Differential X-ray Absorption and Dust-to-Gas Ratios of the Lens Galaxies SBS 0909+523, FBQS 0951+2635, and B 1152+199

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ABSTRACT
We analyzed Chandra observations of three gravitational lenses, SBS 0909+523, FBQS 0951+2635, and B 1152+199, to measure the differential X-ray absorption and the dust-to-gas ratio of the lens galaxies. We successfully detected the differential X-ray absorption in SBS 0909+523 and B 1152+199, and failed to detect it in FBQS 0951+2635 due to the dramatic drop in its flux from the ROSAT epoch. These measurements significantly increase the sample of dust-to-gas ratio measurements in cosmologically distant, normal galaxies. Using the larger sample, we obtain an average dust-to-gas ratio of $E(B-V)/N_H = (1.5 \pm 0.5) \times 10^{-22}$ mag cm$^2$ atoms$^{-1}$ with an estimated intrinsic dispersion in the ratio of $\pm 40\%$. This average dust-to-gas ratio is consistent with our previous measurement and the average Galactic value of $1.7 \times 10^{-22}$ mag cm$^2$ atoms$^{-1}$, and the estimated intrinsic dispersion is also consistent with the $30\%$ observed in the Galaxy. A larger sample size is still needed to improve the measurements and to begin studying the evolution in the ratio with cosmic time. We also detected X-ray microlensing in SBS 0909+523 and significant X-ray variability in FBQS 0951+2635.

Key words: dust, extinction – Galaxy: evolution

Online-only material: color figures

1. INTRODUCTION

The interstellar medium (ISM) and intergalactic medium (IGM) are ubiquitous, and understanding the ISM is crucial to many areas of astronomy such as cosmology (e.g., using Type Ia supernovae or gamma-ray bursts (GRBs) as cosmological probes), the evolution of galaxies, and star formation (e.g., Fall et al. 2006; Madau et al. 1998; Schneider et al. 2004; Corasaniti 2006; Ghirlanda et al. 2006; Lacey et al. 2008). The dust-to-gas ratio is a basic property of the ISM, and it is difficult to measure in distant galaxies. In the Galaxy, it is measured by comparing the optical extinction and Lyα absorption toward stars, and a typical value is $E(B-V)/N_H = 1.7 \times 10^{-22}$ mag cm$^2$ atoms$^{-1}$ with a scatter about the mean of order 30\% (Bohlin et al. 1978). Subsequent studies have extended these measurements to additional lines of sight in our Galaxy and to the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC), but the basic results are little altered aside from some evidence that the dust-to-gas ratios of the LMC and SMC are modestly lower ($\sim 30\%$) than in the Galaxy (see the review by Draine 2003 and references therein). This absorption method is hard to apply to extragalactic sources where we lack precise knowledge of the intrinsic source spectra and tend to be probing low-density parts of the IGM using absorption lines in the spectra of quasars or GRBs (e.g., Kacprzak et al. 2008) rather than the inner regions of normal galaxies. An alternate approach is to use emission by the dust in the far-infrared (FIR) to estimate a dust mass and then compare it to the estimated gas mass (e.g., Contini & Contini 2007).

Gravitational lensing provides a means of studying the properties of the ISM through differential absorption in the lens galaxies between the locations of the quasar images. By studying the differences in the absorption (or extinction) between multiple images, any contamination from the Galaxy in the foreground (Milky Way) or the quasar host galaxy in the background is essentially eliminated and we can be confident that we are probing the ISM of the lens galaxy. Moreover, since we are comparing two images of the same quasar, the method has many of the quantitative advantages of the local approach using stars of known spectral type. In optical bands, this technique has been widely used to study dust extinction and the dust-extinction law in lens galaxies (e.g., Nadeau et al. 1991; Falco et al. 1999; Toft et al. 2000; Motta et al. 2002; Wucknitz et al. 2003; Muñoz et al. 2004; Mediavilla et al. 2005; Eliasdóttir et al. 2006). In X-rays, Dai et al. (2003) and Dai & Kochanek (2005) measured the differential column densities in two lenses, Q 2237+0305 and B 1600+434. Subsequently, Dai et al. (2006) expanded the results to four lenses and proposed that the evolution of the dust-to-gas ratio can be determined given a larger sample. In this paper, we present new measurements based on Chandra observations of the quasar lenses SBS 0909+523 (Kochanek et al. 1997), FBQS 0951+2635 (Schechter et al. 1998), and B 1152+199 (Myers et al. 1999).

2. OBSERVATIONS AND DATA REDUCTION
We observed SBS 0909+523 and FBQS 0951+2635 with the Advanced CCD Imaging Spectrometer (ACIS, Garmire et al. 2003) on board Chandra (Weisskopf et al. 2002) for 19.6 and 34.2 ks on 2006 December 17 and 2007 March 24, respectively. B 1152+199 was observed in a separate program (P.I.: K. Pedersen) with Chandra-ACIS for 16.4 and 8.3 ks on 2005 February 22 and 2005 February 26. The backside-illuminated S3 chip was used in all the observations. A journal of the Chandra observations is presented in Table 1. The Chandra data were reduced using the CIAO 4.0 software tools provided by the Chandra X-ray Center (CXC), following the standard threads on the CXC web site. We used the most recently reprocessed data products (Reprocessing III) and calibration files (CALDB 3.4.2). Only events with standard ASCA grades of 0, 2, 3, 4, and 6 were used in the analysis. We improved the image quality of the data by removing the pixel randomization applied to the data.
event positions by the standard pipeline. In addition, we applied a subpixel resolution technique (Tsunemi et al. 2001; Morie et al. 2001) to the events on the S3 chip of ACIS where the lensed images are located. Figure 1 shows the resulting images.

3. SPECTRAL ANALYSIS

We fit the spectra of the lensed quasars using XSPECV11.3.1 (Arnaud 1996) over the 0.3–8 keV observed energy range. The X-ray spectrum of the $i$th image was modeled as

$$N_i(E, t) = N_{0,i}(t - \Delta t) \left( \frac{E}{E_0} \right)^{-\Gamma(t - \Delta t)} \times \exp(-\sigma(E))N_{H,Gal} - \sigma [E(1 + z_i)]N_{H,i} - \sigma [E(1 + z_s)]N_{H,Src}(t - \Delta t),$$

(1)

where $N_i(E, t)$ is the number of photons per unit energy interval, $N_{H,Gal}$, $N_{H,i}$, and $N_{H,Src}$ are the equivalent hydrogen column densities in our Galaxy, the lens galaxy at the position of image $i$, and in the source galaxy, respectively, $\sigma(E)$ is the photoelectric absorption cross-section, and $\Delta t$ is the time delay. Although absorption by the Galaxy, lens, and source is degenerate when fitting the spectrum of each image, the differential absorption $\Delta N_H$ between the lensed images is not and can be determined from a simultaneous fit to the spectra of the images. The time delay at the source complicates the measurement, since if the absorption at source is variable (e.g., PKS 1830–211, Dai et al. 2008), it will not be exactly canceled when comparing the two spectra. However, since the photoelectric absorption cross-section decreases with energy, $\sigma(E) \propto E^{-3}$, the absorption at the source will affect the spectrum less. Thus, we neglected the time delay between the images and the absorption at the source redshift in this analysis. We note that a significant change in the spectral index on the timescale of the time delays will affect the results, especially for quasars with poor signal-to-noise ratio ($S/N$) spectra where the spectral index is degenerate with the absorption. The problem is less severe for quasars with moderate to high $S/N$ spectra where the spectral index is less degenerate with $N_H$ absorption during spectral modeling.

A second systematic error we must consider is micro lensing of the quasar by the stars in the lens galaxy. Our analysis is only affected by chromatic microlensing, where there are significant changes in the optical and X-ray spectra that alter the estimated extinction or absorption. Indeed, it needs only be achromatic “locally” to separate optical and X-ray wavelength/energy regimes, as global shifts of the optical spectrum relative to the X-ray spectrum by microlensing also have no effect on the results. For the systems we consider, we have only limited control on the level of microlensing. While X-ray microlensing has been detected (Chartas et al. 2002, 2007; Dai et al. 2003; Blackburne et al. 2006; Pooley et al. 2007), X-ray spectral changes due to microlensing have yet to be detected in large part due to the limited sensitivity of the data. Chromatic microlensing in the optical has been observed (PoinDEXTER et al. 2008; Anguita et al. 2008; EIGENBROD et al. 2008) and can create systematic problems for estimates of the extinction as we had already discovered for HE 1104–1805 (Dai et al. 2006). We can, however, compare the optical and X-ray flux ratios, since the evidence to date is that the X-ray sources are much more compact than the optical (Kochanek et al. 2007; Morgan et al. 2008; Chartas et al. 2009) and so more strongly affected by microlensing. If the extinction- and absorption-corrected flux ratios of the images agree, this is a good indication that our estimates are little affected by microlensing.

We used the standard $w_{abs}$ and $zw_{abs}$ models in XSPEC to model the Galactic absorption and absorption at the lens redshift. The $w_{abs}$ and $zw_{abs}$ models use cross sections from Morrison & McCammon (1983) and assume a solar elemental abundance from Anders & EBihara (1982). The Galactic $N_H$ is fixed using the values from Dickey & Lockman (1990). We fixed the intrinsic power-law index $\Gamma$ to be the same for both lensed images, and allowed the absorption at the lens to differ. Since the average lens absorption and the power-law index are correlated in the spectral modeling, the uncertainties in absorption by the lens for the individual images are correlated. To accurately measure the uncertainties in the differential absorption, we used XSPEC to explore the full parameter space

![Figure 1. Chandra images of SBS 0909+523, FBQS 0951+2635, and B 1152+199.](image-url)
of the lens column densities and the power-law index. The fitting results are listed in Table 2, and the spectra and best-fit models are shown in Figures 2–4. We also obtained the unabsorbed flux ratios between the quasar images as part of the model, and verified that adding absorption in the source does not alter the estimates of the differential column densities. We describe the results for each of the three lenses in the following subsections.

3.1. SBS 0909+523

SBS 0909+523 (Kochanek et al. 1997; Oscoz et al. 1997) is a two-image lens system with a source redshift of $z_s = 1.377$ and a lens redshift of $z_L = 0.83$. SBS 0909+523 is well studied in the optical bands, and the extinction curve has been measured using the differential extinction method (Mediavilla et al. 2005) to be a Galactic extinction curve with a strong 2175 Å extinction feature (Motta et al. 2002).

It is clear from the Chandra spectra that image B is more heavily absorbed than image A. We estimate that the difference in the column densities is $\Delta N_{H_{180}} = (0.055^{+0.095}_{-0.025}) \times 10^{22}$ cm$^{-2}$. There are several differential extinction measurements for this system (Falco et al. 1999; Motta et al. 2002; Mediavilla et al. 2005), and we used the most recent measurement, $\Delta (B - V) = 0.32 \pm 0.01$, from Mediavilla et al. (2005). Combined with our differential absorption measurement, we obtained a dust-to-gas ratio of $E(B - V)/N_{H_{180}} = (5.8^{+3.9}_{-1.7}) \times 10^{-22}$ mag cm$^{-2}$ atoms$^{-1}$.

The optical flux ratio of SBS 0909+523 has changed little from its discovery in 1997 through 2006 (Kochanek et al. 1997; Motta et al. 2002; Goicoechea et al. 2008) suggesting that there is little micro lensing variability even if there is evidence for microlensing from the difference between the continuum and emission line flux ratios (Motta et al. 2002; Mediavilla et al. 2005). The extinction- and absorption-corrected optical $(A/B) = 0.35 \pm 0.02$, Mediavilla et al. 2005) and X-ray flux ratios $(A/B) = 0.32 \pm 0.03$ are consistent but differ from the $H$-band $(A/B) = 1.12$, Lehár et al. 2000) and extinction-corrected emission line flux ratios (Mediavilla et al. 2005), indicating that there is microlensing in this system but it is affecting the optical and X-ray similarly. The lack of variability and the similar optical/ X-ray flux ratios suggest the lens is in a region of relatively uniform microlensing magnification. We also note that the X-ray variability of the source is modest. SBS 0909+523 was observed three times by ROSAT, and the source showed moderate X-ray variability of about 40% (Chartas 2000). The flux observed by Chandra is in between the three ROSAT flux measurements, suggesting no significant total X-ray variability.

3.2. FBQS 0951+2635

FBQS 0951+2635 is a two-image lens discovered by Schechter et al. (1998) with a source redshift of $z_s = 1.24$ and a lens redshift of $z_L = 0.26$ (Eigenbrod et al. 2007). FBQS 0951+2635 was detected in the ROSAT All Sky Survey (RASS) with a count rate of 0.02 counts s$^{-1}$ in the 0.1–2.4 keV band (Voges et al. 2000). Our Chandra image shows that FBQS 0951+2635 is the brightest source within a 2 radius circle, which indicates that the source detected in RASS is FBQS 0951+2635. However, the Chandra count rate of FBQS 0951+2635, 0.007 counts s$^{-1}$ in the 0.3–8 keV band, is significantly lower than the predicted count rate (0.06 counts s$^{-1}$) from the RASS, suggesting significant source variability.

The unexpected drop in flux resulted in low S/N spectra that cause significant challenges in measuring the differential absorption. We used the C-statistic (Cash 1979), suitable for small number statistics, to fit the spectra. Using our standard technique, we found a power-law index of $\Gamma = 0.81 \pm 0.15$ for the source. We failed to detect the differential absorption in this lens, as the differential absorption between the two images is consistent with zero. Note, however, that the upper limit for the lens absorption in image B, $N_{H_{180}} < 0.22 \times 10^{22}$ cm$^{-2}$, is larger than that for image A, $N_{H_{180}} < 0.05 \times 10^{22}$ cm$^{-2}$, and that the best-fit power-law index ($\Gamma = 0.81 \pm 0.15$) is unusually flat (e.g., Reeves & Turner 2000; Saez et al. 2008). A more plausible interpretation is that the low-energy part of the spectrum is absorbed. Since the absorption is correlated with the power-law index in the spectral fitting, which is a severe problem for low S/N spectra, as an experiment we first fit the spectra in the hard band (2–8 keV) to find a steeper, and more sensible, intrinsic power law ($\Gamma = 1.32$). Then we held this fixed and fitted for the absorption to find a differential absorption of $\Delta N_{H_{180}} = (0.49^{+0.47}_{-0.41}) \times 10^{22}$ cm$^{-2}$. Due to the low significance of this detection (or no detection at all) because of the low S/N spectra, we will be unable to include this lens in an estimate of the mean dust-to-gas ratio.

3.3. B 1152+199

B 1152+199 (Myers et al. 1999) consists of two $z_s = 1.019$ quasar images lensed by a $z_L = 0.439$ galaxy. The dust-extinction curve of B 1152+199 was measured to be $1.3 < R_V < 2.0$ (Toft et al. 2000) and $R_V = 2.1 \pm 0.1$ (Elisadóttir et al. 2006). The Elisadóttir et al. (2006) results were based on improved data so we adopt their results. The differential absorption can be clearly seen by comparing the Chandra spectra of the two images (Figure 4). Since B 1152+199 was observed by Chandra...
twice, we used our standard method and simultaneously fitted the spectra for both epochs. We detected a large differential absorption $\Delta N_{\text{H}I\alpha} = (0.48 \pm 0.04) \times 10^{22}$ cm$^{-2}$. We also fitted the two Chandra epochs separately, and obtained consistent differential absorptions for both observations (Table 2). We used the model-averaged extinction of $E(B - V) = 1.20 \pm 0.05$ mag from Elíasdóttir et al. (2006), where the small scatter in the value between their models would have little effect on our results. Combining the differential extinction and absorption measurements, we found a dust-to-gas ratio for the lens galaxy of $E(B - V)/N_{\text{H}I} = (2.5 \pm 0.2) \times 10^{-22}$ mag cm$^{-2}$ atoms$^{-1}$. This is the most accurate dust-to-gas ratio measurement we have obtained so far. There is weak evidence ($1.4\sigma$) for a change in the X-ray flux ratios, where the flux ratio $(A/B)$ is larger in the second epoch (see Table 2). The X-ray flux ratios after correcting for absorption $(A/B = 1.87 \pm 0.14$ and $2.28 \pm 0.25)$ are also
consistent with the range of optical flux ratios after correcting for extinction (e.g., $\Delta M = 0.85 \pm 0.07, 0.6 \pm 0.1$, Elíasdóttir et al. 2006).

4. DISCUSSION

We summarize all available differential absorption measurements in Table 3, including the three results from this paper (SBS 0909+523, FBQS 0951+2635, and B 1152+199) and the five existing measurements from Dai et al. (2006). We find an average dust-to-gas ratio of

$$E(B - V)/N_H = (1.5 \pm 0.5) \times 10^{-22} \text{ mag cm}^2 \text{ atoms}^{-1}$$

with an intrinsic scatter of $\simeq 40\%$, where we must exclude FBQS 0951+2635 and HE 1104−1805 from the fits. If we allow for no intrinsic scatter, we found a ratio of $(2.3 \pm 0.2) \times 10^{-22} \text{ mag cm}^2 \text{ atoms}^{-1}$ with $\chi^2/N_{\text{dof}} = 3.0$, indicating the existence of the additional scatter we include in our standard estimate. These estimates are consistent with our previous estimate in Dai et al. (2006) and the average Galactic value of $1.7 \times 10^{-22} \text{ mag cm}^2 \text{ atoms}^{-1}$ (Bohlin et al. 1978). The estimates for the intrinsic scatter are also consistent with local estimates given our small sample size. We compare the results for the lens galaxies to the local stellar sample from Bohlin et al. (1978) in Figure 5, and plot the evolution of dust-to-gas ratios in Figure 6. Contini & Contini (2007) examined this question by modeling the bulk emission of luminous IR galaxies, finding that the dust-to-gas ratio is significantly higher than the Galactic value in star-forming and central nucleus regions (see also Maiolino et al. 2001a, 2001b) and consistent with the Galactic value elsewhere. However, the scatter of their results is significantly larger than our more direct measurements. In

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**Figure 4.** Spectra of images A (top) and B (bottom) of B 1152+199 for both Chandra observations. The black and red lines are the fits for the spectra A and B in the first Chandra epoch, and the green and blue lines are for the second epoch. The lower panel shows the contributions of the residuals to the $\chi^2$-fit statistics. (A color version of this figure is available in the online journal.)

**Table 3**

The Dust-To-Gas Ratio of High Redshift ($z > 0$) Galaxies

| Lens       | $z_l$ | Type       | Between Images | $\Delta N_H$ ($10^{22} \text{ cm}^{-2}$) | $\Delta E(B - V)$ (mag) | $E(B - V)/N_H$ ($10^{-22} \text{ mag cm}^2 \text{ atoms}^{-1}$) |
|------------|------|------------|----------------|---------------------------------------|------------------------|-------------------------------------------------------------|
| SBS 0909+523 | 0.83 | Elliptical | B, A           | 0.055$^{+0.095}_{-0.022}$             | 0.32 ± 0.01            | 5.8$^{+3.7}_{-5.8}$                                         |
| FBQS 0951+2635 | 0.26 | Elliptical | B, A           | 0.49$^{+0.49}_{-0.41}$                | −0.12 ± 0.02           |                                                              |
| B 1152+199    | 0.439| Elliptical | B, A           | 0.48 ± 0.04                           | 1.20 ± 0.05            | 2.5 ± 0.2                                                  |
| MG 0414+0534  | 0.9584| Elliptical | A, B           | 0.33 ± 0.10                           | 0.18 ± 0.11            | 0.55 ± 0.33                                                 |
| HE 1104−1805  | 0.729| Elliptical | A, B           | 0.055 ± 0.030                         | −0.07 ± 0.01           |                                                              |
| B 1600+434    | 0.41 | Spiral     | B, A           | 0.26$^{+0.17}_{-0.12}$                | 0.10 ± 0.03            | 0.38 ± 0.25                                                 |
| PKS 1830−211  | 0.886| Spiral     | B, A           | 1.8$^{+0.3}_{-0.6}$                   | 3.00 ± 0.13            | 1.7 ± 0.6                                                   |
| Q 2237+0305   | 0.0395| Spiral     | A, C           | 0.04 ± 0.03                           | 0.11 ± 0.03            | 2.8 ± 2                                                    |

**Notes.**

a The dust-to-gas ratio was not estimated for FBQS 0951+2635 and HE 1104−1805 because the differential extinction and $N_H$ column measurements give opposite signs.

b Q 2237+0305 is lensed by the central bulge of a spiral galaxy.
addition, Ménard & Chelouche (2009) found several Mg II absorbers at \( z \sim 1 \) which also have dust-to-gas ratios close to the Galactic value. In our present results, we see no evidence for evolution in the dust-to-gas ratio at \( z \gsim 1 \), and with a larger sample we will be able to test the ISM evolution models of simulations (e.g., Dwek 1998; Edmunds 2001; Inoue 2003).

The primary systematic uncertainty for our results comes from chromatic microlensing of the quasar by the lens galaxy distorting the optical and X-ray spectra. Given the available information for the systems we consider, it is possible that HE 1104−1805 and FBQS 0951+2635 are affected by this problem while the rest show no evidence of a problem.

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