Infrared Galaxies

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Abstract. To study large-scale structure in the Universe a full census of the contents are required. This is even more important when the processes of galaxy formation are being investigated. In the last year the population of distant galaxies that emit most of their energy in the infrared waveband have been studied in unprecedented detail. The intensity of background radiation at wavelengths between 3 mm and 10 µm has been determined to within a factor of about 2, and much of this background radiation has been resolved into individual galaxies. These galaxies are largely hidden from view in the optical waveband by absorption due to interstellar dust. By combining this new knowledge with the ever growing body of information gathered using optical telescopes, the process of galaxy formation is slowly being revealed. Great opportunities for studying the distant Universe are promised by advances in instrumentation in the millimeter (mm), submm and far-infrared wavebands over the next decade.

INTRODUCTION

Progress in observational cosmology has been unprecedentedly rapid over the last five years, with the advent of the Hubble Deep Fields, Lyman-break galaxies and the Keck telescopes. However, there is still no detailed understanding of how and when galaxies formed. In the optical waveband progress should continue, due to the large number of 8-m-class telescopes being commissioned, the increasing sophistication of multi-object spectrographs and new wide-field digital surveys.

A large amount of the energy output of galaxies is emitted in the far-infrared waveband, as revealed by the IRAS satellite [1]. This is thermal emission from interstellar dust grains, which efficiently absorb blue and ultraviolet photons, whether from young high-mass stars or active galactic nuclei (AGN). Heated to temperatures of a few tens of Kelvin, the rest-frame emission spectrum of the dust peaks at wavelengths close to 100 µm. In the local Universe, a comparable amount of energy is emitted in the optical and far-infrared wavebands. However, because the IRAS survey extended only to redshifts $z \simeq 0.2$, until recently it was impossible to investigate the reprocessed dust radiation from distant galaxies directly, either individually or as an integrated background [2].
FIGURE 1. The background radiation intensity from the mm to optical waveband. References are numbered. Only [2] was obtained before 1998. Note that at wavelengths of 15 and 850 µm [11,15] most of the background has probably been resolved into its constituent galaxies.

BACKGROUNDs AND DISCRETE SOURCES

Within the last year our knowledge of the quantity of energy re-radiated by dust in distant galaxies has increased dramatically (see Figure 2). Using the FIRAS and DIRBE instruments on the COBE satellite, and the HST (Hubble Space Telescope), the intensity of extragalactic background radiation has been determined to within a factor $\sim 2$ between wavelengths of 1 µm and 2 mm [3–8]. Upper limits to the background intensity from $\gamma-\gamma/e^+e^−$ pair production along the line of sight to nearby AGN have also been tightened [9]. Two years ago, there was only a single background estimate [2]. The new observations represent a tremendous advance.

The first results of direct surveys to detect the faint galaxies that contribute to the infrared background radiation intensity have also been published this year. Varying fractions of the background have been resolved into individual galaxies using three sets of instruments. At long wavelengths of 850 and 450 µm, the SCUBA bolometer array camera [10] at the JCMT (James Clerk Maxwell Telescope) has been used to image the sky behind distant clusters of galaxies. By exploiting their gravitational lensing effect, most of the 850-µm background has been resolved into individual galaxies [11,12]. At shorter wavelengths of 175 and 95 µm, that
are inaccessible from the ground, the ISO satellite has resolved about 10% of the background [13,14]. Extremely faint galaxies at mid-infrared wavelengths of 15 and 7 $\mu$m have also been determined using ISO by exploiting gravitational lensing [15]. The lower limit to the background derived from the 15-$\mu$m observations is close to the $\gamma-\gamma$ upper limit [9], suggesting that a large fraction of the 15-$\mu$m background has been resolved. Several other submm-wave SCUBA surveys have been carried out [16–18], and an interesting upper limit to the surface density of galaxies has been imposed at a wavelength of 2.8 mm [19].

The prime motivation for submm-wave galaxy surveys is their ability to select high-redshift galaxies preferentially. The form of the dust emission spectrum of galaxies is broadly similar to the envelope of the background limits shown in Figure 1. If a high-redshift galaxy is observed at a wavelength of several hundred microns, then its rest-frame spectrum is sampled at a wavelength considerably closer to the peak of the emission spectrum. As a result, the detected flux density is increased; this effect is described as a negative $k$-correction. In some cases this $k$-correction is sufficiently large to overcome the inverse square law dimming of the galaxy with increasing redshift, and so the flux density is almost constant over reasonable redshifts $0.5 \lesssim z \lesssim 10$. This effect is illustrated in Figure 2, for a galaxy with an intrinsic luminosity of $5 \times 10^{12} L_\odot$ and a dust spectrum that provides a good fit to the properties of the background and surface density of dusty galaxies [20]. Note that the $k$-correction is important only at observing wavelengths longer than about 200 $\mu$m.

The spectrum of a dusty galaxy is a power-law at wavelengths longer than a few hundred microns with a temperature dependent turn-over at shorter wavelengths. Measurements of flux density both above and below the wavelength of the turn-over are thus required to determine the dust temperature, which in turn fixes the total luminosity. Hence, there is a very strong case for carrying out galaxy surveys at long submm wavelengths, to exploit the $k$-correction effect, and then conducting follow-up observations of the detected galaxies at shorter wavelengths. For a galaxy discovered in a survey at a wavelength of 500 $\mu$m, a sensitive follow-up observation at 100 $\mu$m is much more useful than one at 1000 $\mu$m.

The recent detection of well defined populations of distant dusty galaxies, especially at wavelengths of 850 and 15 $\mu$m [11,15], confirms that a population of dusty galaxies exists at large redshifts. The background radiation intensity is dominated by galaxies with redshifts $z \simeq 1$, and so the measured background spectrum is not very useful for probing the detailed properties of more distant galaxies. In contrast, the properties of the galaxies detected by SCUBA, especially their redshift distribution [20], will be extremely helpful in this respect.

The best studied galaxy discovered by SCUBA, SMM J02399−0136, is at $z = 2.8$ [21,22]. Most of the other galaxies detected by SCUBA have plausible identifications on deep HST images [23], and so are likely to lie at $z \lesssim 5$. Thanks to the power of the 10-m Keck telescopes, attempts to determine redshifts for 16 SCUBA-selected galaxies [23] are making considerable progress [24], despite the uncertain fraction of their luminosity that is absorbed by interstellar dust.
FIGURE 2. The flux density expected from a galaxy with a fixed rest-frame spectrum as a function of redshift. In the optical (or radio) and mid-infrared wavebands, the received energy falls steadily with redshift. However, at wavelengths longer than 200 $\mu$m, the effect of redshifting the steep far-infrared dust spectrum counteracts the dimming effect of the inverse square law, and can lead to a brightening of the template galaxy as the redshift increases. This effect is responsible for the unique sensitivity of mm/submm-wave surveys to high-redshift galaxies/AGN.

FUTURE INSTRUMENTATION

COBE has done an excellent job of mapping the extragalactic infrared background. However, there is still a great deal of progress to be made in the detection and study of a large sample of galaxies at wavelengths between several mm and 5 $\mu$m. The value of the recent contribution of SCUBA [10] cannot be overstated; however, SCUBA is just the first submm-wave instrument with the sensitivity required to map the distant Universe. SCUBA currently detects a galaxy every few hours, and at 850 $\mu$m is limited by source confusion at its 14-arcsec resolution in a few tens of hours of integration in a single field [25]. Great progress is being made in mm/submm-wave instrumentation, improving both mapping speed and angular resolution. For example, the BOLOCAM instrument [26], destined for the 10-m Caltech Submillimeter Observatory (CSO) and the 50-m Large Millimeter Telescope (LMT), should increase the detection rate by a factor of 100–1000 (see Figure 3). Large ground-based interferometer arrays, such as the MMA, will obtain sub-0.1-arcsec resolution submm-wave images of galaxies, and will be able to detect unknown galaxies at a rate similar to that of the LMT. This resolution will be cru-
The detection rate expected in surveys using future mm/submm/far-infrared instruments. The lines are labeled with the instrument name and the survey wavelength in microns. The left and right end of the lines correspond to the flux density of the confusion limit [25] and the brightest source expected over the whole sky respectively. Note that different points on the same line correspond to independent surveys with different flux density limits and scanning rates. The detection rate expected for SIRTF at a wavelength of 70 µm is even greater than that at 160 µm, although the typical redshift of the detected galaxies will be less. A $5 \times 10^{12}$-$L_\odot$ galaxy at $z = 3$ is expected to produce flux densities of 0.7, 1.5, 6.2, 8.9 and 6.1 mJy at wavelengths of 1100, 850, 450, 200 and 160 µm respectively.

The best strategy for exploiting the great improvements in survey speed and angular resolution of the full range of future mm/submm/far-infrared instruments cannot yet be finalized, and will remain subject to modification until they all are in service with verified sensitivities. Several points about the future of submm-wave galaxy surveys are clear, however:

1. The space-borne 0.3-m WIRE and 0.85-m SIRTF will provide extremely large samples of galaxies/AGN at far-/mid-infrared wavelengths. The areas of their surveys would be ideal targets for future surveys at longer wavelengths.
2. The 2.5-m SOFIA airborne observatory will be very timely, and sufficiently flexible and adaptable in operation, to provide the initial far-/mid-infrared follow-up observations of galaxies detected in the mm/submm waveband using SCUBA and BOLOCAM.

3. Within 10 years, submm-wave surveys using the LMT, MMA, \textit{Planck Surveyor} and 3.5-m \textit{FIRST} will provide huge samples of submm selected high-redshift galaxies/AGN. The \textit{Planck} all-sky map will contain at least as rich a variety of new objects as that obtained by \textit{IRAS} 15 years ago.

4. All detailed follow-up observations, and any morphological studies, will require the sub-arcsecond angular resolution of a large interferometer array.

Once a large sample of $10^5$ or more galaxies/AGN are obtained using these instruments, the well developed techniques of optical observational cosmology, such as the analysis of distribution functions, can be applied to investigate the evolution of galaxies and large-scale structure, independent of the effects of dust obscuration.

**GRAVITATIONAL LENSES**

There is another positive feature of galaxy surveys in the mm/submm waveband. Because the chance of a foreground galaxy being directly aligned on the line of sight to a galaxy – and thus a strong magnification being produced – increases with redshift, and there is a unique high-redshift selection bias in submm-wave surveys, the probability of submm detected galaxies being gravitationally lensed is greater as compared with other wavebands [27]. The most relevant instrument for a lens survey is \textit{Planck Surveyor}, which will detect the brightest lenses over the whole sky [28]. A large sample of gravitational lenses offers the opportunity both to study galaxies that would otherwise be too faint to detect, and to investigate the geometry of the Universe. In order to select the subsample of the detected galaxies that display the distorted and multiply imaged structures typical of a lensed galaxy on arcsecond angular scales, MMA imaging will again be essential.

**CONCLUSIONS**

Within the last year, the intensity of extragalactic background radiation from the mm to the near-infrared waveband has been determined for the first time. This energy was released at shorter wavelengths by star-forming galaxies and AGN during the process of galaxy formation, and has been reprocessed by interstellar dust. The coincident detection of populations of distant dusty galaxies/AGN at six wavelengths from 850 to 7 $\mu$m has provided much more information about the properties of distant infrared galaxies. The population of galaxies discovered using SCUBA at 850 $\mu$m is particularly interesting. Most of the 850-$\mu$m background radiation intensity detected by \textit{COBE} can be accounted for by the existing SCUBA
galaxies, indicating that dust-enshrouded high-redshift galaxies/AGN were rare, but very luminous. The next generation of mm/submm-wave instruments – ground-based, air- and space-borne – will provide much larger samples of distant infrared galaxies. The array of data they provide will be comparable in both volume and quality with that obtained in the optical/near-infrared waveband.

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