DAMPED Lyα ABSORPTION FROM A NEARBY LOW SURFACE BRIGHTNESS GALAXY

DAVID V. BOWEN, TODD M. TRIPP, AND EDWARD B. JENKINS
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544-1001
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ABSTRACT

Ground-based and Hubble Space Telescope (HST) images of the nearby galaxy SBS 1543+593 (z = 0.009) show it to be a low surface brightness (LSB) galaxy with a central surface brightness $\mu_\text{g}(0) = 23.2$ mag arcsec$^{-2}$ and scale length 0.9 $h_{100}^{-1}$ kpc, values typical for the local LSB galaxy population. The galaxy lies directly in front of the quasi-stellar object HS 1543+5921 (z = 0.807); an HST STIS spectrum of the quasar reveals a damped Lyα (DLyα) line at the redshift of the interloper with an H i column density of log N(H i) = 20.35, as well as several low-ionization metal lines with strengths similar to those found in the Milky Way interstellar medium. Our data show that LSB galaxies are certainly able to produce the DLyα lines seen at higher redshift and fuels the speculation that LSB galaxies are a major contributor to that population of absorbers.

Key words: galaxies: individual (SBS 1543+593) — galaxies: structure — quasars: absorption lines — quasars: individual (HS 1543+5921)

1. INTRODUCTION

In the course of spectroscopic follow-up observations of quasar candidates in the Hamburg Quasar Survey, a redshift of z = 0.807 was measured for the quasi-stellar object (QSO) HS 1543+5921. However, Schmidt plate images showed the object to be very extended, suggesting that the QSO might be centered on a low-redshift galaxy. Follow-up observations by Reimers & Hagen (1998, hereafter RH98) found the QSO to be 2′4 (≈ 0.3 $h_{100}$ kpc) from the center of the foreground galaxy SBS 1543+593, and measurement of an H ii region in a spiral arm revealed the galaxy to be at z = 0.009.

Although detecting QSOs close to nearby galaxies is not difficult, finding one that shines through the center of a galaxy and that is bright enough to be observed spectroscopically with Hubble Space Telescope (HST) is extremely rare. In this paper we present ground-based and HST optical images of SBS 1543+593 and show that the galaxy is actually a low surface brightness (LSB) galaxy. We also present an HST spectrum of the background QSO HS 1543+5921, which reveals a damped Lyα (DLyα) absorption line at the redshift of the foreground galaxy.

2. IMAGING: GALAXY PROPERTIES

Three 300 s R-band exposures of the QSO-galaxy pair were taken on 2000 August 5 at the ARC 3.5 m telescope using SPIcam at the Apache Point Observatory. A 2048 × 2048 Site CCD was binned on-chip 2 × 2 to produce 0′28 × 0′28 pixels. The data were reduced in the conventional way and calibrated photometrically with nearby standard stars. Although conditions were not photometric, calibrators were taken shortly after images of SBS 1543+593 and are believed to result in a photometric zero point good to within 0.1–0.2 mag. The seeing was ~1′0.

The co-added data resulted in an image similar to that shown in RH98 and are not reproduced here. We used our data, however, to produce a surface brightness profile of the galaxy, shown in Figure 1. The profile near the center of the galaxy is obviously contaminated by flux from the QSO and the bright star identified by RH98, but the remaining points can be well fitted with a standard exponential profile, $\mu_s = \mu_R(0) + 1.086(r/a)$, where $\mu_R(0)$ is the central surface brightness in mag arcsec$^{-2}$, r is the radius from the galaxy’s center, and a is the scale length. The fit to the data in Figure 1 shows that the galaxy has $\mu_R(0) = 22.6$ mag arcsec$^{-2}$ and a scale length of 7″, or 0.9 $h_{100}$ kpc at the redshift of the galaxy. We make no correction to $\mu_R(0)$ for galaxy inclination since the optical depth effects in LSB galaxies are not known and may be less significant than in high surface brightness (HSB) galaxies if the dust content in LSB galaxies is lower. Moreover, given the difficulty in defining the precise position and extent of the spiral arms in SBS 1543+593, deriving an accurate inclination for the galaxy is extremely hard. If dust does play a significant role in LSB galaxies, then $\mu_R(0)$ is an upper limit and the galaxy may be brighter.

The total R-band magnitude of the galaxy, $m_R(T)$, can be derived from the fit to the surface brightness profile, $m_R(T) = \mu_R(0) - 2.5 \log(2\pi a^2) = 16.3$, in good agreement with the simple integration of the counts that excludes star and QSO. This corresponds to an absolute magnitude of $M_R = -5 \log h_{100} = -15.9$.

We can compare the properties of this galaxy with those found for other local LSB galaxies by correcting the surface brightness in the observed R band to that in the B band. De Blok, McGaugh, & van der Hulst (1996) find that for a sample of nearby LSBs, $\mu_B(0) = \mu_R(0) + 0.78$, which gives $\mu_B(0) = 23.2$ mag arcsec$^{-2}$ for SBS 1543+593. Compared with the sample studied by De Blok, van der Hulst, & Bothun (1995), SBS 1543+593 is a regular LSB galaxy, with $\mu_B(0)$ and a close to the median values of $\mu_B(0) = 23.4$ and $a = 3.2 h_{100}^{-1}$ kpc for local LSB galaxies.

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1 Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

2 Based on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

3 $h_{100} = H_0/100$, where $H_0$ is the Hubble constant and $q_0 = 0$ is assumed throughout this paper.
Three *HST* STIS images were taken of the QSO-galaxy pair on 2000 September 18 with the CCD detector and no filter. The three exposures were medianed to remove cosmic rays, and hot pixels were identified and set to a local background. The co-added image represents a total exposure time of 802 s and is reproduced in Figure 2; the pixel size was originally 0.05 arcsec, but we have smoothed by a boxcar filter of size 3 × 3 pixels to show the LSB features better. The field of view is ~50×50, and the throughput of the detector is such that the image records photons with wavelengths between 2000 and 11000 Å, with the sensitivity peaking at 5852 Å. The image shows that SBS 1543+593 is composed of two primary spiral arms, largely defined by H II regions within the arms. In Figure 2 we mark the outer regions of these two arms with curves. The H II region observed spectroscopically by RH98 is marked and is seen to break up into several discrete regions. There may be evidence for additional spiral structure in the image; for example, a faint diffuse region to the left of the “H II region” labeled at bottom left of Figure 2 may itself be an...
H II region and mark the end of a faint spiral arm that winds back toward the more prominent southern H II cluster already discussed. A second galaxy at bottom right of the figure, which can be seen in RH98's image and identified by them as a point source, is here easily resolved into a barred spiral. No redshift is measured for this galaxy, but given the small angular size and high surface brightness it is probably background to SBS 1543 + 593.

The close alignment of QSO and galaxy is reminiscent of the "cloverleaf" lens H 1413 + 1143 (Magain et al. 1988). The possibility that HS 1543 + 5921 is lensed was discussed in detail by RH98, who concluded that multiple imaging and microlensing were unlikely. The QSO sight line is 2°4 from the center of the galaxy (see Fig. 3 of RH98), and the low surface density of the LSB is probably below the critical density required for lensing. Our STIS image allows us to search more closely for multiple images that are at small separations and undetectable from ground-based images, however. Inspection of the unsmoothed STIS image shows that there exist two faint arcs between the west and southwest diffraction spikes of the QSO (not visible in Fig. 2) at a radius 29–34 pixels from the center of the QSO. These are not lens arcs, however, but are "ghost" reflections known to arise in STIS CCD images of bright objects (R. S. Hill 2000, private communication; the effect can be seen, e.g., in Fig. 2 of Hutchings 1998). Although the very center of the QSO profile suffers from charge-transfer inefficiencies, there is no evidence for any multiple images of the QSO beyond the central 3 pixels of the QSO profile, or 0.15. The optical depth for microlensing is 0.0009(M/L), where M/L is the B-band mass-to-light ratio of the galaxy in solar units (J. S. B. Wytche & E. L. Turner 2000, private communication). Assuming roughly solar mass lensing in solar units (J. S. B. Wyithe & E. L. Turner 2000, private communication), individual microlensing events would last of order several years and occur once per 5000(M/L) -1 yr. For any reasonable value of M/L, microlensing is clearly likely to be a rare event.

3. STIS SPECTROSCOPY: DAMPED Lyα FROM SBS 1543 + 593

Three STIS FUV-MAMA spectra were obtained on 18 September 2000 with the G140L grating and 52 × 0.5 aperture for a total exposure time of 2139 s (HST Archive data set o5l301010). To improve the signal-to-noise ratio of the spectrum over that derived from the pipeline calibration, we used the IRAF APALL routine to extract the individual exposures from the x2d file, paying particular attention to the subtraction of geocoronal Lyα and O I λ1302 emission that filled the aperture. The co-added data were normalized using a fifth-order cubic spline, and a portion of the resulting spectrum is shown in Figure 3. Not shown in that figure is a broad emission line centered at 1397.8 Å, which we identify as Ne VIII λ1770,780 from the QSO, giving an emission redshift of z = 0.804. The value of the flux at 1220 Å is 2.6 × 10^{-15} ergs cm^{-2} s^{-1} Å^{-1} -1 Å^{-1} -1 Å^{-1} -1 Å^{-1}.

Absorption lines in the spectra were identified and equivalent widths measured using standard procedures (see, e.g., Bowen, Blades, & Pettini 1995), and lines found arising from SBS 1543 + 593 are listed in Table 1. Lyα is clearly seen from the galaxy at precisely the redshift expected and appears to be slightly stronger than Galactic Lyα. Strong lines of Si II λ1260, O I λ1302 + Si II λ1304, and C II λ1334 are detected at strengths similar to Milky Way absorption lines. Although the region blueward of Lyα is confused at this resolution, it is likely that we also detect Si II λ1193 blended with Galactic Si III λ1206. We may also detect Si II λ1190 at 1200.8 Å, but, compared with the other Si II lines, the absorption may be too strong to be from the 1190 Å line alone. Although the Milky Way N I λ1200 triplet is expected to be present, the predicted wavelength of the line does not match this feature well. Interestingly, with Galactic coordinates (l, b) = (92.4, 46.4), this sight line passes through the middle of high-velocity cloud (HVC) complex C (Wakker & van Woerden 1991). However, for the two lines at 1200.8 and 1204.9 Å to be identified as Lyα from the HVC complex, they would have to have velocities of about -3700 and -2600 km s^{-1}, respectively, velocities much too large to be associated with HVCs. There are no other obvious absorption line systems that can be identified in the spectrum and could give rise to metal lines at the wavelength of the 1200.8 Å feature, so its identification remains ambiguous.

Measurement of the neutral hydrogen column density along the line of sight is complicated by the shape of the

| j | W_j | \sigma(W_j) | Identification |
|---|---|---|---|
| 1200.8...... | 1.60* | 0.23 | Si II λ1190? (N I λ1200 at z = 0?) |
| 1204.9...... | 1.78* | 0.22 | Si II λ1193, Si III λ1206 at z = 0 |
| 1226.5...... | 9.15* | 0.32 | Lyα |
| 1272.2...... | 1.07 | 0.18 | Si II λ1260 |
| 1314.2...... | 1.30 | 0.15 | O I λ1302 + Si II λ1304 |
| 1347.5...... | 1.19 | 0.12 | C II λ1334 |

* Lower limits, blended with Milky Way lines.
line-spread function (LSF) generated by the G140L grating and the 52 × 0.5 aperture. The resolving power of the G140L is measured to be between 200 and 300 km s⁻¹ (Kimble et al. 1998), but the LSF is not Gaussian and is composed instead of a central narrow core with broad extended wings. Although the widths of the Lyα absorption lines from both the Milky Way and SBS 1543 + 593 are much greater than the FWHM of the core of the LSF, the inclusion of extended wings means that part of the absorption profile is over a velocity interval at least as large as the intrinsic widths of the Lyα lines. The result is that the core of the lines do not reach a flux of zero as might be expected for damped lines if the LSF were a Gaussian 200–300 km s⁻¹ wide.

Hence, to model the Lyα lines from the Galaxy and from SBS 1543 + 593, we have convolved theoretical line profiles with the available LSF calculated at 1200 Å. The H I column density from our own Milky Way is known to be log N(H i) = 20.26 from, e.g., the Bell Labs H I Survey (Stark et al. 1992). The signal-to-noise ratio of the Galactic Lyα absorption line is poor because of the subtraction of intense geocoronal Lyα emission; the minimum and maximum extent of the subtracted profile is shown at the bottom of Figure 3, demonstrating that the spurious point at 1209.4 Å and the pixels separating the Galactic and extragalactic Lyα, which seem anomalously high, are a result of the subtraction of the geocoronal Lyα. Hence we fitted theoretical line profiles to the Lyα absorption lines, keeping log N(H i) fixed for the Milky Way absorption and allowing the redshift, column density, and Doppler parameter to vary for absorption from SBS 1543 + 593. The resulting fits are shown in Figure 3. The profile for Milky Way absorption fits the data well, despite using a value of log N(H i) known a priori, and for SBS 1543 + 593 we derive log N(H i) = 20.35. We note that by not using an LSF with extended wings, by assuming a simple Gaussian LSF, and by correcting the baseline of the spectrum so that the cores of the Lyα lines reached zero flux, N(H i) would be overestimated by ~0.1 dex. A value of log N(H i) = 20.35 is consistent with that derived by simply calculating N(H i) from the measured equivalent width, assuming a damped line: for W_e(Lyα) ≥ 9.15 Å (a lower limit since part of the line is lost though blending with Milky Way Lyα) we derive log N(H i) ≥ 20.27.

Errors on the derived value of N(H i) are hard to quantify precisely because of uncertain systematic errors, but providing the line is damped, N(H i) is probably accurate to within 0.1 dex. It seems likely, therefore, that SBS 1543 + 593 is responsible for a DLyα line. We note, however, that at the resolution of these observations, it is still possible that the line could be composed of several individual components whose distribution of column densities and Doppler parameters with velocity mimics a single DLyα profile. This would mean that the total N(H i) could be less than the derived log N(H i) = 20.35. If true, however, the similarities in equivalent width between the Milky Way metal absorption lines and those arising in the LSB galaxy would imply that the extragalactic interstellar gas was of a higher metallicity than that intercepted locally. Higher resolution observations would obviously confirm the damped nature of the Lyα line.

4. DISCUSSION

Our optical and spectroscopic data have shown that SBS 1543 + 593 is an LSB galaxy causing a DLyα system at z = 0.009 in the spectrum of HS 1543 + 5921. This makes it the lowest redshift DLyα system discovered outside the Local Group. The identification of DLyα from a known LSB is important for the following reasons: so far, results from ground-based and HST imaging of fields around QSOs known to show z < 1 DLyα lines have been surprising, with the detection of a whole variety of galaxy types, including normal early- and late-type HSB spirals and amorphous LSB galaxies, identified as responsible for the absorption (Steidel, Dickinson, & Bowen 1993; Steidel et al. 1994; Lanzetta et al. 1997; Le Brun et al. 1997; Rao & Turnshek 1998; Pettini et al. 2000). This wide variety of absorber types has led to the speculation that DLyα systems may not simply signal the presence of normal gas-rich spiral galaxies after all, as has been postulated since their discovery (Wolfe et al. 1986). It is important to note, however, that in most cases no redshift information exists for the purported absorbers.

Proximity to the line of sight is no guarantee that an "identified" object is the absorber, since there are often several absorption systems at redshifts other than that of the DLyα line along the QSO line of sight. If galaxies are responsible for these other systems, then the chance of misidentification is high (particularly if DLyα systems do not arise in normal galaxies). Further, objects aligned close to the line of sight may also be confused with quasar host galaxies. Hence the detection of a DLyα line from SBS 1543 + 593 is unique in that we know unequivocally that the absorber is an LSB galaxy.

It also seems likely that if SBS 1543 + 593 were moved to a redshift similar to those of the z < 1 DLyα systems already studied, it would be extremely difficult to detect, partly because of its low surface brightness and partly because of its close proximity to the QSO and its small angular size. In fact in this case it is more likely that the nearby barred spiral galaxy southwest of the pair, which we take to be background to SBS 1543 + 593, would be identified as the DLyα absorber if no redshift information were available.

Our observations of SBS 1543 + 593 support the idea that LSB galaxies may contribute significantly to the population of DLyα absorbers, as initially suggested by Impey & Bothun (1989). Although finding a DLyα from an LSB galaxy does not prove that all DLyα systems are LSB galaxies, our detection does prove that LSB galaxies can produce such systems.

Perhaps more significant is the detection of this QSO-galaxy pair in the first place. Finding any bright QSO shining through the center of a nearby galaxy is extremely rare, and it is intriguing that an LSB galaxy is the interloper. LSB galaxies are believed to be relatively free of dust and hence optically thin to the photons of background objects. These may therefore be the best type of galaxies to allow the light of quasars to shine through. This potential selection effect has been a concern for interpreting the copious abundance measurements of high-redshift DLyα systems: if a particular type of galaxy preferentially favors QSO light passing through it, then the derived metallicities are applicable only to that type of galaxy. There are also

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4 Available from the STIS web pages at www.stsci.edu.
5 Obtained from http://asc.harvard.edu/toolkit/colden.jsp.
theoretical bases for the idea that LSB galaxies hold most of the high column density H I cross section: for example, Jimenez, Bowen, & Matteucci (1999) predicted that HSB disks consume neutral gas too fast to explain the observed evolution in the neutral gas mass density with redshift and that consumption of hydrogen by LSB galaxies better fits the abundance measurements.

Our results demonstrate that a relatively unevolved, low-mass system can give rise to a DLy system, as opposed to the giant massive disks usually purported to be responsible for these systems. Unfortunately, just how common such QSO–LSB galaxy alignments are at higher redshift will always be difficult to determine because of the intrinsic faintness of the galaxies, especially if the galaxy is close to the QSO sight line, as with this pair. Finally, we note that HS 1543 + 5921 is bright enough to be used to measure abundances in the interstellar medium of SBS 1543 + 593 with further HST observations. The current data do not have sufficient resolution for reliable metallicity estimates, so follow-up UV observations would be extremely valuable. Comparison of gas metallicities from a known LSB galaxy with higher redshift DLy systems would be useful in deciding whether LSB galaxies are, in general, responsible for the absorption. Measurement of the alpha-to-iron elemental abundances in SBS 1543 + 593 could also be used to derive the star formation history of the galaxy, and relative metal abundances may provide insight into its dust content. Lastly, comparison of the kinematic structure of metal lines arising from SBS 1543 + 593 could be matched to global H I kinematics derived from 21 cm emission maps of the galaxy and to profiles seen in high-redshift DLy lines that are believed by some authors to indicate rotating disks (Prochaska & Wolfe 1998 and references therein).

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