A GRAVITATIONAL LENS SURVEY WITH THE PLANCK SURVEYOR

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The Planck Surveyor cosmic microwave background (CMB) imaging mission will make very sensitive maps of the whole sky at microwave, millimetre (mm) and sub-mm wavelengths. The steep source counts expected in the highest frequency Planck bands are likely to be associated with a strong magnification bias, and so the fraction of galaxies magnified by a factor of two or more could be greater than 10%. In this paper, previous predictions of the significance of the Planck survey for studies of lensing statistics are updated, to reflect our expanded knowledge of the properties of high-redshift dusty galaxies, obtained from far-infrared and sub-mm surveys. A catalogue of probably about $10^4$ galaxies, but perhaps as many as $10^5$ or as few as $10^3$, is expected to be generated from the final Planck all-sky maps. Of order 1000 galaxies, a better determined number, might reasonably be expected to be strongly lensed. Coordinated sub-mm and far-infrared follow-up observations made using the SPIRE and PACS instruments aboard the ESA cornerstone mission FIRST – Planck’s travelling companion to its L2 orbit – and the ground-based ALMA interferometer array will provide accurate positions and very valuable information about the spectral energy distributions (SEDs), redshifts and astrophysical properties of the galaxies in the Planck catalogue. ALMA and radio images will also reveal their morphology, and the characteristic arc and multiple image structures produced by gravitational lensing. Studies of these bright sub-mm-selected galaxies will allow new insight into the process of galaxy formation and evolution.

1 Introduction

The Planck Surveyor CMB imaging satellite will provide a mm/sub-mm-wave map of the whole sky with a resolution of about 5 arcmin down to a detection limit of order 100 mJy at wavelengths of 350, 550 and 850 µm. These wavelengths are expected to be close to the peak of the redshifted thermal dust emission spectrum of distant galaxies. The effect of redshifting the dust spectrum peak into these observing bands is to provide access to the distant Universe, with little contamination from bright low-redshift galaxies. This remarkable, helpful K-correction is confirmed observationally to be effective in the sub-mm waveband, and is an almost unique feature of the waveband, although a similar effect may be at work in the hard X-ray surveys.
now being carried out. A priori, the counts of sub-mm galaxies at the faintest depths probed by *Planck* are expected to be very steep, an expectation which seems to be confirmed by the results of recent ground-based sub-mm-wave surveys.

Very steep sub-mm counts generate a strong positive magnification bias and thus boost the fraction of lensed galaxies in a flux-limited sample. This enhancement to the surface density of lensed galaxies will hopefully be exploited in the *Planck* survey to allow a very large catalogue of mainly unknown strongly lensed galaxies to be compiled.

## 2 Sensitivity and confusion noise in a *Planck* survey

The expected sensitivities of the *Planck*-HFI instrument in its three highest frequency channels, in which the largest number of distant dusty galaxies and lenses will be detected, are listed in Table 1, along with the predicted levels of source confusion noise.

It is important to understand the significance of source confusion noise introduced into the *Planck* images due to the varying number and flux densities of unresolved dusty galaxies in the observing beam. At 5 arcmin across, the *Planck* beam is very much larger than the mean separation of $L^*$ galaxies, and also about 4 times greater in area than the 5-arcmin$^2$ field of view of the SCUBA camera at the JCMT, from which most observational information about the sub-mm source population has thus far been derived.

In Fig. 1 the results of many independent simulations of sampling a random unclustered distribution of sources on the sky with the observing beam in the relevant *Planck*-HFI channels are compared with the estimates of instrumental noise. Confusion noise due to Galactic cirrus predicted by *IRAS*-based studies, and of simple estimates based on the surface density of galaxies, are compared in Table 1. All these calculations of the confusion signal due to extragalactic sources are made assuming a model for the underlying surface density of sources on the sky that is at the top end of the range of possible values, the predictions are therefore likely to be conservatively high, and thus pessimistic for making reliable detections. Extragalactic confusion noise is expected to dominate both the instrumental and Galactic noise in these bands.

In Fig. 1, the results of the simulations are enveloped by solid curves, which represent log-normal distributions providing good representations of the results. The value of $\sigma$ in the log-normal distribution ($\exp\left[-\left[\ln x - \bar{x}\right]^2/2\sigma^2\right]$) at all three frequencies is close to 0.2.

Unfortunately, the actual level of confusion noise that will be contributed to the *Planck* image depends on the uncertain surface density of galaxies that are brighter than those selected in existing sub-mm surveys (several tens of mJy at 850 $\mu$m/350 GHz). The results of future wide-field ground-based sub-mm surveys, and experience gained from the results of long-duration balloon-borne mm- and sub-mm-wave CMB experiments, including the existing BOOMERanG data and forthcoming data from TOPHAT will be useful in this respect. Recent simulations of extraction algorithms, in which the surface density of galaxies is assumed to be a factor of 2-3 times lower than that assumed here, suggest that 350-GHz point sources with flux densities greater than of order 75 mJy could be extracted from the *Planck* all-sky map.

## 3 Expected source density and numbers of detections

The two very different counts of unlensed galaxies shown in Fig. 2 should provide an envelope to the maximum range of possible values of the sub-mm counts at flux densities at which galaxies will be detected using *Planck*. The two underlying models predict very different bright sub-mm counts, but are both consistent with the observed far-infrared and sub-mm-wave counts and background radiation intensity, and with what little is currently known about the redshift distribution of sub-mm-selected galaxies. Our knowledge of the population will continue to
Table 1: Some approximate parameters describing the likely properties of a Planck all-sky survey that are relevant to the detection and study of dusty galaxies. The estimated final sensitivity of the Planck survey $\sigma_{\text{sens}}$, and three estimates of confusion values are listed: that expected from Galactic cirrus $\sigma_{\text{cirrus}}$, a simple estimate of the value expected due to external galaxies – the flux density at which the surface density of galaxies exceeds 1 beam$^{-1}$, $\sigma_{\text{beam}}$, and the width of the distributions shown in Fig. 1, between which 65% of the results of the simulations lie, $\sigma_{\text{sim}}$. Note that the confusion noise predicted by the simulations is log-normal and not Gaussian.

| $\nu$/GHz | $\sigma_{\text{sens}}$/mJy | $\sigma_{\text{beam}}$/mJy | $\sigma_{\text{cirrus}}$/mJy | $\sigma_{\text{sim}}$/mJy |
|-----------|----------------|-----------------|----------------|----------------|
| 353       | 16             | 10              | 1.3             | 40             |
| 545       | 19             | 30              | 9               | 60             |
| 857       | 26             | 63              | 55              | 170            |

Current observational limits to the population of sub-mm galaxies are reasonably well determined at flux densities less than about 10 mJy at 350 GHz from the results of several independent surveys: the surface density of galaxies brighter than 4 mJy at 850 $\mu$m/350 GHz is about 2000 deg$^{-2}$. These surveys have mainly been carried out using the SCUBA camera at the JCMT, but results are also now coming in from the MAMBO 1.25-mm bolometer array camera at the IRAM 30-m telescope. These are flux densities considerably fainter than Planck will probe, and so far, these instruments have mapped only very small regions of sky (several hundred square arcminutes). The counts of objects brighter than about 10 mJy has been only weakly constrained.

Information is also available about the counts at the very brightest flux densities, based on the results of a targeted SCUBA survey of low-redshift galaxies selected from the IRAS catalogue. This survey was used to define a luminosity function of local IRAS galaxies in the sub-mm, which can be used to impose a lower limit to the bright counts at flux densities brighter than the detection limit in the all-sky Planck survey: this lower limit is about 10 sources on the sky brighter than 1 Jy at 850 $\mu$m/350 GHz.

The probability of lensing by foreground galaxies out to the high redshifts, at which a significant fraction of the sources detected in the Planck survey are expected to lie, is reasonably well-known, certainly to within a factor of a few. Specific predictions of this probability, tailored to observations in the sub-mm waveband, are discussed elsewhere. The predicted density of lenses on the sky should also be quite well determined at the flux densities that will be probed by Planck. This is because the intrinsic flux densities of these objects, after correcting for the effect of lensing, are likely to be of order 10 mJy. At this flux density the surface density of galaxies is reasonably well constrained by SCUBA observations. Predicted numbers of lensed objects are shown by the dot-dashed lines in Fig. 2.

A significant potential uncertainty remains in these results, however, because the maximum magnification that can be produced by a lens is limited by the size of the source, being smaller for larger sources. In these calculations, we have assumed that background high-redshift sources are less than about 10 kpc in size, so that a maximum magnification of several tens can be produced. This assumption is supported by high-resolution interferometric observations of the size of the continuum emitting region in low-redshift ultraluminous galaxies, which is found to be much smaller – several 100 pc across. However, there are indications that at least some very luminous dusty high-redshift galaxies display CO and dust emission on scales greater than 10 kpc. Unfortunately, sub-arcsecond resolution images are required in order to measure the sizes of high-redshift dusty galaxies smaller than 10 kpc, and the necessary interferometric observations are difficult and time-consuming. Hence, as we do not yet know the size distribution
Figure 1: Results of simulations of confusion noise expected in the 5-arcmin beam of the Planck-HFI instrument at frequencies of 353 GHz (left), 545 GHz (middle) and 857 GHz (right). The histograms show the results of 3000 different simulation realisations of the predicted galaxy distribution sampled in the Planck beam, with Gaussian instrumental noise added. The solid curves show analytical log-normal distributions that adequately describe the envelopes of the simulation results. The dashed curves show the expected Gaussian instrumental noise in the Planck 14-month survey (16, 19 and 26 mJy beam$^{-1}$ respectively). At frequencies lower than 353 GHz instrumental noise is expected to dominate confusion noise, a trend which can be seen developing from frequency to frequency above. The flux scale has been shifted to give a zero net background. At 353 GHz Galactic foreground confusion noise is not included, as this source of noise is not expected to be more significant than the instrumental noise in regions of low Galactic emission.

of these distant ultraluminous galaxies, we cannot be certain that their sizes are typically small enough for large lensing magnifications to be possible. Despite this caveat, individual examples of high-redshift sub-mm objects lensed by foreground galaxies with magnifications of several tens are known, and so it is likely that Planck will be able to detect a significant number.

Based on an extrapolation of the log-normal distribution of pixel values predicted by the conservative simulations of confusion noise shown in Fig. 1, it is possible to predict the number of pixels that are likely to exceed a certain flux density due to the effects of confusion over the all-sky Planck survey. This expected count of spurious detections, which is shown by the dotted lines in Fig. 2, can then be compared with the expected count of lensed and unlensed galaxies. Reliable detections should be possible if these counts lie safely above the dotted lines at any flux density. Hence, it is likely that lensed galaxies brighter than about 250, 500 and 1500 mJy at 353, 545 and 857 GHz respectively could be detected using Planck, even in this pessimistic model of the confusion noise. At these limits, of order 100 lensed sources are expected over the whole sky. If the counts of bright unlensed sources are less than assumed here, then the confusion noise will be reduced, and a greater number will be detected. The counts shown in Fig. 2 allow these different scenarios to be investigated directly. It is important to note that much better estimates of confusion noise will be available well in advance of the launch of Planck.

The emission from both lensed and unlensed distant galaxies will pass unattenuated through the Galactic plane in the Planck bands; however, the ability to distinguish them against a bright and structured Galactic foreground is likely to be limited. The level of Galactic confusion (see Table 1) depends on the Galactic background intensity $B_0$ as $B_0^{0.5}$. The results suggest that the sensitivity of the Planck survey can only be exploited fully to find extragalactic sources in regions of the sky where the 100-µm surface brightness from the Milky Way is less than about 5 MJy sr$^{-1}$, a condition which is satisfied over most of the sky.

4 Follow-up observations

From the Planck all-sky images alone, point sources will be detectable, but no information will be available about their morphology, including whether or not they display arc and multiple image
Figure 2: Examples of counts of galaxies that will be probed in the Planck survey. The solid line shows the count of galaxies expected in a model of hierarchical merging galaxies. The dashed line shows the count of galaxies expected in a model of luminosity evolution based on the IRAS luminosity function. The dot-dashed line shows the expected count of lensed galaxies, derived in the second model. The dotted line shows the surface density of pixels expected to exceed each flux density due to the effects of source confusion, derived by extrapolating the confusion noise distributions shown by the solid curves in Fig. 1. These correspond to the second source population, and are thus likely to be a conservative, pessimistic estimate of the true confusion noise. To obtain reliable, unconfused detections, the counts of sources being sought must lie above the dotted curves in each figure.

geometries characteristic of lensing. For this diagnosis, sub-arcsecond mm/sub-mm images using the high-resolution extremely-sensitive interferometer array ALMA or very deep radio images using the VLA will be required. Accurate positions for Planck sources will first be required; these could be obtained using either ALMA or the 3.5-m ESA cornerstone FIRST telescope. Note that it is very unlikely for the foreground lens galaxy to be bright in the sub-mm waveband as this would require the foreground lens itself to be a very luminous infrared galaxy, and the space density of such sources is rather low. Hence, only the lensed images will be detected at bright flux levels in an ALMA continuum image, free from the blending and masking effects of emission from the foreground lens. Since the first discussion of a Planck lens survey, the specifications of ALMA have been significantly refined. At sub-mm flux densities of order 100 mJy, ALMA will be able to detect galaxies in integrations lasting much less than a second, and to make high-quality images in only several minutes. ALMA will make it easy to confirm lensing features and obtaining good quality images of the galaxies detected in a Planck survey.

The form of the mid-infrared SED of the galaxies detected using Planck can be determined using the SPIRE and PACS instruments aboard FIRST, allowing the redshift/dust temperature of the detected galaxies to be determined. Direct spectroscopic redshifts for the lensed galaxies should come quite easily from molecular emission line data taken using ALMA or from observations of features in the redshifted mid-infrared spectrum taken using FIRST-PACS. Redshifts for the lensing galaxies should be readily obtained from the frequencies of CO absorption lines imposed on the bright dust continuum emission of the magnified background galaxies due to the interstellar medium in the foreground lens, a technique which has already been developed and demonstrated using existing mm-wave interferometers.

Other relevant information can be provided by the FIRST radio survey at the VLA, which covers over 5000 deg^2 to a depth of about 1 mJy at 1.4 GHz. The high-resolution radio images from FIRST should detect a significant fraction of the Planck detected galaxies with sub-mm flux densities of several hundred mJy, based on our current knowledge of the SEDs of confirmed high-redshift SCUBA galaxies. For example, the 25-mJy 850-µm sub-mm source SMM J02399−0136 has a 1.4-GHz flux of 520 µJy. The brighter cousins of these objects in the Planck survey might typically appear at the faintest levels in the FIRST/VLA survey. The 25-mJy 60-µm all-sky image from the IRIS/ASTRO-F satellite will also be useful for detecting Planck sources.
5 Summary

The Planck Surveyor CMB imaging mission should detect many thousands of high redshift dusty galaxies, a significant fraction of which are expected to be gravitationally lensed. In order to make more detailed predictions it will be necessary to better quantify the abundance of sub-mm-selected galaxies with flux densities of order 100 mJy. By combining the Planck results with observations made using FIRST and ALMA a large catalogue of lenses should be identified, providing a unique sample of objects for further study. The properties of the individual galaxies in the catalogue will be useful for obtaining information about both the geometry of the Universe and the evolution of distant dusty galaxies.

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