DETECTION OF X-RAYS FROM GALAXY GROUPS ASSOCIATED WITH THE
GRAVITATIONALLY LENSED SYSTEMS PG 1115+080 AND B1422+231

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ABSTRACT

Gravitational lenses that produce multiple images of background quasars can be an invaluable cosmological tool. Deriving cosmological parameters, however, requires modeling the potential of the lens itself. It has been estimated that up to a quarter of lensing galaxies are associated with a group or cluster that perturbs the gravitational potential. Detection of X-ray emission from the group or cluster can be used to better model the lens. We report on the first detection in X-rays of the group associated with the lensing system PG 1115+080 and the first X-ray image of the group associated with the system B1422+231. We find a temperature and rest-frame luminosity of $0.8^{+0.1}_{-0.1}$ keV and $7^{+2}_{-1} \times 10^{42}$ erg s$^{-1}$, respectively, for PG 1115+080 and $1.0^{+0.8}_{-0.3}$ keV and $8^{+3}_{-3} \times 10^{42}$ ergs s$^{-1}$, respectively, for B1422+231. We compare the spatial and spectral characteristics of the X-ray emission with the properties of the group galaxies, with lens models, and with the general properties of groups at lower redshift.

Subject headings: gravitational lensing — quasars: individual (PG 1115+080, B1422+231) — X-rays: galaxies: clusters

1. INTRODUCTION

Gravitational lenses that produce multiple images of background quasars can be an invaluable tool for measuring cosmological parameters, to better study the magnified distant quasars, and to explore the structure of the lensing galaxies. Models of some gravitationally lensed systems require significant external shear in addition to the intrinsic asymmetry of the lensing galaxy to reproduce positions and flux ratios of the lensed images (Keeton et al. 1997). Keeton et al. (2000) predict that a quarter of lensing galaxies are associated with a group or cluster that would perturb the gravitational potential. Constraining the distribution of diffuse gas and dark matter in the vicinity of gravitational lenses will help remove one component of uncertainty in determining both the distance scale and the lensing galaxy properties.

Groups of galaxies may make up a significant fraction of the baryonic mass in the universe (Fukugita et al. 1998). Groups also occupy an interesting position in the size hierarchy between galaxies and clusters, in which the effects of nongravitational heating and cooling mechanisms are comparable to those of gravitational effects (Babul et al. 2002; Borgani et al. 2002). Understanding how groups form and evolve may provide significant clues to the development and structure of both clusters and galaxies. Detection of galaxy groups is difficult because of, among other factors, the uncertainty in determining both the distance scale and the lensing galaxy properties.

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We are searching for X-ray emission from groups in the fields of strong gravitational lenses, using Chandra’s resolving power to separate the quasar images from diffuse emission. There are five spectroscopically confirmed galaxy group-lens associations, a few additional systems that seem likely candidates, and an ongoing program to search for these groups in the optical (e.g., Fassnacht & Lubin 2002). We initially chose to concentrate on two systems, PG 1115+080 and B1422+231, as interesting candidate objects because of their long exposure time and their lensing geometry, which requires external shear. Time delays have been measured for both of these systems, and the derived value of $H_0$ depends on the position and mass of the nearby galaxy groups, which have optical properties favorable for detecting X-ray emission. Both systems have been observed by previous X-ray missions (Chartas 2000); however, the strong X-ray emission from the lensed quasar and the proximity of the group to the lens made detection of the faint diffuse group emission impossible.

PG 1115+080 is a quadruply imaged radio-quiet quasar at $z = 1.72$ discovered by Weymann et al. (1980). The lensing galaxy has been shown to be part of a nearby group of galaxies (Young et al. 1981) at $z = 0.310$ (Kundić et al. 1997a; Tonry 1998). The group properties, such as the line-of-sight velocity dispersion of $243^{+234}_{-84}$ km s$^{-1}$ and the harmonic radius of $60 \pm 10$ h$^{-1}$ kpc (Fassnacht & Lubin 2002), are generally consistent with a Hickson compact group (Hickson et al. 1992). Both long (Schechter et al. 1997) and short (Chartas et al. 2004) time delays have been measured between the lensed images, but determination of $H_0$ is difficult because of, among other factors, the uncertainty in the location and mass profile of the associated group (Keeton & Kochanek 1997).

B1422+231 is a quadruply imaged radio-loud quasar at $z = 3.62$ (Patnaik et al. 1992). The lens is a nearby galaxy group (Remy et al. 1992; Yee & Ellingson 1994) at $z = 0.338$ (Kundić et al. 1997b; Tonry 1998). The line-of-sight velocity dispersion, $535^{+312}_{-84}$ km s$^{-1}$, is at the high end for a group, while the harmonic radius, $50 \pm 10$ h$^{-1}$ kpc, is very consistent (Fassnacht & Lubin 2002). Time delays were measured in the
radio by Patnaik & Narasimha (2001). Siebert & Brinkmann (1998) found no evidence for extended emission in a ROSAT HRI observation. Raychadhury et al. (2003) recently reported detection of soft X-ray emission from the group by using the first of the two Chandra observations analyzed here.

We describe the Chandra observations and data reduction in § 2. Detection of the group emission and analysis of the spatial characteristics are presented in § 2.1. Spectral analysis of the X-ray emission is described in § 2.2. In § 3 we compare our results with expectations from the optical data and the lensing models and discuss future prospects for this type of study. A cosmology with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 1$, and $\Lambda = 0$ is always assumed.

2. OBSERVATIONS AND ANALYSIS

Both objects were observed using the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) on Chandra (Weisskopf et al. 2002). The target object was placed on the ACIS-S3 back-illuminated CCD, and the data were taken in the standard faint timed-exposure mode. Table 1 lists the Chandra observational parameters. The CCD frame time was the standard 3.2 s for all but the second observation of B1422+231, ObsID 1631, for which the frame time was reduced to 0.8 s to minimize event pileup in the bright quasar images. The estimated pileup fraction for each lensed image is 1%–4%, except for the earlier B1422+231 observation (ObsID 367), when the pileup fraction came close to 10%. Outside the central few pixels in the quasar images, pileup is completely negligible, since the expected galaxy group emission should be at least an order of magnitude fainter and diffuse.

The data were reduced using the standard Chandra tool package, CIAO, including filtering by event grade and status to remove likely background and cosmic-ray afterglow events. Times of high particle background rates were identified by examining light curves in the 0.3–7 keV band. During approximately 30% of the exposure for ObsID 367 of B1422+231, the rate was unacceptably high (more than twice the quiescent rate), and the affected interval was removed. Exposure times listed in Table 1 were determined after this step. Multiple observations of the same source were merged into a single event file. To maximize the diffuse signal and minimize the background, the event lists were filtered to include only photon energies between 0.5 and 2 keV, for which the relative contribution of the particle background for the ACIS-S3 detector is at its lowest.

2.1. Image Analysis

Two CIAO source detection algorithms were used, wavdetect and rtpdetect, for a number of size scales and significance levels, but no extended sources were found. The expected emission from the group is very weak, however, so the lack of detection by generalized algorithms is not surprising. In addition, no significant X-ray emission was detected from the individual group galaxies. At the redshift of these groups a galaxy with a luminosity of $10^{41}$–$10^{42}$ ergs s$^{-1}$ would produce few to no counts in our observations.

Disentangling the weak group emission from the bright quasar images is a complex task. Even with Chandra’s exquisite resolving power, the wings of the point-spread function (PSF) are a substantial contaminant, which must be quantified and minimized. To better study the spatial distribution of the quasar emission, a model was constructed for the lens and fitted to the image using the Chandra software package SHERPA. The lensed images were fixed to the relative positions found in the literature (Impey et al. 1998; Patnaik et al. 1999) and were represented as narrow Gaussians convolved with the Chandra PSF. The additional broadening introduced by the Gaussians is intended to account for errors in the aspect solution and offsets between the merged data sets and to be a gross approximation to the small distortion of the PSF caused by event pileup. This lens model was subtracted from the original image. The images were then smoothed with a 30 pixel FWHM Gaussian and normalized for exposure variations and instrumental features (30 pixels $\approx 15'' \approx 42$ h$^{-1}$ kpc at the redshift of the groups).

Contours of the smoothed images are shown in Figures 1 and 2. The spatial scale of these figures is much larger than that of the lensed images, which have a maximum separation of 1$''$5–2$''$. The positions of the known group galaxies and the lensing galaxy (labeled “GL”) are also shown. The galaxy positions and designations are from Impey et al. (1998) for PG 1115+080 and from Kundic’ et al. (1997b) for B1422+231. In both cases there is significant X-ray emission that appears to be extended and centered on the galaxy group. The poor photon statistics do not allow for more complicated modeling of the source emission profile.

### Table 1: Observation Data

| Name          | Observation ID | Observation Date | Exposure Time (s) |
|---------------|---------------|------------------|-------------------|
| PG 1115+080... | 363           | 2000 Jun 2       | 26492             |
|               | 1630          | 2000 Nov 3       | 9825              |
| B1422+231..... | 367           | 2000 Jun 1       | 17864             |
|               | 1631          | 2001 May 21      | 10651             |
The strongest emission is near the brightest group (Ponman 2000a). Given the low statistics in the X-ray image, the X-ray centroid of all the group galaxies is shown in Figure 1 and is approximately halfway between the X-ray emission peak and the clump of galaxies at the end of the extended ridge (Impey et al. 1998). Also shown in Figure 1 is the flux-weighted centroid of the four brightest galaxies, which has been used to model the group in previous lens models (C4 in Keeton & Kochanek 1997) and lies near the end of the extended ridge. Given the low statistics in the X-ray image, the X-ray centroid is reasonably consistent with both the optical centroids and the brightest group galaxy, in agreement with global properties of X-ray groups (Zabludoff & Mulchaey 1998; Helsdon & Ponman 2000a).

The B1422+231 group emission appears more regular and compact. The strongest emission is near the brightest group galaxy, G3, and the flux-weighted centroid of the six group galaxies. The maximum X-ray emission for the B1422+231 group is at about $\Delta \alpha = 7''$ and $\Delta \delta = -9''$ relative to image B of the gravitational lens. The additional weaker emission to the northwest may be an extension of the group that, with higher statistics, would be connected to the brighter portion. However, it is only 2 $\sigma$ above the background fluctuations, so it may also be a noise artifact. The group emission is too faint to have been detected in the previous ROSAT HRI observation (Siebert & Brinkmann 1998).

### 2.2. Spectral Analysis

Photons were extracted from a polygonal region that approximates the 2 $\sigma$ contour level shown in Figures 1 and 2. Photons in a circular region around the lensed quasar images were excluded. The radius of the quasar-masking region was determined by minimizing the contribution of the quasar to the extracted group spectrum to 5–6 counts in the 0.5–2 keV band. This required a masked radius of $7''$–$8''$. The CIAO script acisspec was used to extract the photons and create the instrument response products. The additional absorption from the time-dependent contamination of the ACIS detector was included in the effective area calculation using ACISABS.\(^1\) We find a total of 46 net source counts above a background of 46 counts for PG 1115+080 and 51 source counts above a background of 30 counts for B1422+231 in the 0.5–2 keV energy band.

We modeled the spectrum of the galaxy group as an absorbed Raymond-Smith thermal plasma with a metal abundance of 0.3 Z$_{\odot}$. Both the Galactic $N_H$ and $z$ were set to their known values. An additional model component was included to account for residual quasar emission with the spectral forms found in the literature (Gallagher et al. 2002; Raychaudhury et al. 2003). The normalization of the quasar emission was adjusted to produce the number of counts predicted by the model lens image. Because of calibration uncertainties at low energies and lack of photons at high energies, the spectral fitting was done over the energy range 0.3–8 keV. The results of the spectral fitting are shown in Table 2. The fits are formally good, but the statistics are poor, particularly in the case of B1422+231. The flux and luminosity have been adjusted to account for the expected group emission in the masked-quasar region. Because of the flat surface brightness profiles of groups, the measured luminosity in the detection region is most likely an underestimate of the true luminosity (Helsdon & Ponman 2000a).

\(^1\) ACISABS is available from http://www.astro.psu.edu/users/chartas/xcontdir/xcont.html.

### TABLE 2

**Group X-Ray Emission Properties**

| Parameter | PG 1115+080 | B1422+231 |
|-----------|-------------|------------|
| Group redshift | 0.310 | 0.338 |
| Galactic $N_H$ ($10^{20}$ cm$^{-2}$) | 4.0 | 2.7 |
| Group (background) 0.5–2 keV counts | 46 (46) | 51 (30) |
| $kT$ (keV) | $0.8_{-0.1}^{+0.2}$ | $1.0_{-0.3}^{+0.2}$ |
| Absorbed 0.5–2 keV flux (10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$) | $4.1_{-2}^{+1}$ | $3.2_{-1}^{+1}$ |
| Rest-frame bolometric luminosity (10$^{42}$ ergs s$^{-1}$) | $7.2_{-2}^{+2}$ | $7.7_{-2}^{+2}$ |
| X-ray emission peak ($d, \theta$) | $25''$, $-123''$ | $11''$, $144''$ |

*Note.—Errors are 1 $\sigma$ (68%) confidence level. Redshift and Galactic column density are fixed at their known values. The position is relative to image C for PG 1115+080 and image B for B1422+231. The position angle is measured north through east; $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1.0$.\)**
Our results are in general agreement with the findings of Raychaudhury et al. (2003), who found a temperature for the B1422+231 group of 0.71 keV. They did not, however, analyze the extended emission from the lens but instead extracted photons from a 3 arcmin region around the lensed images where quasar contamination is orders of magnitude worse. Their lens X-ray contours seem more extended in the northwestern direction, which may argue for the reality of the larger northern feature seen in Figure 2. In addition, since they did not mention any correction for event pileup yet they extracted the quasar photons from very small regions around the image cores, we must assume that their fitted power-law index for the quasar spectrum, which we use in our spectral analysis, was too hard. Because of the low photon statistics for the group emission, however, this does not have a significant influence on our derived group properties.

3. DISCUSSION

We have detected X-ray emission from the two groups associated with the gravitational lenses. We can now compare the observed X-ray luminosity and temperature for the groups with the optical group characteristics, with global properties of groups at low redshift, and with lens models in the literature. We use the $\sigma - T_X$, $\sigma - L_{bol}$, and $L_{bol} - T_X$ relations from Helsdon & Ponman (2000b), who fitted a large sample of compact and loose groups. Other scaling relations (e.g., Girardi et al. 1996; Xue & Wu 2000; Mahdavi & Geller 2001) yield comparable results.

Figures 3–5 compare the group X-ray luminosity, temperature, and the galaxy velocity dispersion with the scaling relations for low-redshift groups from Helsdon & Ponman (2000b). Both groups are consistent with the scaling relations within the errors of the data and the fit. The temperature for B1422+231 is poorly constrained, but the best-fit value of $L_X$ is consistent with that expected from a normal group. PG 1115+080, while formally consistent, is somewhat over-luminous given the measured velocity dispersion and temperature. These results are in general agreement with Jones et al. (2002), who found no evidence of group evolution out to $z = 5$. 

Given a model for the group potential, the velocity dispersion of the group, $\sigma$, and its position can be used to predict $\gamma$, the external shear at the lens from the group. The same group scaling relations can then further predict the shear given the X-ray temperature or luminosity. For a singular isothermal sphere (SIS) model,

$$\gamma = \frac{2\pi D_{ls}}{r D_{los} c^2} \left( \frac{\sigma}{\sigma_c} \right)^2,$$

where $r$ is the angular distance from the group to the main lensing galaxy and $D_{ls}$ and $D_{los}$ are the angular diameter distances from the lens to the source and from the observer to the source, respectively.

Gravitational lens models of the PG 1115+080 system require an external shear of order $\gamma \sim 0.1$ in the general direction of the galaxy group center to fit the observed image positions (e.g., Keeton et al. 1997). When we model the group as an SIS located at the position of maximum X-ray emission, the shear at the lensing galaxy from the group potential is of order $\gamma \sim 0.01$ using the measured velocity dispersion or using the $\sigma - T_X$ scaling relation and the measured temperature; the shear is of order $\gamma \sim 0.1$ using the $\sigma - L_{bol}$ scaling relation and the measured luminosity. Moving the group center closer to the main lensing galaxy substantially increases the predicted shear.
lensing galaxy would increase the predicted value of $\gamma$. To produce an external shear of order $\gamma \sim 0.1$ given the measured velocity dispersion and X-ray temperature, the group centroid must be no farther than 14" from the lensing galaxy. When Keeton & Kochanek (1997) allowed the group position to be a free parameter in their lens models, the best-fit model had $(d, \theta) = (25^2, -125^\circ)$, very close to the X-ray emission peak. Using better image and lens positions, Impey et al. (1998) found a group position of $(10^\circ, -113^\circ)$, consistent with C4, the luminosity centroid of the brightest four group galaxies. The X-ray group emission profile appears elongated, so the group potential may be better represented by an elliptical rather than spherical model. The external shear can be derived for an elliptical potential, such as that of Blandford & Kochanek (1987). The magnitude of the shear then also depends on the ellipticity of the group potential and the angle between the group major axis and the lens direction. If, as may be true in this case, the major axis is aligned along the direction to the lens, the predicted shear increases. A more accurate model for the group potential would include both the apparent ellipticity, as well as a more refined X-ray centroid. The predicted shear from this model would likely be in agreement with the estimates from lensing models.

The lensed images in B1422+231 are highly asymmetric and so require substantial external shear of order $\gamma \sim 0.2$ in the direction of the galaxy group (e.g., Keeton et al. 1997). Assuming an SIS group at the position of maximum X-ray emission with the measured properties, the external shear from the group potential at the lensing galaxy is in general agreement with lens models.

In both cases, the group parameters derived from the optical properties of the galaxies seem to be in general agreement with those from the X-ray properties; however, interesting problems remain. The elongated structure of the PG 1115+080 group, if real, may be important in determining how much shear and convergence the group contributes to the lens. Better counting statistics would certainly help constrain the group X-ray parameters, and because of the small angular distance and large dynamic range between the quasar images and the group, the high spatial resolution of Chandra will be required in future investigations.

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