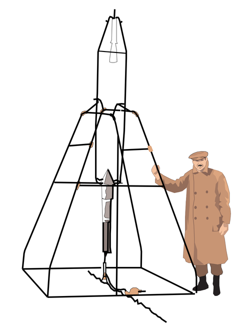
On the Detection of Dust at High Redshifts with SIRCE and SAFIR



Dominic J. Benford, S. Harvey Moseley, David T. Leisawitz, Eli Dwek, Michael J. Amato, Johannes G. Staguhn†, John C. Mather

NASA / Goddard Space Flight Center † SSAI/GSFC

With the recent detection by the WMAP mission of the epoch of reionization at $11 \leq z \leq 30$, we know when the first stars formed. Shortly thereafter, the dust enrichment of the Universe began, when the relic radiation field was at a temperature of 35-85K. Present submillimeter observations have succeeded in detecting the dust in galaxies out to redshifts of $z \approx 5$, covering the majority of the star formation history of the Universe. Future space-based missions can probe this time with great sensitivity. A far-infrared survey mission, SIRCE, is being studied with the goal of characterizing the evolution of dust emission out to $z \approx 7$. Pushing the boundary to $z=10$ or even $z=20$ to trace the origin of dust enrichment is a challenging prospect, but may be possible with the future Single Aperture Far-InfraRed (SAFIR) Observatory. Finding these rare dust-enriched galaxies at high redshifts will require a sky coverage and sensitivity unavailable from ground-based observatories. The missions we describe here use the advantage of the very dark natural sky background accessible from space in the 100µm-500µm wavelength region. Extrapolating from expected results from SIRTF, these missions will open up the high-redshift universe in the far-IR.

Dust and Galaxy Evolution

The Cosmic Infrared Background (CIRB) is the integral of the light from all sources at all distances (Figure 1). Much of this light comes from ultraluminous infrared galaxies (ULIRGs), but some fraction arises in AGN and from normal galaxies. The energy released by the formation of stars and in regions around AGNs is absorbed and reemitted by dust. Half the total luminosity in the Universe is emitted at infrared wavelengths, much of it at ~100µm. The fraction of dust emission was higher in the past than it is today, implying that dusty galaxies produce a greater portion of the luminosity at high redshifts. A complete picture of star formation and AGN activity in the Universe can be obtained only when far-infrared observations reach the ability to probe to high redshifts comparable to that at shorter wavelengths. Finally, the dust emission from the earliest objects – those present at or just after the epoch of reionization at $z \approx 20$ – will appear at wavelengths of ~1mm.

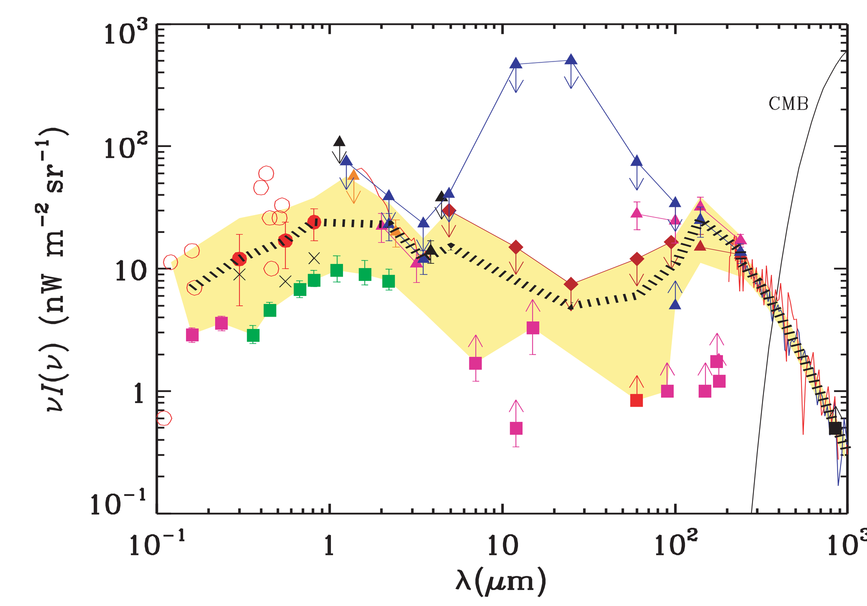


Figure 1. Extragalactic background light (Hauser & Dwek 2001). DIRBE & FIRAS measured the λ>1µm CIRB; two peaks are known, at ~1µm and ~100µm.

Determination of the cosmic star formation rate history, the growth of cosmic structure, and the accompanying energy release requires direct observations of the sources that dominate the luminosity of the early Universe, which were previously seen only as a component of the CIRB.

In order to image to a given sensitivity limit, telescopes need both angular resolution and collecting area. At radio wavelengths, widely separated, small telescopes are needed to achieve both; in the optical, a single mirror suffices. The dividing line is near 100µm, as shown at right.

This confusion limit is the key limitation preventing the detection of dust at high redshifts.

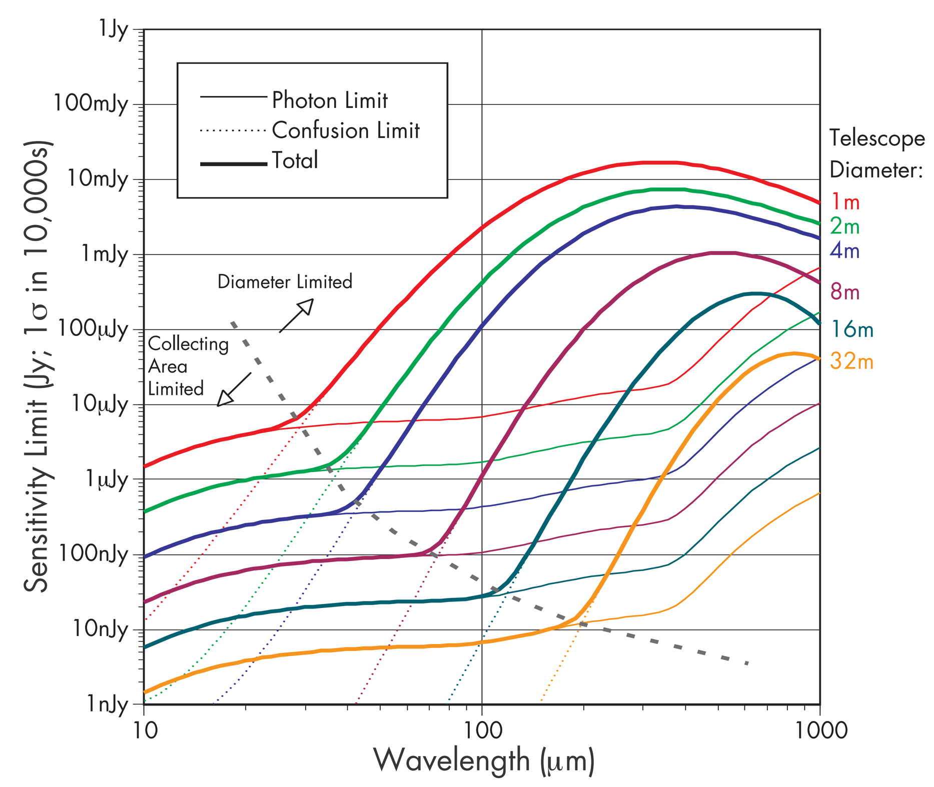


Figure 2. Sensitivity of telescopes as a function of diameter; longer wavelengths need angular resolution whereas shorter wavelengths require collecting area.

Detectability of Redshifted Dust

Shown at right is the flux density of thermal dust emission from a typical ultraluminous infrared galaxy as a function of its redshift. The spectral model of Dwek et al. has been used. At achievable flux density limits (1mJy at 100µm, roughly 1000 times more sensitive than IRAS), thousands of dusty sources at $z>7$ can be discovered – if they exist.

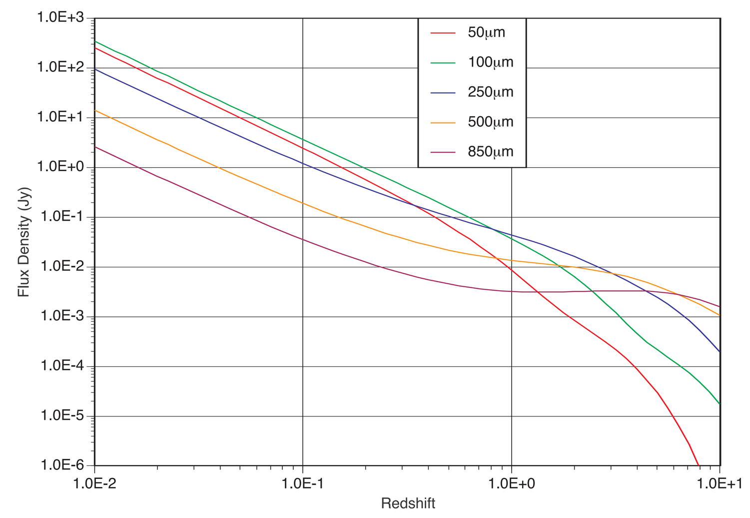


Figure 3. Flux density of a ULIRG as a function of redshift illustrates the sensitivity of submillimeter wavelengths to high redshift galaxies

If we calculate the highest redshift detected galaxy, by comparing the confusion limit to the expected flux, as a function of the wavelength and telescope diameter, we find that detecting ULIRGs at $z \sim 5$ requires a ~2m diameter mirror (Figure 4).

Shown in Figure 5 are the fluxes of a set of template galaxies redshifted until they become too faint to resolve. The paths are generally well separated, enabling reliable photometric estimates of redshift and hence luminosity.

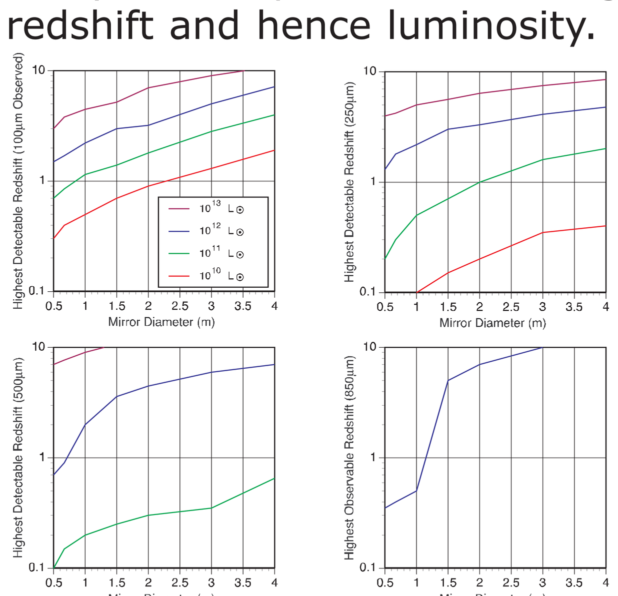


Figure 4. Maximum detectable redshift of galaxies, given the confusion limit, as a function of luminosity, observed wavelength and mirror diameter.

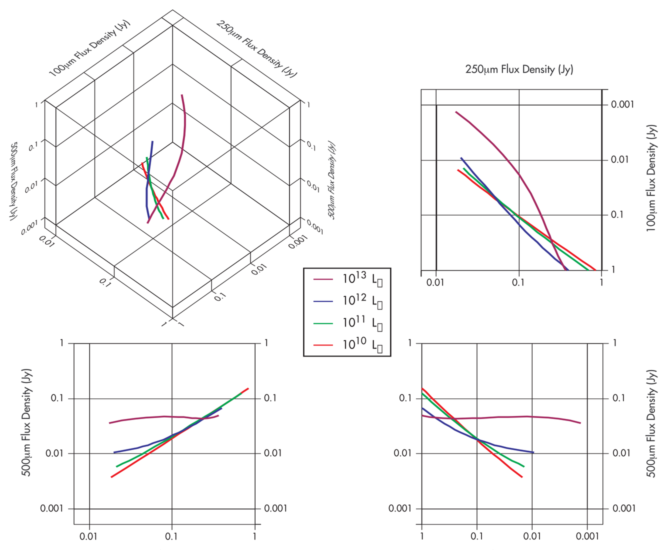


Figure 5. Paths of template galaxies observed in three far-IR bands as they redshift until becoming fainter than the confusion limit.

In order to detect galaxies at redshifts approaching the epoch of reionization – $z>10$ – the flux sensitivity must be better, of order 100µJy at the longest submillimeter wavelengths. It can be shown (Figure 6) that this requires a 10m-class far-IR telescope, and that it will require high sensitivity (and hence cooled optics and large format detector arrays) to permit blind searches for these unknown galaxies. If these galaxies are detectable primarily through their far-infrared emission, it is unlikely that their positions will be known prior to such a telescope.

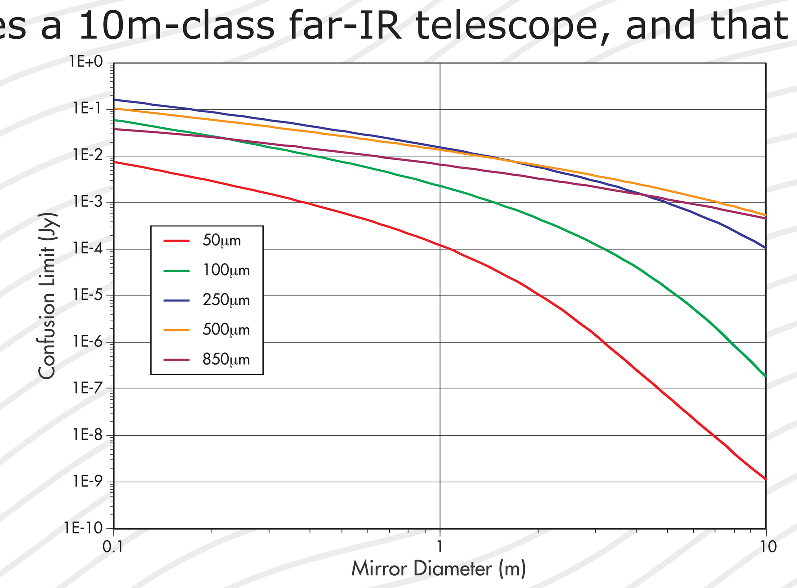


Figure 6. Confusion-limited flux of galaxies as a function of wavelength and telescope diameter.

Future Mission Concepts

SIRCE: Survey of InfraRed Cosmic Evolution

SIRCE is a mission concept developed at NASA/GSFC for a spaceborne observatory that can:

- Map the sky at high spatial resolution (~10′′) at far-infrared wavelengths (~100-500µm)
- Achieve sensitivity high enough to detect very distant objects
- Cover enough sky to enable statistically significant discoveries
- Integrate until images are limited by the confusion of the source distribution.

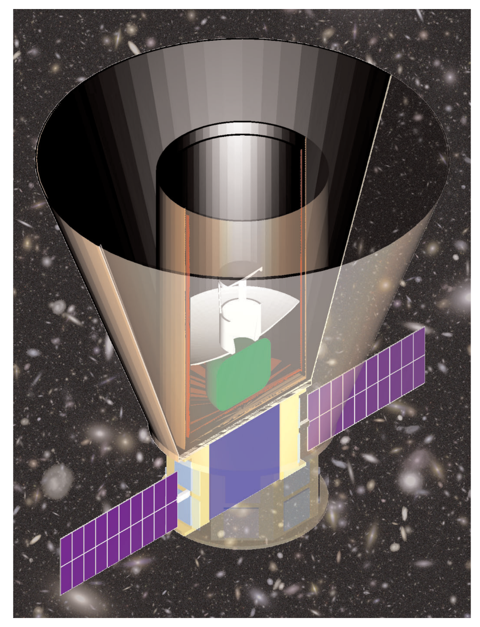


Figure 7. Cutaway view of SIRCE's cryogenically cooled telescope.

The SIRCE mission can be built with existing technologies as a MIDEX-scale mission. SIRCE is envisioned as a 2m-class cryogenically-cooled telescope with high sensitivity imaging arrays. Such a telescope can find tens of thousands of $z>7$ galaxies, directly measuring star formation activity back to an era unreachable by existing telescopes. The core wavelengths of $100µm \leq \lambda \leq 500µm$ are chosen to enable the measurement of photometric redshifts and hence the characterization and classification of the galaxies.

SAFIR: Single Aperture Far-Infrared Observatory

The SAFIR Observatory is a mission in NASA's plan, recommended by the NAS as a follow-on to JWST (previously NGST). At NASA/GSFC, we have developed a conceptual design for the SAFIR observatory based on JWST's current design (Figure 8).

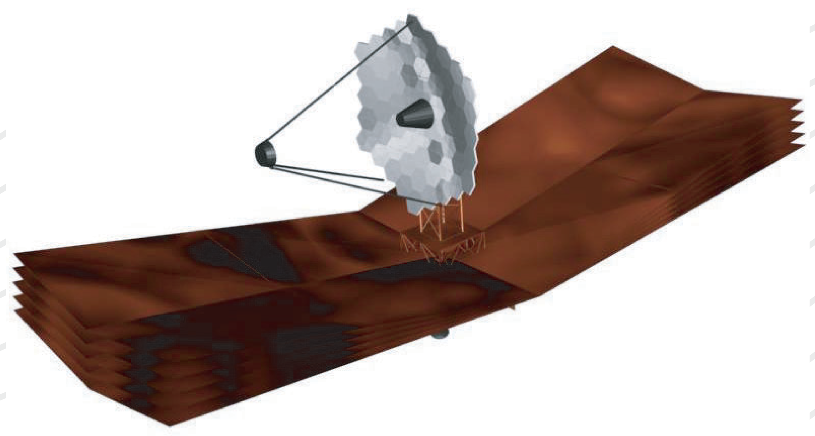


Figure 8. Concept for a SAFIR, a 10m-class,4K-cooled, far-IR (20µm–800µm) observatory.

A detailed analysis has been made of the changes and technologies necessary to produce SAFIR. Crucial technologies requiring innovation include lightweight deployable optics, cryogen-free cooling of optical elements and instruments to <4K (Figure 9), and large arrays of sensitive detectors for wavelengths of $20µm<\lambda<800µm$. As an example of the sensitivity of SAFIR (Figure 10), it will be able to detect the rest frame 10µm+ thermal emission from dust in ultraluminous galaxies at $z=10$ and beyond.

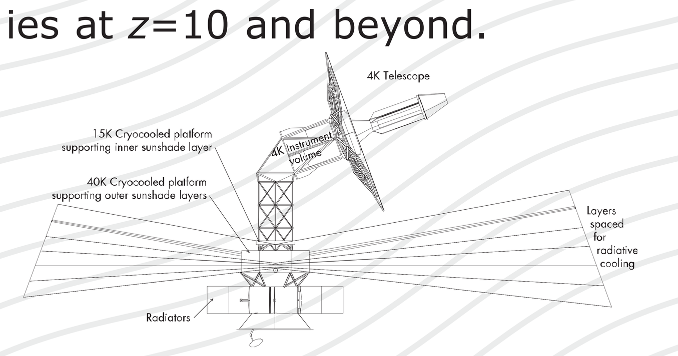


Figure 9. Thermal control for SAFIR concept, providing for a 4K telescope.

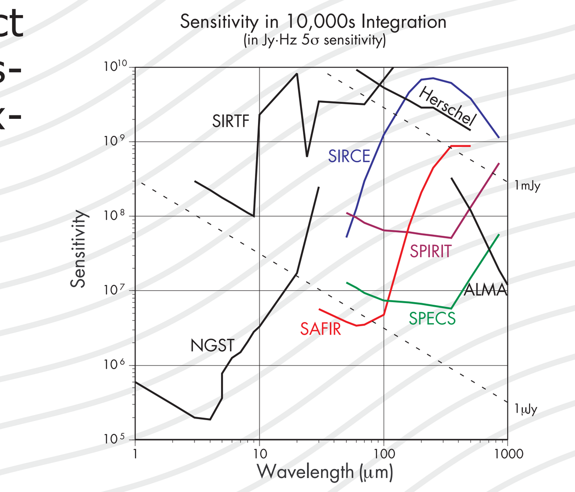


Figure 10. SAFIR and SIRCE sensitivity compared to other missions.