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MODERATE-RESOLUTION SPECTROSCOPY OF THE LENSED QUASAR 2237+0305: A SEARCH FOR Ca II ABSORPTION DUE TO THE INTERSTELLAR MEDIUM IN THE FOREGROUND LENSING GALAXY

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ABSTRACT

The gravitational lens system 2237 + 0305 consists of a low-redshift barred spiral galaxy ($z = 0.0394$) centered on a more distant quasar ($z = 1.695$). Because the lensing galaxy is nearly face on, spectroscopy of the background quasar affords a unique opportunity to study the interstellar medium in the galaxy's center and bulge. We report moderate-resolution spectroscopy of QSO 2237 + 0305 yielding a 3σ upper limit of 72 mÅ for the rest equivalent width of Ca II K absorption due to gas in the intervening galaxy. Since gas in the Milky Way "thick disk" typically produces 220 mÅ Ca II lines along lines of sight at high galactic latitude, while our line of sight to QSO 2237 + 0305 is effectively the weighted mean of four lines of sight, each of which transects an entire halo diameter in the lensing galaxy rather than just a radius, our Ca II upper limit argues against the presence of such a thick disk near the center of the lensing galaxy. Also, published studies indicate that at 8200 Å, QSO 2237 + 0305 suffers roughly 0.5 mag of extinction due to the lensing galaxy. Assuming a normal gas-to-dust ratio and allowing for various sources of uncertainty, this absorption estimate combined with our Ca II K upper limit implies that calcium is depleted with respect to hydrogen by at least 2.7–3.7 dex, compared to solar abundances. This depletion is similar to the more extreme cases seen in our own galaxy, and higher-dispersion observations may further decrease the upper limit on Ca II absorption.

I. INTRODUCTION

Discovered by Huchra *et al.* (1985), the gravitational lens system 2237 + 0305 consists of a radio-quiet quasar ($z = 1.695$) in nearly perfect alignment with the center of a low-redshift barred spiral galaxy ($z = 0.0394$). The low-resolution, moderate S/N spectra presented by Huchra *et al.* demonstrate that the background QSO dominates the light near the galaxy's center; only about 10% of the flux in their spectra was contributed by the galaxy. Their spectrum 5 arcsec offset from the QSO shows that the foreground galaxy has typical stellar absorption features dominated by Ca II H and K and Mg I b. Because the lensing galaxy is nearly face on (inclination angle 65°), this system affords a unique opportunity to study the interstellar medium (ISM) in the central bulge and halo of that galaxy using absorption features seen against the quasar's continuum.

Recent imaging observations suggest that absorption lines due to the foreground galaxy's ISM should indeed be detectable. Tyson (1986) and Schneider *et al.* (1988) presented evidence that the QSO could be resolved into multiple images, as expected under the gravitational lens hypothesis. Yee (1988) cleanly resolved four separate QSO components (maximum separation 1.8 arcsec), and recent spectroscopy confirms that at least three of the components are quasars or quasar images (De Robertis and Yee 1988). Kent and Falco

(1988) found that their models of the lensing system were "reasonably successful" in reproducing Yee's imaging observations. Yee also concluded, based on the colors of the individual components of the quasar, that the QSO images are subject to approximately 0.5 mag of extinction in the "r" passband (8200 ± 600 Å) due to the ISM in the lensing galaxy. If one assumes a normal (Galactic) gas-to-dust ratio, such reddening implies that interstellar absorption lines should be detectable.

II. THE OBSERVATIONS AND DATA REDUCTIONS

QSO 2237 + 0305 was observed with the Blue Channel of the MMT Spectrograph for 100 min on the night of 28 October 1984 (UT), and for 110 min on 17 December 1984. Observations were made at a resolution of 1 Å (FWHM), covering the wavelength range 3650–4540 Å. All data were taken using the Image Stacker (Chaffee and Latham 1982) with 2.5-arcsec-diam circular entrance apertures. The seeing was not measured at the time of the observations and was difficult to estimate from the appearance of the QSO on the guiding television screen, given the presence of the underlying bulge of the lensing galaxy. The multiple nature of the QSO image was neither known nor noticed at the time of the observations. To facilitate subtraction of the polluting starlight from the spectrum of the QSO, a 15 min integration was taken of the M31 globular cluster K225-B280 on 17 December 1984, immediately following the observation of the QSO and using the same instrumental configuration.

Data reductions followed standard procedures. The spectrograph is a two-channel device, allowing nearly simulta-

^{a)} The observations reported here were obtained at the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

neous sky subtraction. The sky spectra were obtained from a position 36 arcsec offset from the QSO. Neither extinction correction nor flux calibration was carried out. Therefore, the spectra were reduced to units of photons/pixel/second versus heliocentric, vacuum wavelength. Since the detector is a photon counter, the variance of each spectrum was calculated on a pixel-by-pixel basis assuming that the noise resulted from photon noise in the object, sky, and dark signal. Data from the two apertures and the two nights were subsequently combined, weighed by the inverse of the variance spectra.

The reduced spectrum of the QSO is presented in Fig. 1. The strong, broad emission line near 4175 Å is C IV 1548 Å, 1550 Å at a redshift of $z(\text{emission}) = 1.695$. Several absorption line systems are evident in the figure. A low-ionization system demonstrating absorption by Mg II and Fe II is seen at $z(\text{absorption}) = 0.5664$, and a complex of C IV absorption appears near the emission-line redshift. The latter complex contains at least two components at $z(\text{absorption}) = 1.694$ and 1.697 and bears a resemblance to the "associated" C IV systems discussed by Foltz *et al.* (1986).

The presence of starlight at the redshift of the lensing galaxy can be seen on the extreme blue wing of the C IV emission line, where broad Ca II H and K absorption is evident. These Ca II lines are almost certainly due to starlight, since the absorption does not break up into narrow components at this spectral resolution and the strengths of the two features are nearly identical. The latter would not be the case if the observed features were blends of unsaturated Ca II doublets.

On the assumption that these broad Ca II absorption features are due to starlight, we have endeavored to remove

them by subtracting a suitably scaled spectrum of the M31 globular cluster K225-B280. To do this, we transformed the spectrum of the globular cluster to the redshift of the galaxy ($z = 0.0390$ *in vacuo*). The transformed spectrum was then scaled by the ratio of the central depth of its Ca II lines compared with the Ca II lines in the QSO 2237 + 0305 spectrum.

The resulting transformed and scaled globular cluster spectrum was then subtracted from that of the QSO. The results of this procedure are shown in Fig. 2. In Fig. 2(a), we present the region of the QSO spectrum containing the C IV emission line and the scaled, transformed spectrum of the globular cluster. The result of the subtraction is shown in Fig. 2(b), where one sees that the broad H and K features are reasonably well removed, yielding a smooth blue wing for the C IV emission in this vicinity. We are, therefore, confident that the broad H and K features are due to starlight. Note that this procedure also introduces spikes in the resulting spectrum at the positions of other strong absorption lines in the globular cluster spectrum, artifacts which are not present in the spectrum of the QSO.

Upper limits on the strength of any unresolved Ca II absorption were measured following the methods of Chaffee, Foltz, and Black (1986). The spectral regions containing the redshifted stellar H and K features were surveyed: 4080–4090 Å for the K line, 4116–4126 Å for H. The 3σ observed upper limits on their equivalent widths (EW) are 75 mÅ for the K line and 50 mÅ for H. A weak feature (EW = 60 mÅ) is seen at 4089.3 Å, but at 2.4σ , its statistical reality is marginal. We adopt 72 mÅ rest equivalent width as an upper limit on any unresolved Ca II K absorption. Note that in the case of unsaturated doublets this leads to a smaller upper

FIG. 1. Spectrum of the lensed QSO 2237 + 0305 obtained with the Blue Channel of the MMT Spectrograph. Strong absorption lines due to several absorption systems are noted, as are the Ca II H and K lines presumably arising from starlight in the lensing galaxy. The lower spectrum in each panel is the 1σ level calculated from photon statistics.

FIG. 2. (a) Top spectrum is the portion of the spectrum of 2237 + 0305 containing H and K from the lensing galaxy. The lower spectrum is that of the M31 globular cluster K225-B280, shifted to the redshift of the lensing galaxy and scaled by the depths of the H and K lines. (b) Presents the result of the subtraction of the two spectra in (a). The approximate expected position of any Ca II absorption in the lensing galaxy is indicated.

limit on the Ca II column density ($\log[N(\text{Ca II})] < 11.9$) than does the observed limit for H.

III. DISCUSSION

The somewhat surprising absence of detectable interstellar Ca II absorption from the lensing galaxy is reminiscent of the Mkn 205–NGC 4319 configuration, where the Mkn 205 line of sight passes through both the disk and halo of NGC 4319 without detectable absorption (Bowen *et al.* 1987; see also the case of 4C 39.47, Hintzen *et al.* 1989). As noted by Blades (1988), such nondetections are as significant as detections in unraveling the properties of the interstellar media in galaxies.

The 2.5-arcsec diam aperture used in our spectroscopic observations included all known components of the QSO, so our 72 mÅ, 3σ upper limit for the combined rest equivalent widths of any Ca II K lines applies to the weighted average of the QSO components.

The upper limit on Ca II K can be directly compared with absorption observed within the Milky Way. York (1982) notes that, for sources at high galactic latitude, various observers find a mean Ca II K absorption equivalent width of 250 mÅ. Morton and Blades (1986) detected Ca II absorption in each of 25 extragalactic sources over a wide range of galactic latitudes. The measured Ca II K equivalent widths ranged from 80 to 400 mÅ, with a mean of 220 mÅ. A similar distribution of absorption systems near the center of the 2237 + 0305 lensing galaxy appears to be ruled out by the present observations, since our line of sight is effectively the weighted mean of four lines of sight, each of which transects an entire halo diameter, rather than just half. Since Morton and Blades conclude that Ca II in the Milky Way is concentrated in a thick disk with scale height $1 (+1, -0.5)$ kpc, our upper limit seems to exclude the possibility of such a thick disk in the bulge of the lensing galaxy.

Morton and Blades also report higher-velocity Ca II absorption in six of 14 cases where their resolution was sufficient to detect such features, and they attribute this absorp-

tion to halo clouds outside the Ca II “thick disk.” Absorption by these “halo clouds” is weaker, averaging 100 ± 50 mÅ EW for Ca II K. In 2237 + 0305, the 1.3–1.8 arcsec separation of the four QSO images corresponds to 700–1000 pc in the projected plane of the lensing galaxy ($H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$). If one assumes that any halo clouds in the lensing galaxy are smaller than these separations, the lines of sight for the four images will sample independent portions of the halo. In that case, Morton and Blades’ results for a pathlength of one halo radius suggest that each of the four images would likely suffer absorption from high-velocity clouds (those outside the thick disk), since they traverse an entire halo diameter. However, once the QSO images were combined in our spectroscopy, our chances of detecting the resulting 40–130 mÅ Ca II K absorption line would be marginal.

In light of the evidence (Yee 1988) that the quasar images are heavily reddened by dust in the lensing galaxy, our upper limit can be used for a crude estimate of Ca II depletion, presumably due to dust formation, in the lensing galaxy’s interstellar medium. Using Yee’s results and assuming the QSO has an intrinsic spectral index $\alpha = 0.7$, we adopt a mean extinction of 0.5 mag at i ($8200 \pm 600 \text{ Å}$) for a chord through the center of the lensing galaxy. That extinction implies $E(B - V) = 0.27$ (Seaton 1979) and an atomic hydrogen column density $[N(\text{H I})] = 1.6 \times 10^{21} \text{ atoms cm}^{-2}$ (Burstein and Heiles 1978, Eq. 7). This hydrogen column density, combined with our 3σ upper limit on Ca II, implies that calcium is depleted by at least 3.7 dex with respect to hydrogen [Morton, York, and Jenkins 1988, Eq. 1 and Tables I and II]. This estimate is comparable to the most extreme calcium depletion seen in galactic studies (e.g., Zeta Oph, Savage and Mathis 1979, p. 97), and more sensitive observations of 2237 + 0305 may show that the Ca II column density is still lower.

However, the estimated depletion is subject to several uncertainties. Burstein and Heiles note that the galactic gas-to-dust ratio varies by up to a factor of 2 for different lines of sight. Decreasing the assumed gas-to-dust ratio by a factor of

2 would proportionally decrease the estimated H I column density and therefore the derived Ca depletion. Also, we have assumed that all of the gaseous calcium is singly ionized. Available data for our own galaxy indicate that 35%–90% of interstellar calcium is Ca II (Stokes 1978; Snow 1984), implying another correction of up to a factor of 3 in the calculated depletion. Finally, changing the adopted intrinsic spectral index of the quasar will change the estimated extinction. For instance, if a much steeper index is adopted ($\alpha = 1.2$), the quasar's intrinsic $(g-i) = 0.4$ (Fig. 8 of Yee 1988). The observed QSO components then have an average $E(B-V) = 0.14$, implying $N(\text{H}) = 1 \times 10^{21} \text{ cm}^{-2}$ for a "normal" gas-to-dust ratio. Adopting $E(B-V) = 0.14$, then decreasing the assumed gas-to-dust ratio by a factor of 2 below "normal," and assuming that only 35% of the interstellar calcium is Ca II, i.e., assuming that all these factors conspire to reduce the Ca depletion, we derive a lower limit of 2.7 dex for the mean calcium depletion in the lensing galaxy. Of course, it is possible that the color differences in the quasar components, noted by both Yee and by Schneider *et al.*, are not due to reddening, though that seems unlikely. In any case, further observations designed to detect Ca II and Na I in the lensing galaxy would be of great interest, as would 21 cm data.

We note in closing that although absorption-line studies of lensed QSOs have yielded important constraints on the sizes of the absorbers (Foltz *et al.* 1984), we are somewhat doubtful regarding the potential for ground-based observations of this system to yield such information about the clouds in the halo of the intervening galaxy. The weakness of any Ca II features in the spectrum of the lensing galaxy demands that any future studies be carried out at very high S/N. This would probably require larger instruments such as the Keck

Telescope or the ESO Very Large Telescope. Finally, size limits are normally derived from observations of the spectra of individual images of the QSO, a difficult task given the small separation of the images in this system compared to typical seeing diameters.

IV. SUMMARY

Because the lensing galaxy in the 2237 + 0305 system is nearly face on, spectroscopy of the background quasar affords a unique opportunity to study the interstellar medium in the galaxy's center and bulge. Our spectroscopy of the QSO yielded a 3σ upper limit of 72 mÅ for the rest equivalent width of the Ca II K absorption due to gas in the lensing galaxy. Note that gas in the Milky Way "thick disk" typically produces 80–400 mÅ Ca II K absorption lines along lines of sight at high galactic latitudes. A similar "thick disk" extending through the bulge of the 2237 + 0305 lensing galaxy is apparently ruled out by the present observations, since our line of sight to the QSO is effectively the weighted mean of four lines of sight, each of which transects an entire halo diameter in the lensing galaxy, rather than just a radius. Finally, our Ca II upper limit combined with a rough estimate of the H I column density, based on reddening of the QSO components, indicates that Ca in the lensing galaxy's ISM is depleted by at least 2.7–3.7 dex compared to solar abundances. This depletion is similar to the more extreme cases seen in our own galaxy.

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