The Planck Surveyor mission and gravitational lenses

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ABSTRACT
An extremely sensitive all-sky survey will be carried out in the millimetre/submillimetre waveband by the forthcoming ESA mission Planck Surveyor. The main scientific goal of the mission is to make very accurate measurements of the spatial power spectrum of primordial anisotropies in the cosmic microwave background radiation; however, hundreds of thousands of distant dusty galaxies and quasars will also be detected. These sources are much more likely to be gravitationally lensed by intervening galaxies compared with sources discovered in surveys in other wavebands. Here the number of lenses expected in the survey is estimated, and techniques for discriminating between lensed and unlensed sources are discussed. A practical strategy for this discrimination is presented, based on exploiting the remarkable sensitivity and resolving power of large ground-based millimetre/submillimetre-wave interferometer arrays. More than a thousand gravitational lenses could be detected: a sample that would be an extremely valuable resource in observational cosmology.

Key words: methods: observational – galaxies: evolution – cosmic microwave background – cosmology: observations – gravitational lensing – radio continuum: galaxies.

1 INTRODUCTION
Both the properties of the population and the individual appearance of distant galaxies can be modified significantly by the gravitational lensing effect of foreground masses. Gravitational lensing has been investigated in most detail in the near-infrared/optical and radio wavebands, in which faint distant galaxies can be observed with subarcsec resolution. However, there are excellent prospects for extending these studies into the submillimetre waveband (Blain 1996, 1997a,b, 1998). The fraction of gravitational lenses expected in a sample of galaxies selected in this waveband can be up to three orders of magnitude larger compared with a sample selected in other wavebands.

The concept of magnification bias provides a useful way of describing the effects of lensing on a population of distant galaxies (Borgeest, Linde & Refsdal 1991). If the surface density of galaxies with flux densities greater than $S_n$ per unit redshift is $n(S_n, z)$ at redshift $z$, then magnification by a factor $A$ due to gravitational lensing would predict a modified count, $n' (S_n, z) = A^{-1} n(S_n A^{-1}, z)$. If $n \propto S_n^\alpha$ locally, then the magnification bias $n'/n$ is given by $A^{-(1+\alpha)}$. Hence, if $\alpha < -1$ then the surface density of galaxies is increased and the magnification bias is positive; if $\alpha > -1$ then the surface density of galaxies is decreased and the magnification bias is negative. Magnification bias was first discussed in the context of samples of bright quasars; however, counts of galaxies at faint flux densities in the submillimetre waveband are expected to be uniquely steep, with $\alpha = -3$ or less (Blain & Longair 1993, 1996), and so the magnification bias for faint galaxies in this waveband is expected to be very significant (Blain 1996). At brighter flux densities the submillimetre-wave counts are expected to be less steep, and to follow the Euclidean slope, with $\alpha = -3/2$. The magnification bias is expected to be largest at flux densities at which the counts begin to rise above the Euclidean slope. If the population of dusty star-forming galaxies evolves strongly, as the first detections of previously unknown galaxies in the submillimetre waveband appear to demonstrate (Smail, Ivison & Blain 1997, hereafter SIB), then the largest magnification bias is predicted to occur at a flux density of 0.1 to 1 Jy, which is comparable with the sensitivity of Planck Surveyor (Bersanelli et al. 1996).

The submillimetre-wave counts of lensed galaxies are expected to be sensitive to changes in both world models (Blain 1998) and scenarios of galaxy formation and evolution. Hence, the properties of the lensed galaxies or quasars detected in the Planck Surveyor mission would allow the values of cosmological parameters to be investigated, even without detailed lens modelling. An Einstein–de Sitter world model and Hubble’s constant $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are assumed throughout.

2 THE PROPERTIES OF LENSES
The surface and flux densities of gravitational lenses in the millimetre/submillimetre wavebands can be predicted by combining models of the population of distant dusty star-forming galaxies (Blain & Longair 1996) with a model of the magnification distribution due to lensing as a function of redshift (Peacock 1982; Pei 1993). The magnification distribution can be derived from the mass distribution of galaxies, and takes the form $a(z)A^{-3}$ if $A$ is
large. Estimates of $a(z)$ are presented in Fig. 1 for both evolving and non-evolving models of the distribution of lensing masses. In the evolving model the mass distribution of the population of lensing galaxies is derived using the Press–Schechter formalism for structure formation by hierarchical clustering (Press & Schechter 1974), in which galaxies typically become smaller and more numerous at larger redshifts. The probability of lensing is predicted to be smaller in the evolving model compared with the non-evolving model. The form of $a(z)$ assumed in this letter is normalized to match the predictions of Pei (1993).

Investigations of the evolution of galaxies and active galactic nuclei (AGN) in many different wavebands (Hewett, Foltz & Chaffee 1993; Dunlop & Peacock 1990; Oliver, Rowan-Robinson & Saunders 1992; Lilly et al. 1996) indicate that the observed evolution of both the global star-formation rate and the luminosity density of AGN is consistent with pure-luminosity evolution (PLE) of the form $(1+z)^{3}$ out to $z = 2$. The observations of SIB can be fitted well by a model of PLE of the 60-$\mu$m luminosity function of IRAS galaxies (Saunders et al. 1990) with the form of $(1+z)^{3}$ out to $z = 2.6$, and a constant luminosity evolution factor of 46.7 in the interval $2.6 < z < 7$. The predictions of this model, which is consistent with other recent observations by Kawara et al. (1997) and Wilner & Wright (1997), are shown in Fig. 2, for both an evolving and a non-evolving distribution of lenses.

The effects of different world models are discussed by Blain (1997a, 1998); a non-zero cosmological constant increases the predicted surface density of lensed galaxies compared with the Einstein–de Sitter model, because both the probability of lensing at a particular redshift is increased and a stronger form of evolution is required in order to explain SIB’s observations, as the volume element is smaller at large redshifts.

The wavelength dependence of both the lensed and unlensed counts is presented in Fig. 3. The principal feature is the large increase in the ratio of the surface densities of lensed and unlensed galaxies at flux densities of between 0.1 and 1 Jy, which correspond to the onset of the steep rise in the unlensed counts above the Euclidean slope at these wavelengths. This increase is by almost two orders of magnitude compared with the 175-$\mu$m counts, which have a form similar to counts expected in the optical or radio wavebands. Another notable feature is the predicted increase in the surface density of unlensed 0.5-Jy galaxies as the observing wavelength decreases. This increase is predicted to be larger by a factor of about 15 between wavelengths of 850 and 350 $\mu$m. The counts of lensed 0.5-Jy galaxies also increase with decreasing wavelength, from 1 mm to about 200 $\mu$m; however, at wavelengths shorter than about 200 $\mu$m this effect is reversed, and the counts are predicted to decrease as the observing wavelength decreases.
3 A LENS SURVEY WITH PLANCK SURVEYOR

Estimates of the numbers of galaxies that could be detected in an all-sky survey are listed in Table 1, based on the sensitivities quoted by Bersanelli et al. (1996) and the counts discussed above. In order to produce conservative estimates, an evolving lens population is assumed. Note that the predicted number of lenses would be increased by a factor of about 5 if both a non-evolving lens model and a non-zero cosmological constant were assumed (Blain 1998).

Between about 0.6 and 5 per cent of the point sources detected by Planck Surveyor are expected to be lensed by a foreground galaxy. Despite a relatively large ratio of lensed to unlensed galaxies at wavelengths of 2000, 1380 and 850 µm, the surface density of detectable sources is expected to be relatively small at these wavelengths, compared with the shorter wavelength passbands at 350 and 550 µm. The most useful wavelengths for detecting a sample of lenses are hence 350 and 550 µm. More than a hundred lenses could be detected per unit solid angle in this systematic survey, and so even if about a third of these lenses are masked by Galactic emission at Galactic latitudes less than about 20°, many hundreds of lenses could still be detected in the survey. This would increase the number of known galaxy-galaxy lenses by an order of magnitude. The bright counts of unlensed galaxies in the submillimetre/far-infrared waveband would also be determined very accurately in such a survey, and so tight limits to the form of evolution of the global star-formation rate could be imposed at moderate redshifts.

4 THE DISCRIMINATION BETWEEN LENSED AND UNLENSED GALAXIES

How efficiently could a thousand lensed sources be separated from a hundred thousand unlensed galaxies detected at 5σ significance in the survey? Planck Surveyor will execute a multiband survey, and so the colours of the detected sources could probably be used to reduce the size of the sample by a small factor. However, none of the sources will be resolved, and their positions will only be known to an accuracy of about ±2 arcmin. Other planned facilities – ESA’s Far-Infrared and Submillimetre Space Telescope (FIRST) (Pilbratt 1997) and large ground-based millimetre/submillimetre-wave interferometer arrays (MIAs; Brown 1986; Downes 1996) – will allow this task to be completed in a practical amount of observing time. A strategy for following up the Planck Surveyor point source catalogue is outlined below.

4.1 Pre-selection using Planck Surveyor colours

Colour–colour and colour–magnitude diagrams for the sources detected in a simulated 100-deg² subfield of the survey are presented in Fig. 4. The distributions of lensed and unlensed galaxies are clearly different in each plot: lensed galaxies are found at large redshifts, and if the dust temperature in star-forming galaxies is correlated with their luminosity, then lenses would be expected to have redder colours compared with unlensed galaxies at the same flux densities. The field of points in the colour–colour plot (Fig. 4a) is bounded at small and large redshifts by lines with a gradient of about 0.6, which reflects the relative wavelengths of the three relevant observing bands. If the emissivity of dust grains was independent of wavelength, then both lensed and unlensed galaxies would lie on a single line with this slope, at positions determined by their redshift and dust temperature. The points in Fig. 4(a) are spread within a box-like region because a wavelength-dependent emissivity is assumed. These plots can be used to determine which sources are probably at low redshifts and to prioritize the sample to enhance the probability of detecting lensed sources earlier in the follow-up work; the subsequent follow-up stages should proceed through the sample working from the bright red sources to the faint blue ones.

4.2 Determining more accurate positions

FIRST will be equipped with a submillimetre-wave bolometer array receiver with a 6-arcmin field of view and a resolution of about 20 arcsec (Griffin 1997). This field of view is accurately matched to the resolution of the pixels in the Planck Surveyor map. The 350-µm flux density of candidate lenses is expected to exceed about 0.2 Jy, Fig. 4(b), and so each source could be detected at 5σ significance and located by FIRST in a 20-s integration. Assuming 200 per cent overheads, follow-up observations of 10² lens candidates would take about 70 days of integration, a period comparable with the time required for a shallow FIRST galaxy survey (Rowan-Robinson 1997). A ground-based instrument such as the Submillimetre Common-User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT) (Cunningham et al. 1994) would require four separate pointings and a total integration time of about 3 h at 850 µm in order to detect a candidate at 5σ significance. Hence existing ground-based facilities are not sufficiently sensitive to carry out this programme.

A large MIA is expected to detect a 50-mJy 850-µm source at 5σ significance in about 28 ms, but can only image about 0.08 arcmin² of sky per pointing. Hence about 250 separate pointings and a total

<table>
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<th>λ / µm</th>
<th>σallens / mJy</th>
<th>σlens / mJy</th>
<th>Sconf / mJy</th>
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<th>N(5σl) / (4π sr)⁻¹</th>
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Either a space-borne submillimetre-wave telescope or a ground-based submillimetre-wave interferometer could locate all the potential lensed sources in the Planck Surveyor catalogue to an accuracy better than about 20 arcsec in about 3 months of observing time. Observations with FIRST have the advantage of simultaneously determining the spectral energy distributions of the candidates at wavelengths shorter than 450 \mu m.

4.3 Diagnosis of lenses

Once reasonably accurate positions are known for the candidates, an MIA can be used to image them at a large signal-to-noise ratio and search for signs of lensed arcs, rings or multiple images. The relative number of 0.1-Jy lenses per unit magnification is expected to be flat out to magnifications of about 50 (Fig. 4 of Blain 1997a), and so most detected lenses should show these clear signatures of strong lensing. The flux densities and redshifts of the candidates are expected to be similar to that of the $z = 2.8$ starburst/AGN recently discovered by Ivison et al. (1998). Several hours of integration were required to image and take the spectrum of this source using 4-m class optical telescopes, and so even with 8-m telescopes available it will be quite impossible to follow up the Planck Surveyor catalogue in the optical/near-infrared waveband in a reasonable time.

In a 1-min 850-\mu m integration on a 2-km baseline, an MIA could reach a 5\sigma flux density limit of about 1 mJy at sub-0.1-arcsec angular resolution. This corresponds to the detection of a lens candidate in the Planck Surveyor catalogue at a significance of about 250\sigma. Any multiple images, arcs or rings in the source will be clearly resolved using such an instrument. Imaging $10^3$ sources in this manner would take about 70 days of dedicated observations. Of course many of the candidates will show no signs of multiple structure, and so could be excluded from the list of candidates in a shorter integration. Note that the lensing galaxy is expected to be optically thin to submillimetre-wave radiation and so differential extinction of multiple images, which affects lens surveys in the optical waveband, will not complicate the selection effects in a Planck Surveyor survey. Possible other selection effects are considered in the following section.

Ultimately the catalogue of good candidates derived from the high-resolution MIA images will require spectroscopic confirmation in the optical/near-infrared in order to diagnose them as lenses unequivocally. The results of the large-area Sloan Digital Sky Survey (Kent 1994) will probably be of great assistance in identifying potential lensing galaxies.

4.4 Potential problems and selection effects

Chance superpositions of sources, multiple components of an unlensed source and emission from the lensing galaxy could bias the selection of candidates in the Planck Surveyor survey and confuse the diagnosis of lenses.

First, the counts at flux densities comparable to the 0.1-Jy selection limit are expected to be about 3 deg$^{-2}$, see Fig. 2, and so the chance alignment of two sources of comparable brightness within about 5 arcsec of each other, which could be mistaken for different components of a multiple image, is expected to be of the order of 0.001 per cent, equivalent to less than one source in the whole catalogue. About 1.5 per cent of the pixels in the Planck Surveyor catalogue at a significance of a few times $10^{-2}$ arcsec, a point source for the purposes of this investigation. Hence, because Planck Surveyor will detect only the most luminous distant galaxies, it is unlikely that intrinsic multiple structure in distant galaxies will lead to the false diagnosis of a large number of lenses.

Thirdly, the emission from a lensing galaxy would make the detection of a lens candidate more likely in the Planck Surveyor survey, and complicate its diagnosis. However, although in the optical waveband lensed images are typically fainter than the lensing galaxy, the situation in the submillimetre waveband is much more similar to that in the radio waveband, in which the lensed images are much brighter than the lensing galaxy. This effect


Figure 4. Colour–colour and colour–magnitude diagrams for both lensed and unlensed galaxies in a simulated 100-deg$^2$ subfield of the Planck Surveyor survey. The flux densities of the plotted galaxies exceed the 5\sigma 550-\mu m sensitivity of the survey; in (b) they also exceed the 5\sigma sensitivity at 350\mu m. Lensed galaxies are always found at redshifts greater than unity, and are typically redder compared with unlensed galaxies.

Integration time of about 7 s would be required to image the field of each Planck Surveyor pixel that contains a candidate lens with such an instrument.

Secondly, although interacting galaxies show clearly separate components in the optical waveband, high-resolution millimetre-wave observations show that dust radiation typically originates from a single core of the order of several hundred parsecs in size (Solomon et al. 1997). At $z = 2$ this corresponds to an angular scale of a few times $10^{-2}$ arcsec, a point source for the purposes of this investigation. Hence, because Planck Surveyor will detect only the most luminous distant galaxies, it is unlikely that intrinsic multiple structure in distant galaxies will lead to the false diagnosis of a large number of lenses.
sample of gravitationally lensed galaxies and quasars. The exact size of the sample will depend on the properties of distant dusty galaxies and quasars, the cosmological parameters, the observing wavelength and the sensitivity of the survey, but about a thousand lenses and about a hundred thousand unlensed galaxies are expected to be detected at a $5\sigma$ significance at wavelengths of 350 and 550 $\mu$m. A practical strategy for submillimetre-based follow-up observations has been outlined using FIRST and a large ground-based millimetre/submillimetre-wave interferometer array. The scientific rewards from the compilation of such a large unbiased sample of lenses would be very considerable, and it is difficult to see how such a sample could be compiled in any other waveband.

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Planck Surveyor and gravitational lenses

5 THE OPTIMAL STRATEGY

It will be practical to compile a sample of about a thousand lenses, starting from the $10^5 \ 5\sigma$ detections expected in the Planck Surveyor point source catalogue, by conducting a concerted programme of observations, using FIRST, large MIAs and conventional optical telescopes, lasting several months. The most promising candidates can be pre-selected for follow-up observations based on their submillimetre-wave colours in the catalogue. FIRST or an MIA can then be used to determine the positions of the candidates with sufficient accuracy to permit a programme of high-resolution follow-up imaging observations using an MIA. Any lensed arcs, rings and multiple images in the candidate sources will be identified at this stage. Finally, the remaining sample of about a thousand excellent candidates would be subjected to spectroscopic confirmation or refutation as lenses using 8-m class telescopes in the optical/near-infrared wavebands.

6 CONCLUSIONS

The Planck Surveyor mission has the potential to detect a very large

Figure 5. The flux density–redshift relations expected for an $L^*$ IRAS galaxy and a lensed object detected at $5\sigma$ at 550 $\mu$m in a Planck Surveyor survey. A low dust temperature of 30 K is assumed to boost the low-redshift flux densities. The upper and lower dotted lines correspond to the approximate $1\sigma$ sensitivities of the Planck Surveyor survey, Table 1, and a 1-min integration with a large MIA respectively.

...was discussed by Blain (1997b) in the context of confusion between distant lensed submillimetre-wave galaxies in the field of a cluster and the cluster galaxies themselves. In Fig. 5 the flux density–redshift relations expected for an $L^*$ IRAS galaxy, with a luminosity of about $6 \times 10^{10} L_\odot$ at the present epoch, and a detectable lens candidate assumed to be at $z > 0.5$, are compared. Unless the lensing galaxy is at $z < 0.1$, which seems rather unlikely for the typical lens candidate at $z > 1$, the flux density from the lensed images is expected to dominate that of the lens, even if the lensing galaxy is a luminous IRAS galaxy. Most lenses would be expected to be quiescent elliptical galaxies with much smaller far-infrared luminosities. If a severe colour-based pre-selection was imposed, then perhaps contamination by the lensing galaxy could introduce a small bias into the sample; however, we have shown that the follow-up of the Planck Surveyor survey is still practical even without any pre-selection.
Submillimetre Universe, ESA SP-401. ESA publications, Noordwijk, p. 139
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