LENSED SUBMILLIMETRE-WAVE FOREGRONDS AND THE CMBR

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Samples of high-redshift galaxies are easy to select in the millimetre/submillimetre (mm/submm) waveband using sensitive telescopes, because their flux density–redshift relations are expected to be flat, and so the selection function is almost redshift-independent at redshifts greater than 0.5. Source counts are expected to be very steep in the mm/submm waveband, and so the magnification bias due to gravitational lensing is expected to be very large, both for lensing by field galaxies and for lensing by clusters. Recent submm-wave observations of lensed images in clusters have constrained the submm-wave counts directly for the first time. In the next ten years our knowledge of galaxy evolution in this waveband will be greatly enhanced by the commissioning of sensitive new instruments and telescopes, including the CMBR imaging space mission Planck Surveyor. This paper highlights the important features of gravitational lensing in the submm waveband and discusses the excellent prospects for lens searches using these forthcoming facilities.

1 Distant dusty galaxies

The flux density–redshift relation for distant dusty star-forming and active galaxies in the submm waveband is expected to be approximately flat at redshifts in the range 0.5 ≤ z ≤ 10, because of the large negative $K$-correction obtained when the steep modified thermal dust spectra of these galaxies, which peak in the rest-frame far-infrared waveband, are redshifted into the observed mm/submm waveband. Consequently, the faint submm-wave source counts are expected to be very steep as compared with the faint counts in other wavebands. The surface density of such galaxies at mJy flux densities was uncertain by up to three orders of magnitude until six sources were detected in the fields of two rich clusters of galaxies in 850-µm observations using the SCUBA bolometer array receiver at the James Clerk Maxwell Telescope (JCMT) last year. It is now known to within a factor of about two. The brightest of these sources has now been identified with an obscured AGN/starburst galaxy at $z = 2.803$. These observations allowed the source confusion noise that will affect mm/submm-wave CMBR observations, made by either balloon-borne experiments or the Planck Surveyor space mission, to be estimated directly for the first time. Lensing is not expected to modify the predicted source confusion noise significantly.

* This work has benefited greatly from the results of observations made using SCUBA at the JCMT in collaboration with Ian Smail, Rob Ivison and Jean-Paul Kneib.
2 Gravitational lensing

Because of the large negative $K$-correction for galaxies in the submm waveband, the redshift distribution of faint galaxies is expected to extend out to much larger redshifts as compared with other wavebands. Hence the gravitational lensing cross section for a typical source is also expected to be large as compared with that in other wavebands. In addition, the steep submm-wave counts are expected to be associated with a large positive magnification bias over a wide range of flux densities; that is, lensing is expected to produce a considerable increase in the surface density of detectable sources. The effects of lensing by both galaxies and clusters and the consequences of different world models for the predictions are described in detail elsewhere. In the light of the first observed 850-µm counts, realistic estimates of the observability of lensed galaxies using existing and future instruments can be made. The details of the observations and lensing calculations are not discussed in this short contribution.

The properties of galaxy–galaxy lenses in the field and images lensed by clusters are considered in Sections 3 and 4 respectively. The catalogues of point sources that will be detected in mm/submm-wave CMBR surveys, and especially in the all-sky Planck Surveyor survey, will allow large samples of galaxy–galaxy lenses to be compiled, as summarized in Section 5.

3 Galaxy–galaxy lensing

The submm-wave source counts are expected to be steep at observable flux densities, and so the corresponding magnification biases are predicted to be large. Predictions of the counts of both lensed and unlensed galaxies at wavelengths of 850 and 500 µm, based on direct submm-wave observations and existing models of both the lensing optical depth and the evolution of galaxies are shown in Fig. 1. The counts are compared with the 3σ sensitivities of long-term surveys made using a range of existing and future mm/submm-wave telescopes; SCUBA at the 15-m JCMT, a large ground-based interferometer array such as the MMA, the 3.5-m space-borne telescope FIRST and the space-borne all-sky CMBR imaging satellite Planck Surveyor. If the curves representing the predicted counts lie above the thin solid line labelled with the name of a particular telescope then that telescope is expected to detect at least one source in the survey. A more detailed description of these instruments and their likely levels of source confusion is given elsewhere.

The ratio of the numbers of lensed to unlensed galaxies with flux densities greater than about 50 mJy – the 3σ sensitivity of the Planck Surveyor – is predicted to be greater than 1%, which illustrates the very large magnification bias. The surface density of such lenses is expected to be between about $10^{-2}$ and 0.1 deg$^{-2}$. Hence, a large sample of lensed star-forming galaxies and quasars could be found in a practical survey using the next generation of submm-wave instruments. The 50-m single-antenna US/Mexican LMT/GTM telescope will also have a formidable performance in a lens search. In a practical Planck-Surveyor-based survey up to $10^3$ lensed sources could be detected. The inclusion of a population of galactic disks in the population of lensing galaxies can increase the optical depth to high-magnification lensing by a significant factor and so this remarkably large number of lens detections expected in the Planck Surveyor survey may actually be a conservative estimate of the true number.

4 Lensing by clusters

The counts on which the results in this paper are based were determined by submm-wave observations of two rich lensing clusters. The large $K$-corrections for background galaxies ensure that galaxies within the clusters at $z \ll 1$ are unlikely to contaminate the results and a sample of six clusters has now been observed. The magnification bias factor in the cores of
Figure 1: Predicted submm-wave source counts of both lensed (dashed lines) and unlensed (solid lines) galaxies at wavelengths of 850 $\mu$m (left) and 500 $\mu$m (right) in three different world models. The Einstein–de Sitter (EdS) model is represented by thick curves; the Flat-$\Lambda$ model, with $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$, is represented by curves of medium thickness, and the Open model, with $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0$, is represented by the thin curves. The counts of unlensed galaxies in the Open and Flat-$\Lambda$ models are almost indistinguishable; they lie below the counts in the EdS model. The predicted counts are consistent with counts and upper limits to counts derived from current observations made at wavelengths of 850 $\mu$m (SIB4), 2.8 mm$^{19}$ and 175 $\mu$m$^{20}$ and with the observed intensity of background radiation.$^{11}$

In the standard notation$^2 p = 3$, $z_0 = 7$; in the EdS, Flat-$\Lambda$ and Open models $z_{\text{max}}$ takes the values 2.6, 2.87 and 3.0 respectively. The sensitivities of existing and future instruments are included for comparison. If the counts lie above the lines representing instrumental sensitivities then $3\sigma$ detections are expected in a survey. An integration time of 200 h is assumed for a SCUBA survey; 1000 h is assumed for FIRST$^{15}$ and the MMA.$^{14}$ The nominal 14-month Planck Surveyor$^6$ mission is assumed. Hubble’s constant $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$.

rich clusters is predicted to be several hundred in the submm waveband, as compared with less than about ten in the optical waveband$^3$ and so these observations offer considerable promise both for investigating the history of star and galaxy formation$^4$ unbiased by the effects of dust extinction, and the values of cosmological parameters.$^4$ Lensing is expected to increase the mean flux density and angular separation of point sources in the fields of clusters, which is expected to increase the severity of source confusion noise in the fields of clusters as compared with the field when observed on arcminute scales in the mm/submm waveband$^3$. Hence, if a very accurate measurement of the Sunyaev–Zel’dovich effect in clusters$^2$ is required then the flux density due to confusing point sources may need to be subtracted from these observations, using arcsecond-resolution maps of the cluster obtained using either a large single-antenna telescope$^4$ or a large interferometer$^4$.

5 Lens surveys in the mm/submm waveband

Although the SCUBA camera at the 15-m JCMT is much more sensitive than previous submm-wave instruments, it is not expected to detect a large number of galaxy–galaxy lenses, as shown in the left-hand panel of Fig. 1 and discussed elsewhere.$^8$ The line represented the sensitivity limit of SCUBA clearly lies above the expected count of lensed sources.

However, the prospects for using future mm/submm-wave telescopes, FIRST, Planck Surveyor, the MMA and the LMT/GTM to detect and study lensed galaxies and quasars appear to be excellent. In Fig. 1 the lines representing the sensitivity limits of FIRST, Planck Surveyor and the MMA all lie significantly below the expected counts of lensed sources. The BOLOCAM receiver at the LMT/GTM will operate at wavelengths longer than 1.1 mm, and although not shown in Fig. 1, its performance is expected to be similar to that of the MMA. Mm/submm-wave surveys using these instruments will all produce a large catalogue of sources, with flux densities in the range 10–100 mJy for the space-borne surveys$^9$ in the range 1–10 mJy for the
LMT/GTM and potentially at 100-µJy flux densities for the MMA. However, only the MMA has the potential to resolve the multiple image components of a lensed system directly. The sample of sources detected using other telescopes will require high-resolution follow-up imaging using an interferometer array, and final spectroscopic confirmation using large near-infrared/optical telescopes in order to decide whether they are lensed or not. These follow-up observations would require a concerted campaign of observing lasting for several months; however, they are practical. A catalogue containing of order 1000 galaxy–galaxy lenses will be the final product of future mm/submm-wave lens surveys.

6 Conclusions

1. The surface density of distant galaxies in the submm waveband, and therefore the expected surface density of gravitational lenses and the effects of source confusion in future observations, is now known with reasonable accuracy.

2. The Planck Surveyor survey and surveys using other forthcoming mm/submm-wave telescopes will produce catalogues of distant sources that will be of great interest for studies of galaxy evolution. Lensed galaxies and quasars will be detected with an efficiency of up to 10% in these surveys, and a sample of order 1000 lenses could be compiled.

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