1. INTRODUCTION

Quasar microlensing is an important new tool for studies of the structure of quasar accretion disks based on the dependence of the microlensing magnification on the source size and position (e.g., Wambsganss 2006; Kochanek et al. 2007). Microlensing was first detected by Irwin et al. (1989) in Q2237+0305 (Huchra et al. 1985). Since then, microlensing effects have been frequently reported in this system in different energy bands (e.g., Wozniak et al. 2000; Dai et al. 2003; Goicoechea et al. 2003; Vakulik et al. 2004; Anguita et al. 2008; Eigenbrod et al. 2008; Mosquera et al. 2009; O'Dowd et al. 2011). The quasar microlensing technique was first used to crudely determine emission regions relative to the Einstein ring size (e.g., Wambsganss et al. 1990; Rauch & Blandford 1991; Falco et al. 1996; Mediavilla et al. 1998; Agol et al. 2000). However, since the magnification diverges on the caustics, the technique can be used to resolve emission regions arbitrarily smaller than the Einstein ring size, which allowed crude measurements of the X-ray continuum and Fe Kα emission regions (e.g., Chartas et al. 2002, 2007; Dai et al. 2003; Ota et al. 2006). Quasar microlensing models have been developed by different groups to interpret the microlensing results, where a major breakthrough occurred in Kochanek (2004) using a Bayesian Monte Carlo model. This approach and its derivatives have successfully reproduced microlensing light curves in the optical and X-ray bands, determined the emission sizes quantitatively (Morgan et al. 2008; Chartas et al. 2009; Dai et al. 2010; Mediavilla et al. 2011), the stellar/dark matter fractions (e.g., Mediavilla et al. 2009; Poindexter & Kochanek 2010a; Bate et al. 2011), and even the inclination angles of accretion disks (Poindexter & Kochanek 2010b).

The X-ray continuum emission of quasars is generally believed to be created by the unsaturated inverse Compton scattering emission between soft UV photons from the disk and hot electrons in the corona, leading to the observed power-law X-ray spectra (e.g., Reynolds & Nowak 2003). Thus, the size of the X-ray emission traces the extent of the corona. Because of its shorter variability timescales, the X-ray continuum emission region is believed to be smaller than the optical emission region. However, the simple variability argument is not conclusive as the variability could be dominated by localized flares rather than corona-scale variability. Recent microlensing results, however, have conclusively shown that the X-ray emission regions are an order of magnitude smaller than the optical (rest-frame UV) emission regions (e.g., Morgan et al. 2008; Chartas et al. 2009; Dai et al. 2010; Blackburne et al. 2011), excluding models where the X-ray corona cover large portions of the accretion disks.

Besides the continuum emission, there are additional X-ray components such as the reflection hump, metal emission lines, soft X-ray excess, and jet emission, which may also contribute to the X-ray spectra of quasars. Quasar microlensing is one of the few tools that can determine the physical size of these different components, and microlensing effects have been detected in the Fe Kα emission line (e.g., Chartas et al. 2002, 2007; Dai et al. 2003; Ota et al. 2006). In addition, if the hot electron distribution is not uniform, we should observe chromatic, energy-dependent microlensing of the X-ray continuum. In this Letter, we report results of our long-term Chandra X-ray monitoring data for the gravitationally lensed quasar Q2237+0305 with 20 epochs spanning 10 years. We easily detect microlensing variability between the images in the full (0.2–8 keV), soft (0.2–2 keV), and hard (2–8 keV) bands at very high confidence. We also detect, for the first time, chromatic microlensing differences between the soft and hard X-ray bands. The hard X-ray band is more strongly microlensed than the soft band, suggesting that the corona above the accretion disk thought to generate the X-rays has a non-uniform electron distribution, in which the hotter and more energetic electrons occupy more compact regions surrounding the black holes. Both the hard and soft X-ray bands are more strongly microlensed than the optical (rest-frame UV) emission, indicating that the X-ray emission is more compact than the optical, confirming the microlensing results from other lenses.

Key words: accretion, accretion disks – black hole physics – gravitational lensing: micro – gravitational lensing: strong – quasars: individual (Q2237+0305)

Online-only material: color figures, machine-readable table

2. OBSERVATIONS AND DATA REDUCTION

In various combinations, we have now observed Q2237+0305 with ACIS (Garmire et al. 2003) on board the Chandra X-Ray Observatory (Weisskopf et al. 2002) for 20 epochs between 2000 September and 2010 November (Table 1). We reprocessed all these data using the CIAO 4.3 software tools by removing the pixel randomization and applying a sub-pixel algorithm for event positions (Tsunemi et al. 2001). We filtered all events using the standard ASCA grades of 0, 2, 3, 4, and 6 with energies between 0.2 and 8 keV (observer’s frame), and further separated...
Figure 1. Combined X-ray image of Q2237+0305 from 20 epochs observed between 2000 and 2010. The total integration time is 292 ks. (A color version of this figure is available in the online journal.)

Table 1

| ObsID | Julian Date | Exposure Time (s) | Image | CRₐₘᵋₑ (×10⁻³ s⁻¹) | CRₕₜₑ (×10⁻³ s⁻¹) | CRₜₜₑ (×10⁻³ s⁻¹) |
|-------|-------------|-------------------|-------|---------------------|---------------------|---------------------|
| 431   | 51794       | 30287             | A     | 114.6 ± 3.7         | 112.8 ± 4.0         | 9.6 ± 0.7           |
| 431   | 51794       | 30287             | B     | 17.3 ± 1.1          | 17.1 ± 1.2          | 1.6 ± 0.3           |
| 431   | 51794       | 30287             | C     | 36.9 ± 1.7          | 35.8 ± 1.8          | 3.5 ± 0.4           |
| 431   | 51794       | 30287             | D     | 26.1 ± 1.8          | 28.2 ± 2.2          | 1.8 ± 0.3           |
| 1632  | 52252       | 9535              | A     | 93.4 ± 7.0          | 85.8 ± 7.3          | 8.5 ± 1.1           |
| 1632  | 52252       | 9535              | B     | 11.4 ± 1.5          | 11.5 ± 1.7          | 1.2 ± 0.4           |
| 1632  | 52252       | 9535              | C     | 21.0 ± 2.2          | 19.3 ± 2.4          | 3.3 ± 0.6           |
| 1632  | 52252       | 9535              | D     | 20.2 ± 2.6          | 23.7 ± 3.8          | 1.3 ± 0.4           |
| 6831  | 53745       | 7264              | A     | 38.2 ± 4.0          | 35.2 ± 4.2          | 4.0 ± 0.8           |
| 6831  | 53745       | 7264              | B     | 22.7 ± 2.5          | 20.4 ± 2.5          | 3.4 ± 0.8           |
| 6831  | 53745       | 7264              | C     | 7.7 ± 1.5           | 6.4 ± 1.5           | 1.3 ± 0.5           |
| 6831  | 53745       | 7264              | D     | 21.3 ± 3.2          | 22.3 ± 3.8          | 1.7 ± 0.6           |
| 6832  | 53856       | 7936              | A     | 75.4 ± 5.4          | 73.7 ± 6.1          | 7.4 ± 1.1           |
| 6832  | 53856       | 7936              | B     | 29.1 ± 2.8          | 27.2 ± 2.9          | 3.6 ± 0.8           |
| 6832  | 53856       | 7936              | C     | 24.8 ± 2.7          | 21.5 ± 2.7          | 3.4 ± 0.7           |
| 6832  | 53856       | 7936              | D     | 32.4 ± 3.9          | 33.3 ± 4.6          | 2.3 ± 0.6           |

Notes. The full, soft, and hard bands are the observed energy bands between 0.2–8, 0.2–2, and 2–8 keV, respectively. (This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

the events into soft (0.2–2.0 keV) and hard (2.0–8.0 keV) bands for our subsequent analyses. For each band, we extracted the total counts from all four images within 3′′ radius circular regions and the background counts from concentric annular regions with inner/outer radii of 10′′ and 20′′, respectively. We then used the point-spread function (PSF) fitting method to model the relative count rates between the images, fixing the relative image positions to the Hubble Space Telescope positions. We binned the X-ray images in 0′′.0984, and fit these binned images using Sherpa to minimize the Cash C-statistic between the observed and model images. The final count rates were normalized by partitioning the background-subtracted total source counts using the (unnormalized) relative count rates for each image obtained from the PSF fits. The average pileup fraction is 2% for image A (the brightest one) and <1% for the other three images, and we therefore can ignore the pileup effect in our analysis. We also obtained a stacked image of Q2237+0305 (Figure 1) based on the image positions obtained from the PSF fitting results.

http://cfa-www.harvard.edu/glensdata/
We obtained combined spectra for each image by stacking the images using a simple power-law plus Gaussian emission lines model. We fit the spectra of the individual (stacked) images using XSPEC V12. We fit the spectra of the individual images in 0.5–10 keV rest-frame confirming the results of Dai et al. (2003). The spectra of image A and D furthermore suggest a second metal line (Ni xxi x x vii x xii) at $E \sim 7.8$ keV. After obtaining the best fits, we calculated the ratios of the photon count rates between the absorbed and unabsorbed models for the full, soft, and hard bands, respectively. These mean ratios were then applied to the count rates of individual epochs and images to estimate the absorption-corrected photon count rates. The absorption-corrected count rates for these observations in the 0.5–10 keV band, and our results are consistent.

3. ANALYSIS

Figures 2 and 3 show the time evolution of the flux ratios between various images. Since the time delays between different images of Q2237+0305 are short—less than 1 day—from both theoretical and observational constraints (e.g., Schmidt et al. 1998; Dai et al. 2003), and since intraday intrinsic variability can only have a small contribution in flux (e.g., 4%, Chartas et al. 2001; Dai et al. 2003), the changes in the flux ratios are then essentially unaffected by intrinsic variability, and thus must be due to microlensing by stars in the foreground lensing galaxy.

We first fit the full, soft, and hard band light curves in Figures 2 and 3 to constants to test the significance of the microlensing signal. For the full band, the smallest $\chi^2$ for no microlensing is for the case B/A, with $\chi^2 = 97.2$ for 19 degrees of freedom (dof) and a null hypothesis probability of NP $= 2 \times 10^{-12}$, while the largest is for the case of C/D with $\chi^2 = 396.8$ and NP $= 2 \times 10^{-72}$. For the soft band, the smallest $\chi^2 = 70.2$ is for B/A with NP $= 8 \times 10^{-8}$ and the largest $\chi^2 = 312.0$ is for C/A with NP $= 7 \times 10^{-55}$. For the hard band, the smallest is $\chi^2 = 44.35$ for B/D with NP $= 0.00084$ and the largest $\chi^2 = 147.95$ is for D/A with NP $= 5 \times 10^{-22}$. The null hypothesis is ruled out for all six image pairs for the full, soft, and hard bands. X-ray microlensing is detected with very high confidence. The X-ray flux ratios are different from the radio and infrared flux ratios (Falco et al. 1996; Agol et al. 2009) which

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**Figure 2.** Chromatic X-ray microlensing light curves of Q2237+0305 in the full X-ray band (0.2–8.0 keV, red circles), soft X-ray band (0.2–2 keV, green triangles), hard X-ray band (2–8 keV, blue diamonds), and OGLE $V$ band (Woźniak et al. 2000; Udalski et al. 2006) and our SMARTS data (orange circles) for image pairs B/A, C/A, and D/A. We slightly offset the observation dates for the soft and hard bands to make the difference more visible.

(A color version of this figure is available in the online journal.)
are less affected by the microlensing and absorption effects, confirming our microlensing interpretations.

Next, we compare the hard and soft bands to test for chromatic microlensing. Assuming no chromatic microlensing, we compute the $\chi^2$ for the hard and soft bands showing the same flux ratio evolution for three ways of combining the images into pairs, i.e., B/A plus C/D, C/A plus B/D, and D/A plus C/B. The $\chi^2$ value for B/A+C/D is $\chi^2 = 89.8$ for 40 dof with a null hypothesis probability of NP $= 1.1 \times 10^{-5}$. For C/A+B/D, we find $\chi^2 = 91.0$ with NP $= 7.6 \times 10^{-6}$. For the D/A+C/B pairs, we find $\chi^2 = 50.5$ with NP $= 0.12$. These results indicate that there is significant chromatic X-ray microlensing in Q2237+0305. Figures 2 and 3 also show that the hard band microlensing variability of Q2237+0305 has a larger amplitude than that in the soft band. To compare the amplitudes of variability in the soft and hard bands, we calculate the rms variability for each image pair and show the results in Figure 4. The soft and hard microlensing variability amplitudes are different at the 99% confidence for the B/A plus C/D pairs, and at the 99.7% confidence for the C/A plus B/D pairs. In the last cases, D/A and C/B, the difference in the variability amplitudes are not well resolved. Noting that between JD 2,453,800 and 2,454,200 (the nine observations in the second column of Figures 2 and 3) the flux ratios of the C/B pair are roughly consistent with constants, we assume that the variability of B and C is mainly intrinsic during this period. We therefore constructed an intrinsic variability template (IVT) by combining the light curves of B and C. We extracted the microlensing signals by dividing the light curves of image A and D by IVT, and we detected chromatic microlensing for D/IVT at the 93% confidence, and for A/IVT, an NP value of $5.5 \times 10^{-11}$.

4. DISCUSSION

As in previous studies, we detect significant microlensing in Q2237+0305 in the full X-ray band, where the flux ratio changes are dramatically different from those in the optical microlensing light curves, as shown in Figures 2 and 3. These results confirm the earlier studies in other gravitational lenses that the X-ray continuum emission regions are more compact than the optical emission regions (Morgan et al. 2008; Chartas et al. 2009; Dai et al. 2010). By dividing the X-ray energy band (0.2–8.0 keV) into soft and hard bands, we detect for the first time chromatic microlensing of the X-ray continuum in the sense that the hard band is more strongly microlensed than the soft. For our radio-quiet quasar at $z_s = 1.69$, the observed 0.2–8 keV band probes the rest frame 0.5–22 keV band. Our spectral analysis does not reveal a reflection or a soft X-ray excess component. The metal emission lines, e.g., Fe Kα, will fall in this band; however, their equivalent widths are small (<0.3 keV) such that the broadband flux is little affected. We also tested by excluding the spectral segment containing the Fe Kα emission (2.0–2.5 keV observed frame) in our analysis, and our main results were unchanged. Therefore, the chromatic X-ray microlensing occurs in the X-ray continuum emission in Q2237+0305. We note that if additional X-ray emission components exist in the quasar spectra, the interpretation of chromatic X-ray microlensing could be more complicated.

If the X-ray continuum emission was generated through the inverse Compton scattering of the soft UV photons from the accretion disk by hot electrons from the corona (Reynolds & Nowak 2003), our results indicate that the distribution of hot electrons in the corona is not uniform, and that the hot electrons are more compact than the cool electrons. Thus, even
if the observed X-ray continua emission can be modeled as simple power laws, our results indicate that the real emission mechanism has spatial structures. The evidence of structure in the “corona” favors complicated geometrical configuration such as the light bending (Fabian et al. 2005) or aborted jet models (Ghisellini et al. 2004). Previous microlensing analyses have constrained the size of the X-ray continuum to about $\sim 10^7$ pc (e.g., Morgan et al. 2008; Chartas et al. 2009; Dai et al. 2010), and our results in this Letter suggest even smaller hard emission regions tracking the event horizon of the black holes. An alternative explanation for the chromatic X-ray microlensing discovered in this Letter is that the soft and hard X-ray emission sources are located at different regions, and therefore they cross different magnification patterns. A detailed microlensing model of the microlensed X-ray emission from Q2237+0305 will be presented in a forthcoming paper.

We acknowledge the anonymous referee for helpful suggestions and the financial support from NASA/SAO grants GO6-7093X, GO0-11121A/B/C, and GO1-12139A/B/C, a NASA grant NNX11AD09G, and NSF grants AST-0708082 and AST-1009756.

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![Figure 4. X-ray microlensing variability amplitudes in the full, soft, and hard bands.](image-url)