Gravitationally Lensed Sub-mm Sources towards Galaxy Clusters

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Abstract. Recent observations of galaxy clusters with the SCUBA instrument on the James Clarke Maxwell Telescope have revealed a sample of gravitationally lensed sources at sub-mm wavelengths. We extend our previous calculation on the expected number of lensed optical arcs and radio sources to study the sub-mm lensed source statistics due to foreground massive clusters. For a flat cosmology with $\Omega_m = 0.4$ and $\Omega_\Lambda = 0.6$, we predict $\sim 1.5 \times 10^4$ lensed sub-mm sources with flux densities greater than $\sim 4$ mJy at 850 $\mu$m, and with amplifications due to lensing greater than 2, towards galaxy clusters with X-ray luminosities greater than $8 \times 10^{44} h^{-2}$ ergs s$^{-1}$ (0.3 to 3.5 keV band). We compare our predictions with the observations from the SCUBA instrument, and briefly consider the possibility of using the South Pole 10-m sub-mm telescope and the Planck surveyor to identify lensed sub-mm sources. A catalog of around 100 gravitationally lensed sources at 353 GHz may be a useful by-product of Planck.

Key words: cosmology: observations — gravitational lensing — galaxies: clusters — infrared: galaxies

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, we calculated the expected number of gravitationally lensed optical arcs and radio sources (Cooray 1998; hereafter C98) on the sky due to foreground galaxy clusters as a function of the cosmological parameters. The expected number of lensed sources was calculated based on the redshift distribution of the Hubble Deep Field (HDF; Williams et al. 1996) galaxies, with an extrapolation to the whole sky. Here, we extend our calculations to estimate the number of expected sub-mm sources on the whole sky due to foreground clusters. Our calculation is prompted by recent observational results from the new Sub-millimeter Common-User Bolometer Array (SCUBA; see, e.g., Cunningham et al. 1994) on the James Clerk Maxwell Telescope, where a sample of gravitationally lensed sub-mm sources has now been observed by Smail et al. (1997 & 1998).

The gravitational lensing of background sub-mm sources due to foreground galaxy clusters was first studied by Blain (1997), using a model of a lensing cluster with predicted source counts for background sources. Blain (1997) showed that the surface and flux densities of lensed sources exceed those of galaxies within the lensing cluster, and their values. This behavior, primarily due to the slope of the source counts and the fact that the distance sources are intrinsically brighter at sub-mm wavelengths, has now allowed the observation of moderate to high redshift dusty star forming galaxies, which are amplified through the cluster potentials (e.g., Ivison et al. 1998). Even though lensing of sub-mm sources have been studied in literature, no clear prediction has been made on the total number of sources lensed due to foreground clusters. Also, past calculations have relied mostly on models of background source counts, which were based on different evolutionary scenarios for star forming galaxies. Even though background source evolution has been considered in these calculations, no attempt has been made to consider the redshift evolution of foreground lensing clusters.

Thus, past calculations are limited if one were to consider the possibility of using lensed sub-mm source statistics towards clusters to constrain the cosmological parameters. We consider an alternative approach, primarily based on the observational data to study the number statistics of lensed sub-mm sources on the whole sky due to galaxy clusters. We calculate the foreground lensing galaxy cluster number density and redshift distribution using a Press-Schechter (PS; Press & Schechter 1974) analysis for different cosmological models and describe the background sub-mm sources using observational data towards the HDF at 850 $\mu$m (Hughes et al. 1998).
2. Expected Number of Lensed Sub-mm Sources

In order to calculate the lensing rate for background sub-mm sources, we use the redshift and number distribution observed towards the HDF sources by Hughes et al. (1998). The main advantage in using the HDF data is the availability of redshift information for sub-mm sources. Also, HDF is one of the few areas where a deep survey at 850 μm down to a flux limit of ~ 2 mJy has been carried out. The HDF contains 5 sources with flux densities of the order of ~ 2 to 7 mJy. Hughes et al. (1998) studied the probable redshifts of the detected sources by considering the optical counterparts and assigning probabilities for likely associations. We used the tabulated redshifts in table 2 of Hughes et al. (1998) to describe the background sources, and calculated the lensing probability using filled-beam formalism. Similar to C98, we calculated the < F(z) > parameter in lensing (see, C98) as a function of the cosmological parameters by describing the foreground lensing clusters with a lower limit on the X-ray luminosity of 8 × 10^{44} h^{-2} ergs s^{-1} in the EMSS bandpass of 0.3 to 3.5 keV. This lower limit on the foreground cluster X-ray luminosity allows a direct comparison between the number statistics of lensed sub-mm sources and that of the luminous optical arcs.

We calculated the expected number, \( \bar{N} \), of gravitationally lensed radio sources on the sky as a function of \( \Omega_m \) and \( \Omega_A \), and for a minimum amplification, \( A_{\text{min}} \), 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. In Table 1, we list the expected number of lensed sources on the sky for \( A_{\text{min}} = 2 \) and 10.

### Table 1. Predicted number of lensed sub-mm sources on the sky down to a flux density limit of 2 mJy at 850 μm. \( \bar{N}_{\text{Planck}} \) is the expected number of lensed sub-mm sources, with flux densities greater than 50 mJy at 850 μm, towards clusters that are expected to be detected with Planck Surveyor (see, Section 3).

| \( \Omega_m \) | \( \Omega_A \) | \( \bar{N}(A_{\text{min}} \geq 2) \) | \( \bar{N}(A_{\text{min}} \geq 10) \) | \( \bar{N}_{\text{Planck}}(A_{\text{min}} \geq 2) \) |
|---|---|---|---|---|
| 0.1 | 0.0 | 14815 | 183 | 115 |
| 0.2 | 0.0 | 9010 | 123 | 75 |
| 0.3 | 0.0 | 6010 | 75 | 55 |
| 0.4 | 0.0 | 3635 | 49 | 32 |
| 0.5 | 0.0 | 2270 | 28 | 21 |
| 0.6 | 0.0 | 1450 | 18 | 13 |
| 0.7 | 0.0 | 790 | 10 | 9 |
| 0.8 | 0.0 | 485 | 6 | 7 |
| 0.9 | 0.0 | 310 | 4 | 4 |
| 1.0 | 0.0 | 225 | 3 | 2 |
| 0.1 | 0.9 | 270350 | 3340 | 2150 |
| 0.2 | 0.8 | 101640 | 1255 | 785 |
| 0.3 | 0.7 | 37835 | 468 | 290 |
| 0.4 | 0.6 | 15050 | 186 | 105 |
| 0.5 | 0.5 | 6470 | 80 | 45 |
| 0.6 | 0.4 | 2975 | 37 | 25 |
| 0.7 | 0.3 | 1440 | 18 | 15 |
| 0.8 | 0.2 | 735 | 9 | 7 |
| 0.9 | 0.1 | 390 | 5 | 4 |

3. Discussion

Using the redshift and flux distribution observed for HDF sub-mm sources, we have calculated the expected number of gravitationally lensed sources on the sky due to foreground clusters at a wavelength of 850 μm. 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 detected sub-mm sources, which is currently not available for other fields with sub-mm source observations.

We have predicted \( \sim 1.5 \times 10^4 \) lensed sub-mm sources with flux densities greater than 2 mJy at 850 μm, and with amplifications greater than 2, on the sky towards clusters with X-ray luminosities greater than \( 8 \times 10^{44} h^{-2} \text{ ergs s}^{-1} \), in the 0.3 to 3.5 keV EMSS band, for a cosmology with \( \Omega_m = 0.4 \) and \( \Omega_A = 0.6 \). This cosmology is consistent with recent results based on lensing (CQG; Kochanek 1996), type Ia supernovae (Riess et al. 1998), and galaxy cluster baryonic fraction (Evrard 1997). The number with \( A_{\text{min}} > 4 \) for the same cosmology is \( \sim 1000 \), while the number with \( A_{\text{min}} > 10 \) is \( \sim 200 \). 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, with length-to-width ratios greater than 10, per cluster has been found down to a R band magnitude of $\sim 21.5$. There are $\sim 7000 \pm 1000$ such clusters on the whole sky. We predict a lensing rate of $\sim 2$ sources per cluster with amplifications greater than 2 down to a flux limit of 2 mJy.

We compare our predicted number of lensed sources to the observed number towards a sample of galaxy clusters imaged with the SCUBA by Smail et al. (1997 & 1998). This sample contains 7 clusters with redshifts in the range $\sim 0.2$ to 0.4. All of these clusters are well known lensing clusters in the optical wavelengths. Unfortunately, this sample is incomplete either in terms of X-ray luminosity or total mass. This incompleteness doesn’t allow us to perform a direct comparison between the predicted and observed numbers. Out of the 7 clusters, 3 clusters have X-ray luminosities greater than the lower limit imposed in our calculation. Towards these three clusters, A370, A2390 & A1835, there are 8 sub-mm sources, all of which may be gravitationally lensed. This implies a total of $\sim 2 \times 10^4$ lensed sub-mm sources on the whole sky. Based on our lensing rate, we expect $\sim 6$ lensed sources towards 3 clusters; this exact number is strongly sensitive to the cosmological parameters. Here, we have assumed a spatially-flat cosmological model with $\Omega_m = 0.4$ and $\Omega_\Lambda = 0.6$. The predicted and observed numbers seem to be in agreement with each other for low $\Omega_m$ values in a flat universe ($\Omega_m + \Omega_\Lambda = 1$).

However, we cannot use the present observational data to derive cosmological parameters for several reasons. These reasons include source contamination in the lensed source sample and systematic biases in the foreground cluster sample. For example, it is likely that the lensed source sample presented by Smail et al. (1998) contain foreground and cluster-member sources. Since the foreground or cluster-member sources are less bright than the background lensed sources, this contamination is likely to be small (see, Blain 1997). An additional systematic bias comes from the selection effects associated with the foreground cluster sample. Since the observed clusters are well known lensing clusters with high lensing rates at optical wavelengths, it is likely that there may be more lensed sub-mm sources towards these clusters than generally expected. This increase is due to the complex potentials, dominated by substructures, of these clusters. Even though spherical models, such as the SIS model, can produce the overall lensed source statistics accurately, such models cannot reproduce the observed arc statistics of clusters with bimodal and other complex potentials. Therefore, it is likely that the Smail et al. (1998) sample is biased towards a higher number of lensed sub-mm sources, and by a simple comparison based on observed and expected number of optical arcs for these clusters, we find that this overestimate can be as high as a factor of 2 to 3.

In order to constrain cosmological parameters based on statistics of lensed sub-mm sources, results from a complete sample of galaxy clusters, preferably from a large area survey, are needed. Further SCUBA observations of galaxy clusters, perhaps the same cluster sample as the Le Fèvre et al. (1994) sample, would be helpful in this regard. However, such a survey will require a considerable amount of observing time, suggesting that current instruments may not be able to obtain the necessary statistics. However, in the near future there will be two opportunities to perform a large area sub-mm survey of galaxy clusters: the Planck Surveyor and the South Pole 10-m sub-mm telescope.

**South Pole 10 m sub-mm telescope**—The planned South Pole (SP) 10-m sub-mm telescope\(^1\) is expected to begin observations around year 2003 (see, Stark et al. 1998). At 850 $\mu$m, it is expected that within $\sim 90$ hours a square degree area will be surveyed down to a flux limit of 1 mJy. Given the resolution and flux sensitivity, it is likely that the SP telescope would be an ideal instrument to survey either a sample of clusters or random areas to obtain lensed source statistics down to few mJy. To obtain reliable values of the cosmological parameters based on the sub-mm lensed source statistics, a survey of several hundred square degrees down to few $\times$ 1 mJy will be needed. A more direct approach within a reasonable amount of observing time would be to survey a carefully selected sample of galaxy clusters, either based on X-ray luminosity or total mass, from which lensed source statistics can easily be derived.

**Planck Surveyor**—Considering the amplification distribution for SIS lens model, and the number counts defined by Scott & White (1998), we find that roughly 100 lensed sub-mm sources may be detected with the Planck Surveyor towards galaxy clusters (e.g., Bersanelli et al. 1996\(^2\)). In Table 1, we list the number expected as a function of the cosmological parameters and assuming that the Planck data will allow detection of sources down to 50 mJy. However, given the limited observational data on source counts at 850 $\mu$m, we note that the predicted numbers may have large errors. We also note that the Planck data will be highly confused, as the beam size of Planck is $\sim$ few arcmins at 850 $\mu$m; even with $\sim 2$ arcmin physical pixels for high signal-to-noise data, most of the sources down to 50 mJy would be separated by only one or two pixels. Assuming pixel sizes of the order beam size, the probability of finding two sources with flux densities greater than 50 mJy in one Planck pixel would be $\sim 0.2$ to 0.3. Thus, it is more likely that the Planck data will allow clear detection of sources down to $\sim 100$ mJy, but with additional information, such as from other frequency channels and filtering techniques (see, e.g., Tegmark & de

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1. [http://cfa-www.harvard.edu/aas/tenmeter/tenmeter.html](http://cfa-www.harvard.edu/aas/tenmeter/tenmeter.html)
2. [http://astro.estec.esa.nl/Planck/](http://astro.estec.esa.nl/Planck/)
Oliviera-Costa 1998), it may be possible to lower this flux limit.

Also, it is likely that the lensed background sources will contaminate the detection of Sunyaev-Zel’dovich (SZ) effect in galaxy clusters (1998; see, Aghanim et al. 1997; Blain 1998). Since the SZ effect and sub-mm sources have different spectral distributions, it is possible that with extra information on flux at different frequencies, both the SZ effect and the source fluxes may be recovered. However, due to the uncertainties involved with such an analysis, as well as the effects due to source confusion, it is likely that Planck data would not readily allow an adequate determination of lensed sub-mm source statistics to constrain cosmological parameters. It is more likely that the lensed sub-mm source catalog from Planck would contain sub-mm sources fainter than the current limit predicted to be observable with Planck for unlensed sources.

4. Summary

Using the redshift and flux information for HDF sub-mm sources and a Press-Schechter analysis for foreground lenses, we have calculated the expected number of lensed sources at 850 \( \mu \)m towards galaxy clusters. In a cosmology with \( \Omega_m = 0.4 \) and \( \Omega_\Lambda = 0.6 \), we predict \( \sim 1.5 \times 10^4 \) lensed sources towards clusters with X-ray luminosities greater than \( 8 \times 10^{44} h^{-2} \text{ergs s}^{-1} \), and with amplifications due to lensing greater than 2. We have compared our predicted numbers to the observed number of lensed sub-mm sources towards a sample of galaxy clusters. However, various biases in this observed sample and possible source contamination, do not allow us to constrain cosmological parameters based on current statistics. We have briefly studied the possibility of using the Planck surveyor and the South Pole 10-m telescope data to perform this task. A catalog of \( \sim 100 \) lensed sources towards clusters is likely to be a useful by-product of Planck.

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