Gravitationally Lensed $\mu$Jy Radio Sources towards Galaxy Clusters

Asantha R. Cooray
Department of Astronomy and Astrophysics, University of Chicago, Chicago IL 60637, USA. E-mail: asante@hyde.uchicago.edu

Received: February 22, 2017; accepted

Abstract. Galaxy clusters are expected to gravitationally lens background radio sources. However, due to the smaller surface density of radio sources, when compared to optical galaxies, such lensed events are rare. For an example, it is expected that there is no lensed radio source due to foreground galaxy clusters in the 1.4 GHz VLA FIRST survey. However, at the $\mu$Jy level, the surface density of radio sources increases. Using the radio properties of the Hubble Deep Field (HDF) galaxies, we calculate the expected number of gravitationally lensed $\mu$Jy radio sources on the sky due to foreground galaxy clusters for different cosmological models. For a flat cosmology with $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$, we predict $\sim 1500$ lensed radio sources with flux densities $\sim 10$ to $1000$ $\mu$Jy at 1.4 GHz. We discuss the possibility of detecting lensed $\mu$Jy radio sources towards clusters with deep radio surveys. Given the recent detection of a sub-mm selected lensed $\mu$Jy radio source towards A370, it is suggested that deep radio observations of clusters should already contain such lensed sources. Aided by amplification due to gravitational lensing, the search for lensed $\mu$Jy radio sources towards clusters are likely to recover star-forming galaxies at redshifts of 1 to 3.

Key words: cosmology: observations — gravitational lensing — radio surveys

1. Introduction

It is now well known that gravitational lensing statistics is a useful probe of the geometry of the universe, especially for the determination of the cosmological constant. In a recent paper (Cooray 1998; hereafter C98), we calculated the expected number of gravitationally lensed arcs on the sky due to foreground galaxy clusters as a function of cosmological parameters. The expected number of arcs was calculated based on the redshift distribution of HDF galaxies (Williams et al. 1996), as determined by the photometric redshift catalog of Sawicki et al. (1997), with an extrapolation to the whole sky. Similar to optical arcs, galaxy clusters are expected to lens background radio sources. Such lensed sources with high magnification should appear as arcs in radio surveys. The number statistics of lensed radio sources can be used to determine the cosmological parameters, to study the radio source evolution at high redshifts, and as discussed later, properties of star forming galaxies at moderate to high redshifts.

The number statistics of lensed radio sources due to foreground clusters were first calculated by Wu & Hammer (1993). They predicted $\sim 10$ lensed radio sources on the sky down to a flux density limit of 0.1 mJy, and $\sim 100$ lensed radio sources down to 10 $\mu$Jy at 2.7 GHz (Figure 10 in Wu & Hammer 1993). At the source detection level of the VLA FIRST survey ($\sim 1$ mJy; Becker, White & Helfand 1995), there is only $\sim 2$ to 3 lensed radio sources expected on the whole sky, and when compared to the area of the survey and its resolution, it is likely that there is no lensed source present. This prediction is compatible with observational attempts to find lensed radio sources; Andernach, Gubanov & Slee (1997) searched the FIRST survey near Abell cluster cores and found no convincing candidates, and a statistical analysis of the radio positions towards clusters showed no preferential tangential orientation, as expected from gravitational lensing. Recently, a sub-mm selected source, SMM02399-0136, towards cluster A370 was found to be lensed with an amplification of 2.5 (Ivison et al. 1997). The source was detected at 1.4 GHz, with a flux density of $\sim 525$ $\mu$Jy. This detection prompted us to calculate the expected number of lensed $\mu$Jy sources present on the sky due to foreground clusters, and to refine the previous predictions in Wu & Hammer (1993). Since the predictions in Wu & Hammer (1993) for sources down to mJy level are still expected to be valid, we will only concentrate on the $\mu$Jy sources here.

In § 2 we describe our calculation and its inputs. In § 3 we discuss the possibility of detecting lensed $\mu$Jy sources. We follow the conventions that the Hubble constant, $H_0$, is $100 h$ km s$^{-1}$ Mpc$^{-1}$, the present mean density in the universe in units of the closure density is $\Omega_m$, and the
present normalized cosmological constant is \( \Omega_\Lambda \). In a flat universe, \( \Omega_m + \Omega_\Lambda = 1 \).

2. Expected Number of Lensed Sources

In order to calculate the lensing rate for background \( \mu \)Jy sources due to foreground galaxy clusters, we model the lensing clusters as singular isothermal spheres (SIS) and use the analytical filled-beam approximation (see, e.g., Fukugita et al. 1992). Our calculation is similar to that of C98 in which we calculated the expected number of lensed optical arcs on the sky due to foreground galaxy clusters (see, also, Cooray, Quashnock & Miller 1998; hereafter CQM). A main difference between the present paper and C98 is that we have not corrected for magnification bias in the present predictions (see, e.g., Kochanek 1991), primarily due to the lack of knowledge on the \( \mu \)Jy source luminosity function. Depending on the shape of the luminosity function, or the slope of the number counts, the predicted numbers will either increase or decrease due to magnification. The current consensus on the slope of the \( \mu \)Jy counts (see, e.g., Windhorst et al. 1985) suggests that there will be a slight excess in the number of sources towards clusters due to gravitational lensing amplification.

In order to describe the background \( \mu \)Jy sources, we describe the redshift and number distribution observed towards the HDF radio sources by Richards et al. (1998). The main advantage in using the HDF data is the availability of redshift information for \( \mu \)Jy sources. Also, HDF is one of the few areas where a deep radio survey down to a flux limit of \( \sim 2 \) \( \mu \)Jy at 1.4 GHz has been carried out. The HDF contains 14 sources with flux densities of the order \( \sim 6 \) to 500 \( \mu \)Jy at 8.5 GHz, and 11 of these sources have measured spectroscopic redshifts. We converted the 8.5 GHz flux densities to 1.4 GHz using individual spectral indices as presented by Richards et al. (1998). For sources with no measured spectral indices, we assumed an index of 0.4, the mean spectral index observed for \( \mu \)Jy sources (Fomalont et al. 1991; Windhorst et al. 1993; Richards et al. 1998). For the 3 sources with no measured spectroscopic redshifts, we used photometric redshifts from the catalog of Fernández-Soto, Lanzetta & Yahil (1998). We binned the redshift-number distribution in redshift steps of 0.25, and calculated the lensing probability using filled-beam formalism. Similar to C98, we calculated the \( F \) parameter in lensing by describing the foreground lensing clusters using a Press-Schechter analysis.

We calculated the expected number, \( \bar{N} \), of gravitationally lensed radio sources on the sky as a function of \( \Omega_m \) and \( \Omega_\Lambda \), and for a minimum amplification of \( A_{\text{min}} \) of 2 and 10 respectively. Since we are using the SIS model, the amplification is simply equal to the ratio of length to width in observed lensing arcs (see, e.g., Wu & Mao 1996). In Table 1, we list the expected number of strongly lensed arcs on the sky for \( A_{\text{min}} = 2 \) and 10.

### Table 1. Predicted number of lensed \( \mu \)Jy radio sources on the sky down to a flux density limit of 10 \( \mu \)Jy

| \( \Omega_m \) | \( \Omega_\Lambda \) | \( \bar{N}(A_{\text{min}} \geq 2) \) | \( \bar{N}(A_{\text{min}} \geq 10) \) |
|---|---|---|---|
| 0.1 | 0.0 | 2155 | 25 |
| 0.2 | 0.0 | 1303 | 16 |
| 0.3 | 0.0 | 693 | 8 |
| 0.4 | 0.0 | 376 | 4 |
| 0.5 | 0.0 | 212 | 3 |
| 0.6 | 0.0 | 123 | 1.5 |
| 0.7 | 0.0 | 73 | 1 |
| 0.8 | 0.0 | 46 | 0.5 |
| 0.9 | 0.0 | 29 | 0.3 |
| 1.0 | 0.0 | 19 | 0.2 |
| 0.1 | 0.9 | 16465 | 163 |
| 0.2 | 0.8 | 6697 | 65 |
| 0.3 | 0.7 | 1581 | 16 |
| 0.4 | 0.6 | 624 | 66 |
| 0.5 | 0.5 | 326 | 36 |
| 0.6 | 0.4 | 178 | 18 |
| 0.7 | 0.3 | 103 | 11 |
| 0.8 | 0.2 | 63 | 6 |
| 0.9 | 0.1 | 40 | 3 |

3. Discussion

Using the redshift and flux distribution observed for HDF radio sources, we have calculated the expected number of lensed \( \mu \)Jy sources on the sky due to foreground clusters. By extrapolating the observed properties towards the HDF to the whole sky, we have assumed that the HDF is a fair sample of the distant universe. This assumption may be invalid given that the HDF was carefully selected to avoid bright galaxies and radio sources. However, we have selected to use the HDF data primarily because of the redshift information for all \( \mu \)Jy sources detected, which is currently not available for other radio surveys with flux limits down to few \( \mu \)Jys.

We have predicted \( \sim 1500 \) lensed \( \mu \)Jy sources on the sky towards clusters with X-ray luminosities greater than \( 8 \times 10^{44} \text{ergs s}^{-1} \), for a cosmology with \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \), consistent with recent results based on lensing (CQM; Kochanek 1996), type Ia supernovae (Riess et al. 1998), and galaxy cluster baryonic fraction (Evrard 1997). The X-ray flux limit for foreground clusters in our analysis is same as that of the clusters in the Le Fèvre et al. (1994) and Gioia & Luppino (1994) optical arc surveys, where 0.2 to 0.3 optical arc per cluster has been found down to a R band magnitude of \( \sim 21.5 \). There are \( \sim 7000 \) to 8000 such clusters on the whole sky (Bartelmann et al. 1997). We predict a similar, or slightly lower, rate for the \( \mu \)Jy sources, down to a flux density limit of 10 \( \mu \)Jy.

We briefly describe the possibility of detecting such lensed sources in deep radio surveys. Unlike optical sur-
surveys, radio surveys with interferometers such as VLA and MERLIN are subjected to effects arising from instrumental limitations, primarily effects associated with resolution. For example, there is a minimum and a maximum size for sources that can be detected and resolved with an interferometer. The largest angular scale to which the interferometer is sensitive restricts the detection of high amplification sources, which are expected to appear as arcs, with length to width ratios equal to amplification factors. For the VLA A-array at 1.4 GHz, sources larger than $\sim 15''$ may not likely to be detected. Thus, observations of radio arcs with length to width ratios greater than 10 may not easily be possible. In SIS model for gravitational lensing, most of the lensed sources appear with amplification factors of 2 to 10. However, due to the convolution with synthesized beam, ranging from $\sim 2$ to 10. The largest angular scale to which the interferometer is sensitive restricts the detection of high amplification sources, which are expected to appear as arcs, with length to width ratios equal to amplification factors. For the VLA A-array at 1.4 GHz, sources larger than $\sim 15''$ may not likely to be detected. Thus, observations of radio arcs with length to width ratios greater than 10 may not easily be possible. In SIS model for gravitational lensing, most of the lensed sources appear with amplification factors of 2 to 10. However, due to the convolution with synthesized beam, ranging from $\sim 2$ to 10.

4. Summary

Using the redshift and flux information for HDF radio sources and a Press-Schechter analysis for clusters of galaxies, we have calculated the expected number of lensed $\mu$Jy sources towards galaxy clusters. In a cosmology with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, we predict $\sim 1500$ lensed sources towards clusters. The radio emission associated with $\mu$Jy sources are expected to be associated with star forming galaxies and search for such lensed sources are likely to recover star forming galaxies at redshifts between 1 and 3. The possibility of detecting such lensed $\mu$Jy sources has already been demonstrated by the recovery of a sub-mm selected galaxy at 1.4 GHz. We suggest that similar deep VLA observations may already contain lensed $\mu$Jy sources and that a careful analysis may be required to establish the lensing nature of such sources.

Acknowledgements. I would like to acknowledge useful discussions and correspondences with Heinz Andernach, André Fletcher, Frazer Owen and Ian Smail on gravitational lensing of radio sources due to foreground clusters and the possibility of an observational search to find such sources.

References

Andernach, H., Gubanov, A. G., Slee, O. B. 1997, astro-ph/9704136.
Bartelmann, M., et al. 1998, A&A, 330, 1.
Becker, R. H., White, R. L., Helfand, D. J. 1995, ApJ, 450, 559.
Bézecourt, J. 1998 [astro-ph/9802107].
Cooray, A. R., Quashnock, J. M., Miller, M. C. 1998, submitted to ApJ [astro-ph/9806080], [CQM].
Cooray, A. R. 1998, submitted to A&A Letters.
Ebeling, H., et al. 1997, ApJL, 479, 101.
Evrard, A. E. 1997, MNRAS, 292, 289.
Fernández-Soto, A., Lanzetta, K. M., Yahil, A. 1998, ApJ submitted.
Fomalont, E. B., Windhorst, R. A., Kristian, J. A., Kellerman, K. I. 1991, AJ, 102, 1258.
Fukugita, M., Futamase, T., Kasai, M., Turner, E. L. 1992, ApJ, 393, 3.
Fioia, I. M., Luppino, G. A. 1994, ApJS, 94, 583.
Ivison, R. et al. 1997 [astro-ph/9712161].
Kochanek, C. S. 1991, ApJ, 379, 517.
Kochanek, C. S. 1996, ApJ, 466, 638.
Le Fèvre, O., et al. 1994, ApJL, 425, 5.
Richards, E. A., Kellerman, K. I., Fomalont, E. B., Windhorst, R. A., Partridge, R. B. 1988, submitted to AJ [astro-ph/9803343].
Riess, A. G. et al. 1998, AJ, in print [astro-ph/9805201].
Sawicki, M. J., Lin, H., Yee, H. K. C. 1997, AJ, 113, 1.
Smail, I., Ivison, R. J., Blain, A. W. 1997, ApJL, 490, 5.
White, D. A., Jones, C., Forman, W. 1997, MNRAS, 292, 419.
Williams, R. E. et al. 19996, AJ, 112, 1335.
Windhorst, R. A., Miley, G. K., Owen, F. N., Kron, R. G., Koo, D. C. 1985, ApJ, 289, 494.
Windhorst, R. A., Fomalont, E. B., Partridge, R. B., Lowenthal, J. D. 1993, ApJ, 405, 498.
Wu, X.-P., Hammer, F. 1993, MNRAS, 262, 187.
Wu, X.-P., Mao, S. 1996, ApJ, 463, 404.