector was aligned perpendicular to the azimuth, while at Green Bank and Bonn the *E*-vector was north-south. Since AO 0235+164 passes close to the zenith at Arecibo and data were not recorded within 5° of the zenith at this site, the *E*-vectors of all antennas were coincident to within 5° during the observations. On both days the source was observed for approximately 4 hours at Green Bank and Bonn. Because of its tracking limitations, Arecibo could observe for only 2 hours each day. Approximately 1.5 hours of data were obtained off the source for use in correcting non-uniformities in the bandpass characteristics of the VLB video converter.

The data were reduced on the NRAO Mark II processor in Charlottesville, Virginia (Clark 1973). The output from the processor were cross-correlation (interference) spectra with 96 independent frequency points for a single baseline and a 96 point autocorrelation function for each telescope. The spectral resolution

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TABLE 1

SYSTEM PARAMETERS

Station	Telescope Diameter (m)	System Temperature (K)	Aperture Efficiency (%)	Sensitivity (Jy/K)	Frequency Standard	Polarization
Bonn................	100	600	0.55	0.64	rubidium	linear
Arecibo..............	140[a]	125	0.55	0.27	rubidium	linear
Green Bank..........	43	140	0.30	6.4	H-maser	linear

[a] A phase-correcting line feed illuminated only a diameter of 140 m of the full 305 m diameter.

was 12.5 kHz, or 4.02 km s^{-1}. The cross-correlation spectra were coherently averaged for 12–15 minutes after fringe rate and delay offsets had been removed. Then final averages of all the data for each baseline were made. The autocorrelation functions were averaged and Fourier transformed to give power (single antenna) spectra having equal resolution to that of the cross-correlated spectra. All spectra were corrected for the effects of nonuniformities in the bandpass by using the data taken off source. The normalized fringe visibility was calculated for each spectral point by dividing the fringe amplitude by the geometric mean of the power spectra from the individual telescopes and dividing the result by the empirically determined constant of 1.34 to normalize the cross-correlation amplitude due to the lobe rotator and other effects. No useful spectral information was obtained on the Green Bank–Bonn baseline because of low sensitivity.

III. RESULTS

The cross-correlation phase for the Arecibo-Bonn baseline and the autocorrelation spectrum at Arecibo are shown in Figure 1. A linear baseline has been removed from the autocorrelation spectrum. The interferometer continuum visibility on the long Arecibo–Bonn baseline appears to be $\sim$0.54, while on the $\sim$2 times shorter (in projection) Arecibo–Green Bank baseline it is $\sim$0.66, and on the only 10% shorter Bonn–Green Bank baseline it is $\sim$1.0. Because this is inconsistent and previous measurements on the Arecibo–Green Bank baseline show that the visibility is close to 1.0 (Wolfe *et al.* 1978), we are led to believe that the local oscillator at Arecibo had short period instabilities ($<0^{s}2$) which caused a loss in cross-correlated signal. Additional evidence confirming this assumption are phase jumps exceeding 180° seen sometimes on baselines including Arecibo.

Correcting the Arecibo baselines for this effect yields a continuum visibility of 0.8 $\pm$ 0.2 for the long baseline—a number not securely determined. The relative values of the spectra are not beset by any systematic effects from the problem with the Arecibo local oscillator other than having poorer signal-to-noise ratios. The relative visibility amplitude is constant across the spectrum with an rms scatter of 2%. The visibility phase is constant with an rms scatter of 1°. The phase scatter within the four strong features is about twice as great as outside these features; there is also a 3 σ deviation at 932.14 MHz in the bottom of one of the four strong features. If that 3 σ variation is real, it implies that the centroid of the absorption has shifted by 4° $\pm$ 1° of phase, which in turn implies that the continuum source must be larger than 0.1 milli-arcsec, corresponding to a brightness temperature no larger than $\sim 10^{14.5}$ K for a circularly symmetric source. We must stress that the purported phase shift is marginally statistically significant.

IV. DISCUSSION

Although the velocity resolution is different (i.e., 4.02 km s^{-1} in this paper versus 1.57 km s^{-1} in Wolfe *et al.* 1978), the spectrum displayed in Figure 1 appears quite similar to that taken in 1976 December (Wolfe *et al.* 1978). Thus, there has been no significant change in the absorption spectrum despite the fact that AO 0235+164 has decreased in intensity by $\sim$20% between 1976 December and 1977 July (Wolfe and Davis 1979).

In view of the corrections for the local oscillator problems, the scaling for the visibility amplitude should be viewed with caution—as well as the associated Gaussian half-power diameter of 3 milli-arcsec derived assuming a visibility of 0.8 on the 18 Mλ projection of the Arecibo–Bonn baseline.

For the 1976 December experiment, the ratio of the equivalent width of the absorption features for the single dish and cross-correlation spectrum is 0.94 $\pm$ 0.02. For the present experiment, it is 1.01 $\pm$ 0.02 on the twice-longer Arecibo–Bonn baseline. These

TABLE 2

BASELINE PARAMETERS

Station	*BX* (m)	*BY* (m)	*BZ* (m)	Length (m)	Length (λ)	Fringe Spacing (arcseconds)
Arecibo–Bonn.................	+1643442.7	−6051753.6	+2905754.3	6911422.2	2.147×10^{7}	9.6×10^{-3}
Arecibo–GB..................	−1507614.2	− 640289.8	+1949481.5	2546242.2	7.911×10^{6}	2.6×10^{-2}
Bonn–GB.....................	−3151056.9	+5411463.8	− 956272.8	6334631.6	1.968×10^{7}	1.05×10^{-2}

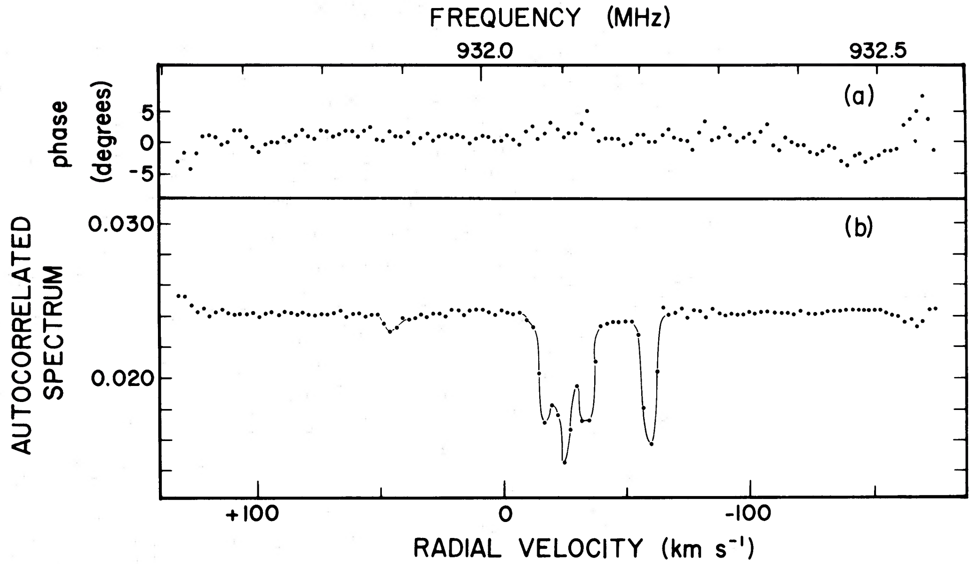

FIG. 1.—(*a*) Spectrum of the average interferometer phase and (*b*) autocorrelation spectrum at Arecibo for AO 0235+164 for 1977 July. The spectral resolution is 4.02 km s^{-1} (12.5 kHz). The radial velocity is the Doppler velocity relative to a 21 cm line redshifted by $z = 0.524$. The autocorrelated spectrum amplitude is the raw autocorrelation amplitude at Arecibo relative to a system temperature of 125 K.

numbers are not significantly different, especially when it is realized that a smaller-than-unity value of this ratio has no reasonable physical interpretation when there is no amplitude or phase variation of the complex visibility spectrum. Thus the size of the source in absorption is not detectably smaller than the unabsorbed source. There are two situations in which this can prevail: the absorbing clouds are much larger in angular size than the continuum source; or both the absorbing clouds and the continuum source are still unresolved.

Applying the Monte Carlo analysis used in Wolfe *et al.* (1978) for AO 0235+164, and correcting for the differences between the present and previous observations, one can show that a source larger than that limit set by Compton cooling is compatible only with clouds smaller than about 10 pc or larger than twice the size of the continuum source (≥ 50 pc, in order to avoid the Compton catastrophe). If the continuum source is resolved and the clouds are small, they must be distributed relatively uniformly across the face of the continuum source, independently of velocity, in order to keep the phase variations small and the equivalent widths of the single dish and interferometer absorption spectrum the same.

Thus the present observations argue for the absorber to be either many small clouds uniformly distributed across the continuum source or a few clouds rather larger than the continuum source if the continuum source is resolved. The lack of temporal variation in the spectrum in the face of variations in the continuum flux argues for this second interpretation even if the source is unresolved. If there are many small clouds rather than a few large clouds, the large gap with no large absorption between 932.15 and 932.20 MHz is surprising.

Scattering by the ionized plasma irregularities which might be associated with the H I absorbing system places no interesting constraints on the system, but could prevent the source from having interstellar scintillations. The relationship between the scattering angle Θ_s in the frame of the absorption system and Θ, the observed angular size due to scattering, in the absence of other broadening influences, is given by

$$\Theta = \frac{\Theta_s}{(1 - kL^2)^{1/2}} \frac{l_1}{l_1 + l_2},$$

where l_1 and l_2 are the (parallax) distances to us and the continuum source, respectively, from the absorbing system, and depend, along with $(1 - kL^2)^{1/2}$, on the world model chosen and the redshifts involved.

For a Milne World Model ($q_0 = 0, k = -1, \sigma_0 = 0, \lambda_0 = 0$) (von Hoerner 1974),

$$l = \frac{cz(1 + z/2)}{h(1 + z + z^2/2)}$$

and

$$(1 - kL^2)^{1/2} = \frac{1 + z(z^2/2)}{1 + z}.$$

The redshift to be used for computing this second expression should be that of the observer as seen by the absorber. The redshifts for the distances are also measured in the frame of the absorber. When the deceleration parameter is constant, redshifts do not change. If z_c is the redshift of the continuum source and z_A the redshift of the absorber, both as measured by us, then the redshift of the continuum source as measured in the frame of the absorber is given by

$$1 + z_2 = \frac{1 + z_c}{1 + z_A}.$$

With $z_c = 0.852$ and $z_A = 0.524$ we find ultimately

$$\Theta = 0.3\Theta_s .$$

Supposing that the scattering arises in an intervening galaxy, we can obtain an expression for Θ_s from scattering data in the solar neighborhood of our own Galaxy. Readhead and Duffett-Smith (1975) have given an expression for the angular size of a source, due to scattering, as a function of galactic latitude. In the same paper they show that the scale height of the turbulent plasma layer is 500 pc. Were the radiation to go through our entire galactic plane, instead of being stopped at the middle because our telescopes intercepted the radiation, then the scattering angle would be $\sqrt{2}$ larger because the scattering angle scales as the square root of the path length through the scatterer. Thus

$$\Theta_s = \frac{17\lambda^2}{(\sin i)^{1/2}} \text{ milli-arcsec} ,$$

where λ is in meters and i is the inclination angle of the intervening galaxy. For λ it is appropriate to use 0.21 m because this is the wavelength of the radiation when it is being scattered by the intervening galaxy.

Using our limit of 3 milli-arcsec for Θ we can solve for the minimum inclination angle which the intervening galaxy could have if it were like our own Galaxy in terms of its scattering properties. We find i must be greater than 0°3. For such low-inclination angles, the validity of the Readhead–Duffett-Smith results breaks down for our Galaxy as it probably would for an intervening galaxy in the sense that there should be even more scattering. Consequently, the minimum limit might be somewhat larger than 0°3. However, even a highly inclined galaxy would be able to broaden the continuum signal enough to quench interstellar scintillations of the continuum object even if its intrinsic brightness temperature were much higher. At 932 MHz, as seen by us, if the intervening galaxy is like ours, then the minimum apparent angular size is 0.2 milli-arcsec; this is large enough to inhibit interstellar scintillations.

We have also searched for changes in the velocities of the spectral features by cross-correlating the two Arecibo total-power (autocorrelation) spectra obtained in 1976 December and 1977 July. No velocity shift was observed, and the 3 rms upper limit to the velocity change of the overall absorption spectrum is 0.12 km s^{-1}. This corresponds to an upper limit of 1×10^{-3} cm s^{-2} for the acceleration of the whole absorbing region. The relative accelerations of the material producing the four strong absorptions are less than 2×10^{-3} cm s^{-2}.

V. CONCLUSIONS

Despite an increase in resolution by a factor of 2.3 over our previous observations (Wolfe *et al.* 1978), we have been unable to find any detectable transverse spatial differences in the absorbing and continuum regions in AO 0235+164. It appears now that if the clouds of absorbing hydrogen have a mean optical depth of 1, either there must be many of them $\leq$10 pc distributed uniformly (randomly) across the face of the source or else they must be greater than twice as large as the source in angular extent. The character of the spectrum (four major features) argues for the clouds being large. This could bode ill for the intervening galaxy hypothesis in that it might require clouds larger than a galaxy could sustain. Still, because the galaxy would be a lot younger than ours, perhaps the large clouds would not be unreasonable.

The neutral hydrogen cloud in front of AO 0235+164 provides an unusually strict test of ejection models for QSO absorption systems because it has such a high column density ($\sim 3 \times 10^{-3}$ gm cm^{-2} if $T_s \sim 100$) and because changes in its radial velocity can be measured so precisely by radio astronomical methods. We have already argued on geometrical grounds that the absorbing region must be quite distant from the continuum source (Wolfe *et al.* 1978). Our upper limit of $\alpha = 10^{-3}$ cm s^{-2} to the cloud acceleration provides independent evidence that the absorber is not close to the continuum source, although some means of extrapolating the present data back in time is required if a quantitative limit to their separation is to be estimated.

The absorber is moving away from the continuum source with a velocity of at least $v = 4.8 \times 10^4$ km s^{-1}. If it was radiatively accelerated, then the dynamical models of Kippenhahn, Perry, and Röser (1974) indicate that the observed high velocity and low acceleration are reached only for separations of $r = 3 \times 10^3$ pc or more. These models assume that the absorber is not always opaque in the Lyman continuum. The radiative acceleration of the optically thick clouds in front of AO 0235+164 is, to first order, independent of separation if the material is driven radially outward. Thus the separation of these clouds might have to be as high as $r \approx v^2/2\alpha = 6 \times 10^{13}$ pc to be consistent with our data. In either case, the separation is so large that the total photon momentum of the continuum source appears to be inadequate to accelerate the absorbing clouds to their present relative velocity (cf. Wolfe *et al.* 1978).

Assuming that the absorber is an intervening galaxy with an ionized turbulent component like that in our solar neighborhood, the galaxy could have almost any inclination angle and still not have detectably broadened the continuum radiation. At any inclination angle, however, the broadening would be sufficient to quench interstellar scintillations in our own Galaxy.

Since this baseline is the largest, adequately sensitive, baseline and will be for some time to come, we can learn little more directly about the source structure unless it changes—and, specifically, unless it gets large enough to observe.

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