Far-Infrared and Submillimeter Observations of High Redshift Galaxies

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Abstract.

Observations at far-infrared and submillimeter wavelengths promise to revolutionize the study of high redshift galaxies and AGN by providing a unique probe of the conditions within heavily extinguished regions of star formation and nuclear activity. Observational capabilities in this spectral region will expand greatly in the next decade as new observatories are developed both in space and on the ground. These facilities include the Space Infrared Telescope Facility (SIRTF), the far-infrared and submillimeter telescope (FIRST) and the millimeter array (MMA). In the longer term, the requirements of high angular resolution (comparable to that of HST), full wavelength coverage, and high sensitivity (approaching the fundamental limit imposed by photon counting statistics) will motivate the development of far-IR and submillimeter space interferometry using cold telescopes and incoherent detector arrays.

INTRODUCTION

Key scientific questions about the Universe that have been raised at this meeting and elsewhere include

• What is the history of star formation in the Universe?
• What is the history of metallicity and dust content in the Universe?
• What is the origin of the extragalactic background observed by the DIRBE experiment on COBE?
• What are the relative contributions of stars and of active galactic nuclei to the luminosity of the Universe, and how do they vary with redshift?

In this paper, I will argue that observations in the far-infrared and submillimeter wavelength region (40 – 1000 µm, corresponding to rest wavelengths in the range 5 – 300 µm for galaxies at z = 2 – 5) offer a unique probe of the high redshift Universe that will address these questions. The happy coincidence of several astronomical facts make far-infrared and submillimeter observations particularly powerful.
First, galaxies are extremely luminous at far-infrared rest wavelengths. The spectrum of our own Milky Way galaxy, for example, shown in Figure 1, exhibits two distinct peaks, the first at around 1 μm resulting from the integrated emission from stars, and the second at around 100 μm resulting from interstellar dust emission. The representation given here (in which equal areas correspond to equal rates of photon emission) shows that most of the Galaxy’s photons emerge in the far-infrared region. The Milky Way is entirely unremarkable in this regard: indeed, in many starburst galaxies even the energy output is dominated by far-infrared radiation. The strength of the far-infrared emission from galaxies simply reflects that fact that the average visual extinction is sufficient to allow a significant fraction of the starlight to be reprocessed by interstellar dust.

Second, the opacity of interstellar dust is a strongly decreasing function of wavelength, allowing embedded regions of star formation and nuclear activity that are invisible at optical and even near-infrared wavelengths to be detected in the far-infrared and submillimeter spectral regions. A second implication of the strong wavelength-dependence of the dust opacity is that the submillimeter region provides a unique cosmological window to the high redshift Universe, the background caused by dust emission from $z \sim 0$ (local galaxies) dropping rapidly with increasing wavelength longward of $\sim 200 \mu$m and the background from $z = 1500$ (the CMB) dropping rapidly with decreasing wavelength shortward of $\sim 800 \mu$m.
Third, the $5 - 300 \, \mu m$ (rest) wavelength range is extremely rich in atomic and molecular diagnostics that can serve as powerful probes of the physics and chemistry of interstellar gas and dust. The remarkable richness of the mid- and far-infrared spectral region is demonstrated by the Infrared Space Observatory (ISO) spectrum of the Orion region (van Dishoeck et al. 1998) in Figure 2, which shows numerous rotational lines of $H_2$ and $H_2O$, fine structure emissions from a wide variety of atomic ions, as well as several broader features associated with interstellar dust. In the next section, I will discuss the potential importance of such spectral features in constraining the properties of high-redshift galaxies.
EMISSION MECHANISMS AT FAR-INFRARED AND SUBMILLIMETER WAVELENGTHS

**Interstellar dust** is the dominant source of far-infrared and submillimeter radiation in galaxies. Recent SCUBA observations of dust continuum radiation – reported, for example, at this meeting by Ian Smail – have already demonstrated the power of submillimeter observations to probe the Universe at high redshift. Some – although by no means all – of the identified SCUBA sources are galaxies at redshifts $z > 2$ (e.g. Ivison et al. 1998), and the $\sim 25\%$ of SCUBA sources for which no optical counterpart can be found may well be sources at very high redshift (or alternatively low-redshift galaxies or AGN that are very heavily extinguished). Although the field is currently in its infancy, observations of dust continuum radiation will ultimately allow the the effects of dust absorption to be corrected for quantitatively in models for the luminosity history of the Universe, and will elucidate the relative contribution of sources at different redshifts to the extragalactic background detected by the DIRBE experiment on COBE (Hauser et al. 1998).

Although it shows a continuum spectrum, emission from dust is not featureless. It exhibits several broad features of large equivalent width, most notably the silicate feature at 9.7 $\mu$m and several bands in the 3.3 – 11.3 $\mu$m range that have been attributed to polycyclic aromatic hydrocarbons (Allamandola, Tielens & Barker 1985), and these features may allow redshifts to be estimated from far-infrared observations of very modest spectral resolving power.

**Interstellar gas** emits a rich spectrum of atomic and molecular line radiation in the 5 – 300 $\mu$m range, which – although a negligible contribution to the overall far-infrared and submillimeter emission – dominates the cooling of the interstellar gas and provides valuable diagnostics of the physical and chemical conditions.

Fine-structure emissions from the low-ionization species C$^+$ and O dominate the cooling of neutral atomic gas clouds. The C$^+$ $^2P_{3/2} - ^2P_{1/2}$ line at 158 $\mu$m has an upper state energy ($E_u/k$) corresponding to only 92 K and is therefore readily excited in cold atomic clouds. In most galaxies, the C$^+$ 158 $\mu$m line is the strongest source of line emission and accounts for 0.2 – 1 % of the total far-infrared luminosity (Malhotra et al. 1997), this percentage representing the fraction of the absorbed radiant energy from stars that is deposited in the interstellar gas rather than the dust.$^1$ Spectroscopic observations of the C$^+$ 158 $\mu$m line along with the O 63$\mu$m and 145$\mu$m lines ($^3P_1 - ^3P_2$ and $^3P_0 - ^3P_1$ with $E_u/k = 227$ and 326 K respectively) from high-redshift galaxies will yield reliable redshifts and will allow the heating rate for the interstellar gas to be determined.

$^1$ Note, however, that the relative strength of the C$^+$ 158 $\mu$m line is considerably smaller in those galaxies that show the strongest far-infrared continuum emission. Malhotra et al. (1997) have argued that this effect likely arises because the larger ultraviolet fluxes incident upon cold clouds within such galaxies lead to larger positive charges on the interstellar dust grains and a resultant decrease in the efficiency of grain photoelectric emission that is the primary mechanism for heating the gas.
In dense regions of the interstellar medium that are well shielded from starlight, the gas is primarily molecular and its emission is dominated by rotational emissions from molecules. Gas temperatures in molecular regions range from $\sim 10$ K in quiescent clouds to several hundred Kelvin in gas that has been heated by a nearby star or protostar, or even several thousand Kelvin in shocked regions. The radiative cooling of molecular clouds is an essential feature of the star formation process, because cloud collapse involves the conversion of gravitational potential energy to thermal energy and can proceed only if the latter is efficiently removed. Theoretical calculations (e.g. Neufeld, Lepp & Melnick 1995) predict that over a wide range of physical conditions the radiative cooling of molecular gas is dominated by rotational transitions of the molecules H$_2$, CO and H$_2$O in the 7 – 600 $\mu$m region. At low temperatures, submillimeter transitions of CO are the primary coolant, while at higher temperatures pure rotational lines of H$_2$ (e.g. the S(0), S(1), S(2), S(3), S(4) and S(5) lines at 28.3, 17.0, 12.3, 9.66, 8.03, 6.91 $\mu$m) and of H$_2$O (many lines in the 40 - 600 $\mu$m region) are expected to dominate the cooling. This prediction is corroborated by recent ISO observations of H$_2$ and H$_2$O emissions from nearby regions of star formation (e.g. van Dishoeck et al. 1998, see Figure 2; Harwit et al. 1998) and by extensive ground-based observations of CO carried out previously toward both nearby and high-redshift galaxies (e.g. Omont et al. 1996). Measurements of line ratios permit the density, temperature, and molecular abundances within the molecular gas to be constrained.

In addition to probing cold atomic and molecular gas, far-infrared and submillimeter observations of high redshift galaxies also promise to yield invaluable information about photoionized regions. Many galaxies are luminous sources of mid IR fine structure emissions from NeII (12.8 $\mu$m), OIII (52, 88 $\mu$m), NeIII (15.6, 36.0 $\mu$m), NeV (14.3, 24.2 $\mu$m) and several other ions that result from photoionization by radiation shortward of the Lyman limit. Such mid-IR lines provide unique information about the metallicity and gas density in ionized regions, as well the spectral shape of the ionizing radiation field (e.g. Voit 1992). These transitions show several important advantages over the optical wavelength lines traditionally used to study HII regions: they are not heavily extinguished by interstellar dust; their luminosities are only weakly dependent on temperature and therefore provide model-independent estimates of metallicity; and they provide line ratios that are useful diagnostics of density over a wide dynamic range (e.g. Spinoglio & Malkan 1992). The availability of rare gas elements (e.g. Ne, Ar) allows the metallicity to be determined without the complicating effects of interstellar depletion, and the availability of a wide range of ionization states (e.g. NeII and NeV) provides an excellent discriminant between regions that are ionized by hot stars and those that are ionized by a harder source of radiation such as an AGN. The power of that discriminant has been demonstrated by the recent ISO observations shown in Figure 3 (Moorwood et al. 1996). Here the otherwise similar spectra of the starburst galaxy M82 and the Circinus galaxy (which contains an active nucleus) are distinguished by the presence in Circinus of a variety of highly ionized species such as NeV and Ne VI that can only result from a very hard source of ionizing radiation.
FIGURE 3. Comparison of ISO Short Wavelength Spectrometer spectra of M82 and Circinus, demonstrating the power of mid-IR fine structure lines as discriminants of the ionizing spectrum (from the ISO science gallery, credit: ESA/ISO, SWS, Moorwood; see also Moorwood et al. 1996)
Figure 4, from the review paper of Hollenbach & Tielens (1997), is a schematic representation of the interaction between starlight and the interstellar medium that summarizes the various far-infrared and submillimeter emission mechanisms described above. Most of the radiant energy from starlight is deposited at moderate visual extinctions, $A_V \sim 1$. Roughly 99% of the starlight heats the interstellar dust and is reprocessed as far-infrared continuum radiation, while very roughly 1% heats the gas and is reprocessed as line radiation (primarily the $C^+$ 158 $\mu$m line). At visual extinctions $A_V > 3$ (rightmost region), the gas is primarily molecular, and the gas cooling is dominated by infrared and submillimeter rotational lines of molecules, particularly $H_2$, CO, and $H_2O$. In unshielded regions of high ultraviolet flux (leftmost region), the gas is highly ionized, and the cooling is dominated by optical and ultraviolet line emission. In this zone, mid-infrared fine structure lines, although not the major coolant, are powerful diagnostic probes.
OBSERVATIONAL CAPABILITIES IN THE NEXT DECADE

The next decade (2001 – 2010) promises substantial improvements in observational capabilities in the far-infrared and submillimeter spectral regions, thanks to several new observatories that are expected to begin operations. My goal in this article is not to give a comprehensive review of all these new facilities but rather to discuss briefly selected observatories that will offer capabilities most directly relevant to the study of galaxies at high redshift.

The **Space Infrared Telescope Facility** (SIRTF)\(^2\), scheduled for launch at the end of 2001, will deploy a liquid helium cooled 85 cm telescope capable of carrying out observations of extremely high sensitivity. The Multiband Imaging Photometer (MIPS) instrument on board SIRTF will offer diffraction-limited imaging using sensitive detector arrays at wavelengths of 24, 70 and 160 $\mu$m, as well as very low resolution ($\lambda/\Delta\lambda \sim 10$) spectroscopy in the 50 – 100 $\mu$m region. The principal limitation of SIRTF for the detection of galaxies at far-infrared wavelengths is the large size of the diffraction-limited beam: particularly at 160 $\mu$m, MIPS will be source confusion limited for observations of relatively short duration. The Infrared Spectrograph (IRS) instrument will be capable of moderate resolution spectroscopy ($\lambda/\Delta\lambda \sim 600$) over the 10 – 37 $\mu$m range, with a large spectral multiplex advantage that will allow full, high-quality spectra to be obtained very much more quickly than was possible with ISO. While the wavelength coverage of IRS does not quite reach the 40 – 1000 $\mu$m range that is the subject of this article, IRS deserves mention here because of its capability for detecting mid-infrared line emission from ions in HII regions.

The **Far Infrared and Submillimeter Telescope** (FIRST)\(^3\) will be a space observatory with a much larger (∼ 350 cm) primary mirror, but one that is not actively cooled. Current plans call for the launch of FIRST in 2007, with instrumentation capable of carrying out broad band photometry, imaging spectroscopy, and high-resolution heterodyne spectroscopy. The wavelength coverage will extend to much longer wavelengths than SIRTF, allowing a far wider range of atomic and molecular line emissions to be studied spectroscopically. Again, the relatively large diffraction limit at these wavelengths for any single dish instrument of reasonable size means that source confusion will be significant except for observations of short duration (e.g. Blain, Ivison & Smail 1998). Thus interferometers will be critical for the study of all but the most luminous galaxies at high redshift, and the most important impact of SIRTF and FIRST on studies of high redshift galaxies is likely to be in measuring spectra of low redshift galaxies that can be used as templates for understanding future interferometric observations.

The **Millimeter Array** (MMA)\(^4\) will have an extremely powerful interferomet-

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\(^2\) The SIRTF home page is at http://sirtf.jpl.nasa.gov

\(^3\) The FIRST home page is at http://astro.estec.esa.nl/SA-general/Projects/First/first.html

\(^4\) The MMA home page is at http://www.mma.nrao.edu
ric capability, providing spatial resolution as good as $\sim 0.01''$, wavelength coverage down to $350 \, \mu m$, and high spectral resolution. MMA promises to allow large numbers of high redshift sources to be detected routinely and associated unambiguously with optical counterparts. It will make use of $\sim 36$ antennae of diameter $\sim 10 \, m$ that can be deployed over baselines of several kilometers on a high plateau site in Chile. An observatory of more modest collecting area – the Smithsonian Astrophysical Observatory’s Submillimeter Array (SMA) – will operate in a Northern Hemisphere site (Mauna Kea). The primary limitations of these ground-based facilities are those imposed by Earth’s atmosphere, which only permits observations in a series of submillimeter windows all longward of $300 \, \mu m$, and by the fundamental sensitivity limits set by heterodyne receivers and warm telescopes.

THE LONGER TERM: FAR-INFRARED AND SUBMILLIMETER INTERFEROMETRY FROM SPACE

The ideal instrument for the study of far-infrared and submillimeter emissions from high redshift galaxies would combine (1) full wavelength coverage; (2) HST-like spatial resolution; (3) sensitivity approaching the fundamental limit imposed by photon-counting statistics; (4) high spectral resolution ($\lambda/\Delta\lambda$ of at least $10^4$). The first and third of these capabilities require a space observatory; the second requires interferometry; and the third requires a cooled telescope (barely warmer than the CMB) equipped with a new (not presently existing) generation of incoherent detectors rather than heterodyne receivers; and the fourth can be accomplished by means of a Fabry-Perot or Michelson interferometer.

In a recent white paper (Mather et al. 1998), we have presented a preliminary study of such an instrument – dubbed the Submillimeter Probe of the Evolution of Cosmic Structure, SPECS$^5$ – in which we envisaged a Michelson interferometer providing spatial and spectral interferometry with three, cold, free-flying elements of diameter $\sim 3 \, m$ deployable over baselines $\sim 1 \, km$. Although such a facility may lie significantly beyond what could be built today, Mather et al. 1998 have emphasized the importance of developing key technologies over the next decade to make such an instrument feasible in the decade 2011 – 2020; those technologies include formation flying, active cooling of large mirrors, and the development of sensitive incoherent detector arrays. In particular, photon-counting incoherent detectors – which do not yet exist at these wavelengths but would likely be some type of superconductive device – would offer enormous sensitivity advantages for faint sources both over current bolometers and relative to the fundamental limit of a heterodyne receiver.$^6$

$^5$ The SPECS home page is at http://www.gsfc.nasa.gov/astro/specs

$^6$ A perfect photon-counting detector is more sensitive than a perfect heterodyne receiver by a factor $\sim (\Delta \nu / R)^{1/2}$, where $\Delta \nu$ is the bandwidth and $R$ is the photon arrival rate, a factor much larger than unity for faint extragalactic sources.
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