Resolving Complex Inner X-Ray Structure of the Gravitationally Lensed AGN MG B2016+112

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Abstract

We use a Chandra X-ray observation of the gravitationally lensed system MG B2016+112 at $z=3.273$ to elucidate the presence of at least two X-ray sources. We find that these sources are consistent with the very long baseline interferometry (VLBI) components measured by Spingola, which are separated by $\sim200$ pc. Their intrinsic $0.5–7$ keV source frame luminosities are $1.5 \times 10^{43}$ and $1.8 \times 10^{44}$ erg s$^{-1}$, respectively. Most likely this system contains a dual active galactic nucleus (AGN), but we are possibly detecting an AGN plus a parsec-scale X-ray jet, the latter lying in a region at very high magnification. The quadruply lensed X-ray source is within $\pm 40$ pc (1$\sigma$) of its VLBI counterpart. Using a gravitational lens as a telescope, and a novel statistical application, we have achieved unprecedented accuracy for measuring metric distances at such large redshifts in X-ray astronomy. This is tens of mas if the source is located close to the caustics, while it is of hundreds of mas if the source is in a region at lower amplification. The present demonstration of this approach has implications for future X-ray investigations of large numbers of lensed systems.

Unified Astronomy Thesaurus concepts: Gravitational lensing (670); Radio loud quasars (1349); X-ray active galactic nuclei (2035); Astrometry (80)

1. Introduction

The X-ray emission from inner regions of active galaxies is a key to our understanding of supermassive black hole growth, mergers, and accretion processes. However, the study of formation of galaxies in the early universe is limited by the inability of telescopes to detect and resolve inner regions of these faint objects. At high energies, physical constraints limit further improvements of the resolution of these telescopes. As a result, present and future missions will not provide sufficient resolution to resolve inner regions of merging galaxies potentially hosting multiple active galactic nuclei (AGNs).

Here we use a novel approach of combining gravitational lensing with the capabilities of the Chandra Observatory to study the system MG B2016+112\(^4\), located at a redshift of 3.273 (Lawrence et al. 1993), when the Universe was just less than 2 billion years old. This complex source has a peak magnification of a factor of $\mu \sim 1.5$ (doubly imaged region) and a peak magnification factor of $\mu \sim 300$ (quadruply imaged region) by gravitational lensing due to its proximity to the caustic of the lens. Such huge magnification is accompanied by spatial amplification that allows us not only to observe a source that would be otherwise too faint, but also to elucidate its structure as well as resolve spectra of individual lensed images of multiple sources. Radio observations reported by Spingola et al. (2019) suggested possible dual-AGN-like structures with misaligned jets, and measured the relative motions of the components. If confirmed, MG B2016+112 would be the first gravitationally lensed dual AGN discovered.

1.1. Galaxy Formation and Evolution in the Early Universe

Hierarchical structure formation simulations show that galaxies merge, and thus their central black holes should form dual AGNs (separation less than $10$ kpc) and physical binary AGNs (separation less than $100$ pc; Burke-Spolaor et al. 2014). The occurrence of binary and dual AGNs has important implications for assessing the time needed for the final stage of merging of the two supermassive black holes (SMBHs). The eventual coalescence of such SMBH binaries is expected to be a major source of gravitational waves detected by the Laser Interferometer Space Antenna (LISA), or by the Pulsar Timing Array (PTA) if $M > 10^7 M_\odot$ (Sesana et al. 2009; Dal Canton et al. 2019; DeGraf & Sijacki 2020).

So far the search for dual AGNs has mostly been limited to low redshift ($z \ll 1$) and large separation ($\gg$kpc) using a variety of methods. For instance, the ultraluminous infrared galaxy NGC 6240 at $z=0.024$ was the first X-ray source shown to be a dual AGN (Komossa et al. 2003). Rubinur et al. (2019) have found low-$z$ candidates among double peaked emission line radio galaxies, but they note that core-jet, rotating disks, and jet-ISM interactions can also give such signatures. Hwang et al. (2019) have proposed to use variable sources causing astrometric noise in Gaia to uncover sub-kiloparsec AGN using ACS imaging on Hubble. Gross et al. (2019) found low luminosity dual AGN at $z < 0.22$ with both AGN emitting X-rays at separations from 4 to 7 kpc. Deane et al. (2014) found a triple SMBH system at $z=0.39$, with two SMBH separated by only 140 pc, using high resolution interferometric radio observations. Connor et al. (2019) found tentative evidence for AGNs at 11 kpc separation in a merging system at $z=6.23$, using a 150 ks Chandra observation. Those references reflect...
the state of the art techniques for identifying dual AGNs. Contrast to the results presented here, using a 7.77 ks Chandra observation.

1.2. X-Ray Emission from the Inner Regions of Active Galaxies

It is widely assumed that the multiwavelength nonthermal emission in quasars has a coincident origin near the central SMBH. However, X-ray observations at redshifts greater than a few tenths allow access only to kiloparsec scales, thus providing 1000 times worse resolution as compared to radio observations. These technical limitations prohibit the direct study of the origin of X-ray emission from AGN and their relativistic jets. There is much more to learn about the origin and structure of jets if we could probe in greater spatial detail in all wave bands. We know that the origin of variable emission and structure of jets if we could probe in greater spatial detail in relativistic jets. There is much more to learn about the origin of variable emission need not be within the parsec-scale core.

In the nearby source M87, Chandra imaging resolved a huge flare in the HST-1 knot 60 pc from the core (Harris et al. 2003). This knot dominated the X-ray emission from the nucleus for more than 4 yr. Marshall et al. (2010) and Hardcastle et al. (2016) suggested X-ray flaring in a knot of the Pic A jet, tens of kiloparsecs from the nucleus. Jones et al. (2020) report that 20% of the X-rays, including an Fe K line, are more than 1 kpc from the nucleus in the nearby Compton thick AGN NGC 7212. Similar kiloparsec-scale X-rays are also seen in several other nearby AGNs (e.g., Arévalo et al. 2014; Bauer et al. 2015; Fabbiano et al. 2017).

1.3. Gravitational Lenses as High Resolution Telescopes

Gravitational lensing is the most powerful tool to spatially amplify the images of cosmologically distant sources (Barnacka 2017, 2018). Galaxies may act as gravitational telescopes by means of their mass distributions. As a result of gravitational lensing, multiple images of the same background source (e.g., a quasar or a dual-AGN system) may be observed, which can help uncover complex multiwavelength structure at distances otherwise impossible to reach with current instruments (e.g., Congdon & Keeton 2018).

As discussed in Barnacka (2018), high precision astrometric measurements have potential to reveal and elucidate diverse phenomena. Gravitationally lensed γ-ray flares were shown to occur 1.5 kpc from the nucleus in the blazar PKS 1830-211 at \( z = 2.507 \) (Barnacka et al. 2015). For the lensed blazar B2 0218 +35 at \( z = 0.944 \), Barnacka et al. (2016) showed that the γ-ray flare was separated by at least 60 pc from the radio core. Direct measurement of optical to radio offsets at \( z > 1 \) has been investigated by Spingola & Barnacka (2020). The authors found an offset of 214 ± 137 pc between the optical and radio emission of CLASS B1608+656, and that optical and radio were cospatial in CLASS B0712+472 to within 17 ± 42 pc. Also, the lensing amplification enabled to find that AGN jets and star-forming regions are not spatially coincident in JVAS B1938+666 at \( z = 2.059 \) and MG J0751+2716 at \( z = 3.2 \) (Spingola et al. 2020), and RX 1131-1231 at \( z = 0.654 \) (Paraficz et al. 2018), possibly showing AGN feedback in action.

Multiwavelength studies are important for all these objectives; however, high energy wave bands are limited by the resolution capability of current and even planned instrumentation. In the X-ray band, the state of the art angular resolution is provided by the Chandra observatory. The Chandra precision of offset measurements is generally limited by the absolute celestial location aspect solution, which currently is 0′/8 to 90% confidence for sources within 3′ of the optical axis. At redshifts greater than a few tenths, 0′/8 corresponds to several kiloparsec uncertainty. Gravitational lenses can be used to reduce this uncertainty by up to two orders of magnitude, as we demonstrate herein for the dual-AGN candidate MG B2016+112. We thus move astrometric investigation of cospatial emission to the high energy part of the electromagnetic spectrum.

The paper is organized as follows. In Section 2, we describe properties of radio-loud gravitationally lensed quasar MG B2016+112. Section 3 describes our Bayesian method, while we report our results on the X-ray emission of MG B2016+112 in Section 4. Finally, we discuss the results and present our conclusions in Section 5.

2. MG B2016+112

MG B2016+112 is a radio-loud source at a redshift of 3.273 (Lawrence et al. 1993) that is gravitationally lensed mainly by an early-type galaxy and its faint satellite at a redshift of 1.001 (Schneider et al. 1986; Koopmans & Treu 2002). The lensing galaxies are part of a large cluster of galaxies as indicated by the observation of six galaxies at that redshift by Soucail et al. (2001). At half-arcsec angular resolution, this system consists of three lensed images, separated by \( 3'5 \). Original X-ray detections by Hattori et al. (1997) were interpreted as from the cluster, however Chandra observation by Chartas et al. (2001) resolved three faint, point-like images consistent with the radio positions. Using the notation of Spingola et al. (2019) we will call the X-ray images A1, B1, and C11.

With continuing observations of this system, the lens model has been refined. More et al. (2009) considered a range of models, adding the satellite galaxy G1 discussed by Chen et al. (2007). However, adding a third galaxy did not significantly improve the match to the positions and fluxes. In this paper we use the lens model presented in Table 3 of Spingola et al. (2019), summarized as follows. The main lensing galaxy is an elliptical with velocity dispersion 328 ± 118 km s^{-1} (Koopmans & Treu 2002). While an isothermal profile is not assumed, the best fit density slope is found to be \( 2.09_{-0.05}^{+0.09} \), consistent with the isothermal value 2. A small satellite galaxy is included as a singular isothermal sphere with 9% of the mass of the elliptical. The cluster properties are not determined in detail, and approximated by an external shear giving the best fit to the very long baseline interferometry (VLBI) positions. The fit to the mass model contains eight free parameters: the mass, coordinates, ellipticity, positional angle and density slope of an elliptical model to galaxy D, plus external shear and shear position angle to account for the cluster of galaxies, and in addition uses the More et al. (2009) singular isothermal sphere parameters for the satellite galaxy. The probability densities for the parameters are shown in Figure 3 of Spingola et al. (2019), while their Table 3 includes the parameter uncertainties. While all of the models are acknowledged to fall short of perfect reproduction of the observations, in the present paper we conclude that the X-ray and VLBI-lensed images may be cospatial, the lens systematical errors are achromatic and will have identical effects on both bands so they do not change any relative positions. In the optical and radio bands image C is

\[ \text{https://cxc.harvard.edu/cal/ASPECT/celmon/} \]
extended into a small arc (Koopmans & Treu 2002), and consists of the blending of the so-called “merging images” (C11+C21) of a quadruply imaged system, but the two counter images were too faint to be detected in the radio with the VLBI observations of More et al. (2009) and Spingola et al. (2019). In fact, the lens mass model predicts these two images to be very close to images A1 and B1 and extremely faint (with flux density at 1.7 GHz of a few μJy, Spingola et al. 2019). Instead, images A and B are mirror images of the part of the source lying outside the caustic in the doubly imaged region. At the radio wavelengths it is possible to spatially resolve on mas-scales all of the lensed images using VLBI observations. More et al. (2009) find that the lensed images are resolved into multiple compact and extended components with flat and steep radio spectra.

By comparing the position of these sub-components as measured with two VLBI observations separated by \(~14\) yr, Spingola et al. (2019) found a significant positional change for four of them. The proper motions were of a few micro-arcseconds per year in the source plane for two of the radio components of the system MG B2016+112. At the redshift of MG B2016+112, \(1\) μarcsec = 0.00767 pc. Such motion, once focused back in the source plane, suggested two possible scenarios for the nature of the source. The first hypothesis consists of a single AGN source, seen at a small viewing angle to the line of sight, where the doubly imaged jet is Doppler boosted (hence, the superluminal velocity) while the quadruply imaged counter-jet is not boosted (hence, the subluminal velocity). The other possibility is that of a dual-AGN scenario, where there would be two jetted AGNs (one doubly imaged and one quadruply imaged), seen under different viewing angles (one significantly Doppler boosted), separated by \(~200\) pc, thus very close to being a physically bound AGN system. This scenario is supported by the detection of proper motion of the quadruply imaged radio core, which is usually observed as a stationary component of the jet (e.g., Boccardi et al. 2017), and the multiwavelength photometric and spectroscopic properties of the system (see Section 5.2 of Spingola et al. 2019 for a detailed discussion).

To assess the nature of this system, it is therefore fundamental to investigate its X-ray properties. The presence of two X-ray sources, both with a flat photon index or intrinsic absorption, would be the smoking gun for confirming the dual-AGN nature of MG B2016+112.

### 3. X-Ray Astrometry

We present our X-ray analysis of the Chandra archival data in Section 3.1 and apply raytrace lensing analysis in Section 3.2. To further improve localization of the X-ray emission, in Section 3.3 we introduce and apply a method based on Bayesian prior constraints on the relative positions and intensities imposed by the model of the lens.

#### 3.1. X-Ray Analysis

We have re-analyzed the Chandra data of (Chartas et al. 2001, ObsID 429) using REPRO4, and the energy dependent subpixel event redistribution (EDSER) algorithm. Figure 1 shows the 0.5 to 7 keV band image that we use for astrometric measurements. There are three distinct regions consistent with point sources in this very short 7.77 ks observation. The regions are well separated in X-rays, and highly significant above the background of 0.01 count arcsec\(^{-2}\). The 7.77 ks observation yielded very few counts, 7, 4, and 13 for images A, B, and C, respectively. With such poor statistics, independent estimates of the location of each image have \(\sim 0.3\) arcsec relative errors, in addition to the 0.8 absolute celestial location uncertainty.

#### 3.2. Raytrace Lensing Analysis

We began by conducting inverse raytrace analysis following Spingola & Barnacka (2020). Combining a well reconstructed model of the lens and positions of the X-ray emission identified as the three images A1, B1, and C1 resulted in position errors of \(\pm 80\) to \(\pm 100\) mas for the location of the X-ray emission projected to the source plane. At the scale 7.7 pc per mas, this is already unparalleled metric accuracy for an X-ray image at a redshift greater than 3. The two sources turn out to be 53 mas apart in the source plane, but with the large errors quoted.

#### 3.3. Bayesian Lensing Analysis

To further improve accuracy of localizing and resolving X-ray emission of MG B2016+112 we developed a new method based on the Bayesian approach. We use the Bayesian prior constraints on the relative position and intensities imposed by the model of the lens. This approach improves the location of the X-ray sources relative to the radio sources by another order of magnitude. We use the maximum likelihood correlation technique as presented in C. Spingola et al. (2021, in preparation), and summarized briefly here.

**Step 1:** For the Chandra response to a point source we run 1000 simulations with the actual aspect solution, dither, and...
total source flux from ObsID 429, and merge the results. Pileup is negligible for such a weak source.

Step 2: At each step of two linear arrays of source plane positions we generate a high fidelity prediction for the resulting lensed images designated A1, B1, C11, and C21 in Spingola et al. (2019). These positions combine the uncertainties in the lens model with the errors on the observed positions, as in Step 3 of Section 2 of Spingola & Barnacka (2020). One array considers trial source plane positions perpendicular to the caustic, spaced 10 mas apart. From SE to NW positions 3–25 are outside the caustic (doubly imaged) and positions 26–63 are inside the caustic and quadruply imaged (Figure 2). The other array generates positions inside and parallel to the caustic and spaced 50 mas apart, numbered 64–75 from NE to SW. Since the amplification of the lens depends primarily on the distance from the caustic, our ability to distinguish positions parallel to the caustic is much coarser.

For this grid of trial source positions we use the lensing mass model derived from the radio observations (Spingola et al. 2019) to predict the separations and magnifications of the four lensed images.

Step 3: We construct a model placing the simulated point source images from Step 1 at the predicted separations and with the predicted relative intensities.

Step 4: We bin the observed X-ray data into a 28 × 26 array of 0.″246 square pixels, with ni observed counts in each.

Step 5: We raster our model of the four simulated lensed images plus background in two dimensions in steps of 24.6 mas and re-sort into the bins of the observed data array to predict the expected counts, $\lambda_i$, for each of the 728 data bins.

Step 6: We compute the maximum likelihood for observing the counts in each bin based on Poisson statistics.

$$ C = -2P = -2 \sum_{i=1}^{728} \log (\lambda_i^n \exp(-\lambda_i)/n!) \quad (1) $$

Step 7: We linearly interpolate between raster coordinates to get the minimum value of $-1/2 \ C$ (which we loosely refer to as the “likelihood”), for each trial source position.

We analyze two scenarios; Scenario 1: One single source inside the caustic, or Scenario 2: two sources one inside and one outside the caustic. For each scenario, we consider whether the relative fluxes of the lensed images are exactly as predicted from the lens model, or whether the amplitudes of each lensed image are free variables. In each case, we have only one interesting parameter per source: the number of the trial source position, or equivalently the position of the source perpendicular to or parallel to the local caustic in the source plane. We use Wilks’ theorem (Wilks 1938; Cash 1979) that the differences of the likelihood function are distributed as $\chi^2$ with one degree of freedom for each interesting parameter. Numerically, we compute $-1/2 \ C$ and fit the 2D raster position, the relative amplitudes of the lensed images (in cases where we allow them to vary from the lens model prediction), and the overall normalization of the simulated number of counts, all of which are “uninteresting parameters,” to the observed total counts to give the minimum value for each trial source plane position.

4. Results

4.1. Single Source Scenario

Figure 3 shows our results for the case where we assume there is only one X-ray source and allow the amplitudes of all lensed images to vary. Holding all amplitudes at the values of the predicted magnifications, we find a minimum likelihood value above 85, and thus can reject that hypothesis. We can also reject this relative to the two source scenario, since the minimum likelihood value is 74.9 in that case. We plot $-1/2 \ C$ for each of a series of trial source plane positions, as numbered. Position 26 is the inferred position of source 4 epoch 1 from Table 4 of Spingola et al. (2019). To 90% confidence one X-ray
source is within 12 mas of the VLBI position perpendicular to the caustic, and within 70 mas parallel to the caustic. However, there are some problems with this interpretation. Figure 4 shows the ratios of the expected magnifications of image C to image A (or to B) divided by the ratio of the numbers of counts that best fit image C to those best fitting image A (or B). The ratios near the maximum likelihood positions, #26 and #67-#69 are much larger than 1. This is because the fitted counts in images A and B are much larger than expected, so the ratio C to A (or to B) is a smaller number in the denominator of the ratio that is plotted. Microlensing of any of the images is a reasonable explanation for what have long been observed as anomalous ratios among lensed images. In this case, however, both A and B are coincidentally both microlensed, and both by very nearly the same large factor, \( \approx 14 \) to 18. Both the size and similarity of these factors are surprising and unlikely, noting that image A1 is much further from the lensing galaxy than image B1. Furthermore, from Koopmans et al. (2002) Table 1, the summed flux ratio of images C to images A+B is 1.82 ± 0.06, which we do not expect to be subject to extreme microlensing due to the size of the radio components. That ratio is consistent with the poorly determined ratio of 13/11 in the X-ray image.

The possibility that there is only one source, outside the caustic, can be rejected, since that would predict no X-ray flux at the position of C11+C21. The latter would then have to be an unrelated foreground or background source, for which the probability of being within 1° of the VLBI source is only of order \( 10^{-5} \).

4.2. Double Source Scenario

For the lens model to predict substantial counts as observed for images A and B, without extreme microlensing, we require a second X-ray source outside the caustic. This had been concluded from the VLBI observations (More et al. 2009; Spingola et al. 2019), and we now establish that the X-rays also require a source inside and another outside the caustic. We successively take five trial source positions spaced 50 mas apart perpendicular to and outside of the caustic. For each of those positions we compute the maximum likelihood as above (Section 3.3), pairing with all the positions inside the caustic. Since the amplification of the lens decreases rapidly outside the caustic to less than a factor of 2, we are much less sensitive to measuring the position of this outside source.

Allowing all the image amplitudes to vary results in flux ratios within a factor of 3 of the predicted magnifications, and gives the minimum values for our likelihood statistic. Freezing amplitudes at their predicted ratios gives just slightly higher values. These are statistically allowed and give smaller regions of allowed locations. We report results based on the variable image ratios as these are more conservative, and can be explained by reasonable microlensing and/or source variability.

Figure 5 summarizes our position determinations for each of the two sources. We take the two one-dimensional arrays of the quantity \(-1/2 \) C and extrapolate into a continuous two-dimensional grid, taking cognizance that the lensing positions are fairly insensitive to the source positions parallel to the caustic. For source 1 (source 2) we marginalize over the likelihood of source 2 (source 1) to construct confidence contours considering two interesting degrees of freedom. Using the reference position deduced for source 4, epoch 1, in Table 4 of Spingola et al. (2019) we convert to R.A., decl. coordinates. To within a full range of \( \pm 1 \sigma \) (alternately, of \( \pm 90\% \) confidence we locate source 1 within 10 (20) mas perpendicular to the caustic, and 170 (315) mas parallel to the caustic. For source 2 our analysis is much less restrictive because the lower amplification changes the image positions by smaller angular distances than can be distinguished for such few X-ray counts. With \( 1\sigma \) confidence, source 2 is restricted to be within 160 mas perpendicular to the caustic, and within 200 mas parallel to the caustic. To 90% confidence we limit source 2 within 500 mas parallel to the caustic, but do not restrain its perpendicular extent outside the caustic. Those are the full range of uncertainty, conventionally those uncertainties would be reported as \( \pm 1/2 \) the numbers quoted above, so that the two sources would be 650 ± 650 (1\( \sigma \)) pc apart.

We have measured the location of source 1 within a region \( 77 \times 1300 \) pc, to 68% confidence. This is unprecedented metric accuracy in X-ray astronomy for an object at such a large redshift.

5. Discussion and Conclusions

5.1. The Nature of the Two X-Ray Sources

We fit the 24 photons from all the lensed images to a power law plus galactic absorption of \( 0.15 \times 10^{22} \) cm\(^{-2} \). The fit gives a power law photon index \( \Gamma = 0.82 \pm 0.39 \), where \( \dndE = E^{-\Gamma} \). This would be an extremely flat value for an AGN. A better fit is obtained by allowing intrinsic absorption at the source redshift. We find \( (17 \pm 14) \times 10^{22} \) cm\(^{-2} \), and a photon power law index of 1.52 ± 0.46 that would be reasonable for a quasar. Within a 95% confidence interval, the total energy flux measured from 0.5 to 7 keV would be \( (3.1 \pm 1.1 \pm 1.5) \times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1} \), or 1.3 and 1.8 \( \times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1} \) for source 2 (which contributes 93% of each of images A and B) and source 1 (which contributes 7% to each of A and B, and is the only contributor to image C), respectively. Flux errors on the two sources separately are about a factor of two considering the statistics of 11 and 13 photons. The 11 photons in images A and B are distributed between 818 and 5753 eV, while the 13 photons in image C are distributed from 1294 to 4313 eV. This...
hints that source 1 has a steeper spectrum and more intrinsic absorption, but the sparse statistics allow all the spectra to be identical. If the two X-ray sources were actually at the positions allowed locations of source 1, which therefore could have an intrinsic luminosity several times more or even 10 times less, while source 2 could be about 10% less or a factor of 3 more luminous, in both cases just due to the magnification uncertainty.

The X-ray results are completely consistent with observing two gravitationally lensed AGNs. The usual interpretation of radio-quiet AGNs is that the X-ray emission is from a hot corona, very near to the supermassive black hole. The enhanced X-ray to optical ratios for radio-loud AGNs have been suggested to be due to beamed X-ray emission (e.g., Zamorani et al. 1981; Worrall et al. 1987). A dual-AGN interpretation is consistent with the narrow emission line spectra observations of Yamada et al. (2001) that showed different ionization properties for A+B versus for C. Both AGNs would be relatively low luminosity type II quasars, consistent with the large intrinsic X-ray absorption.

While the VLBI observations also favor a dual AGN (Spingola et al. 2019), we cannot rule out interpretation as a single X-ray AGN, where we separately image the core and its extended X-ray jet. The intrinsic ratio of 20 for source 2 to source 1 would be consistent with observation of kiloparsec X-ray jets, which found a median of about 50 for a set of low redshift quasars (Marshall et al. 2018). However, such a small contribution from a jet would not explain the enhanced ratio of X-ray to optical emission from radio-loud quasars. Observations of the X-ray spectra of the three images will be crucial to establish a dual AGN.

5.2. The Future of X-Ray Astrometry Using Gravitational Lensing

MG B2016+112 was only the fourth gravitational lens system to be discovered and only the second to be a radio source (Lawrence et al. 1984). It may prove to be an important “Rosetta Stone” for high energy astrophysics. Most exciting is the prospect that we are imaging an X-ray jet on the scale of parsecs from a supermassive black hole at large redshift. Alternately, establishing a dual or possibly binary supermassive black hole at $z > 3$ will have implications for the frequency of such systems in the early universe.

C. Spingola et al. (2021, in preparation) and the present study are the first to exploit the power of gravitational lenses as telescopes for the measurement of X-ray source positions. With a high fidelity lens mass model we used the predicted constraints on the lensed images to locate by direct observation that an X-ray source was within a few tens of parsecs of VLBI emission in MG B2016+112, a quasar at redshift 3.273. Many X-ray lens systems have far greater photon statistics, and will be a crucial resource for astrometric study of X-ray structure at large redshift.

Future surveys with the next generation of radio and optical telescopes, such as the Square Kilometre Array (SKA), Euclid and the “Vera C. Rubin” Observatory, will allow the discovery of $\sim 10^5$ strong lensing systems (Oguri & Marshall 2010; Collett 2015; McKean et al. 2015). Among them, there will be rare background sources, such as dual and binary AGN candidates. If quadruply imaged, like MG B2016+112, these systems will provide an unprecedented opportunity to investigate the final SMBH merging stages at high spatial resolution and at cosmological distances. Nevertheless, it will still be necessary to confirm the dual/binary AGN nature of these sources. The X-ray properties are crucial for this aim, e.g., by comparing the sources photon index and intrinsic absorption. Our novel method can be applied to X-ray follow-up observations of the most promising dual and binary AGN candidates that will be discovered in the future lensing surveys.
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**References**

Arévalo, P., Bauer, F. E., Puccetti, S., et al. 2014, *ApJ*, 791, 81
Barnacka, A. 2017, *ApJ*, 846, 157
Barnacka, A. 2018, *PhD*, 778, 1
Barnacka, A., Geller, M. J., Dell’Antonio, I. P., & Benbow, W. 2015, *ApJ*, 809, 100
Barnacka, A., Geller, M. J., Dell’Antonio, I. P., & Zitrin, A. 2016, *ApJ*, 821, 58
Bauer, F. E., Arévalo, P., Walton, D. J., et al. 2015, *ApJ*, 812, 116
Boccardi, B., Krichbaum, T. P., Ros, E., et al. 2017, *A&ARv*, 25, 4
Burke-Spolaor, S., Brazier, A., Chatterjee, S., et al. 2014, arXiv:1402.0548
Cash, W. 1979, *ApJ*, 228, 939
Chartas, G., Bautz, M., Garmire, G., et al. 2001, *ApJL*, 550, L163
Chen, J., Rozo, E., Dalal, N., et al. 2007, *ApJ*, 659, 52
Collett, T. E. 2015, *ApJ*, 811, 20
Congdon, A. B., & Keeton, C. 2018, Principles of Gravitational Lensing: Light Deflection as a Probe of Astrophysics and Cosmology (Berlin: Springer)
Connor, T., Bañados, E., Stern, D., et al. 2019, *ApJ*, 887, 171
Dal Canton, T., Mangiagli, A., Noble, S. C., et al. 2019, *ApJ*, 886, 146
Davis, J. E., Bautz, M. W., Dewey, D., et al. 2012, *Proc. SPIE*, 8443, 84431A
Deane, R. P., Paragi, Z., Jarvis, M. J., et al. 2014, *Natur*, 511, 57
DeGraf, C., & Sijacki, D. 2020, *MNRAS*, 491, 4973
Fabbiano, G., Elvis, M., Paggi, A., et al. 2017, *ApJL*, 842, L4
Fruscione, A., McDoell, J. C., Allen, G. E., et al. 2006, *Proc. SPIE*, 6270, 62701V
Gross, A. C., Fu, H., Myers, A. D., et al. 2019, *ApJ*, 883, 50
Hardcastle, M. J., Lenc, E., Birkinshaw, M., et al. 2016, *MNRAS*, 455, 3526
Harris, D. E., Biretta, J. A., Junor, W., et al. 2003, *ApJL*, 586, L41
Hattori, M., Ikebe, Y., Asaoka, I., et al. 1997, *Natur*, 388, 146
Hwang, H.-C., Liu, X., Shen, Y., et al. 2019, *HST* Proposal, 15900
Jerius, D. H., Cohen, L., Edgar, R. J., et al. 2004, *Proc. SPIE*, 5165, 402
Jones, M. L., Fabbiano, G., Elvis, M., et al. 2020, *ApJ*, 891, 133
Joye, W. A., & Mandel, E. 2003, in ASP Conf. Ser. 295, Astronomical Data Analysis Software and Systems XII, ed. H. E. Payne, R. I. Jedrzejewski, & R. N. Hook (San Francisco, CA: ASP), 489
Komossa, S., Burwitz, V., Hasinger, G., et al. 2003, *ApJL*, 582, L15
Koopmans, L. V. E., Garrett, M. A., Blandford, R. D., et al. 2002, *MNRAS*, 334, 39
Koopmans, L. V. E., & Treu, T. 2002, *ApJL*, 568, L5
Lawrence, C. R., Neugebauer, G., & Matthews, K. 1993, *AJ*, 105, 17
Lawrence, C. R., Schneider, D. P., Schmidt, M., et al. 1984, *Sci*, 223, 46
Marshall, H. L., Gelbord, J. M., Worrall, D. M., et al. 2018, *ApJ*, 856, 66
Marshall, H. L., Hardcastle, M. J., Birkinshaw, M., et al. 2010, *ApJL*, 714, L213
McKean, J., Jackson, N., Vegetti, S., et al. 2015, in Proc. of Advancing Astrophysics with the Square Kilometre Array (AASKA14) (Trieste: SISSA), 84
More, A., McKeen, J. P., More, S., et al. 2009, *MNRAS*, 394, 174
Oguri, M., & Marshall, P. J. 2010, *MNRAS*, 405, 2579
Paraíso, D., Rybak, M., McKeen, J. P., et al. 2018, *A&A*, 613, A34
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, *A&A*, 594, A13
Robitaille, T., & Bressert, E. 2012, *APLpy*: Astronomical Plotting Library in Python, Astrophysics Source Code Library, ascl:1208.017
Rubinur, K., Das, M., & Kharb, P. 2019, *MNRAS*, 484, 4933
Schneider, D. P., Gunn, J. E., Turner, E. L., et al. 1986, *AJ*, 91, 991
Sesana, A., Vecchiou, A., & Volonteri, M. 2009, *MNRAS*, 394, 2255
Soucail, G., Kneib, J.-P., Jaunsen, A. O., et al. 2001, *ApJL*, 560, L163
Spingola, C., McKean, J. P., Massari, D., et al. 2019, *A&A*, 630, A108
Spingola, C., McKean, J. P., Vegetti, S., et al. 2020, *MNRAS*, 495, 2387
Wilks, S. S. 1938, *Ann. Math. Stat.*, 9, 60
Worrall, D. M., Giommi, P., Tananbaum, H., et al. 1987, *ApJ*, 313, 596
Yamada, T., Yamazaki, S., Hattori, M., et al. 2001, *A&A*, 367, 51
Zamorani, G., Henry, J. P., Maccacaro, T., et al. 1981, *ApJ*, 245, 357