

Infrared Science Revolutionary Opportunities

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Abstract

The foundation for many of the missions recommended by the decadal survey is advances in infrared and submm detectors and receivers. We illustrate how NGST, SAFIR, and far infrared interferometry can use such devices to address fundamental questions in cosmology and star and planet formation, and furthermore how they enable a large discovery space.

1. Introduction

The power of many envisioned major new NASA missions depends on advances in infrared and submm detector and receiver technology. I illustrate the extent of these advances with examples of their potential impact on our understanding of the formation of the first galaxies and the formation and evolution of stars and planetary systems, and through their discovery potential.

2. How stars and Galaxies Emerged from the Big Bang

The history of star formation determines the evolution of galaxies and the generation rate for heavy elements. It has been traced by deep Hubble Space Telescope (HST) imaging photometry to identify objects where the Lyman limit probably falls in the optical regime, followed up with spectroscopy using the Keck Telescope. However, for objects at $z > 4$, the Lyman limit is no longer an advantage, since it drops the fluxes of possible galaxies below the detection limits. Deep HST imaging at 1.6 μm reveals a number of galaxies that are candidates to be at higher redshift (Thompson et al. 1999), but they are too faint for further study.

To extend our understanding of the history of star formation requires better observations in the near and mid infrared. [Figure 1](#) illustrates the possibilities with NGST to extend traditional optical approaches to extremely high redshifts. Selected objects are labeled with their redshifts. The simulation assumed traditional passive evolution from $z=0$ to $z=5$ and a Press-Schechter formula to model the light for star forming protogalaxies between $z = 5$ to $z = 20$.

However, reddening can compromise sorting in redshift by identifying Lyman dropout

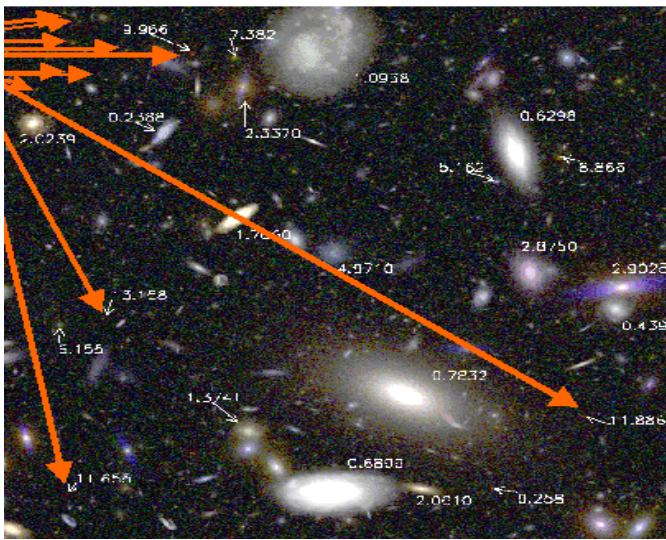


Figure 1

galaxies, as shown in [Figure 2](#). Already at an age of 10 million years for the stellar population, the break is substantially attenuated and softened by the expected amount of reddening, and for ages greater than 50 million years it is likely to fall below the detection thresholds. Fortunately, there are strong, broad spectral features that are less affected by reddening and emerge at these ages – the H and K break at 0.4 m m and the

spectral peak at 1.6 m m due to the H- opacity minimum in the atmospheres of cool stars. Therefore, they can be used for more robust photometric redshift estimation than is possible with Lyman dropout observations. To utilize them requires near and mid-infrared imaging, as shown in [Figure 2](#). Only NGST has the sensitivity to advance this program, and to follow up its discoveries through deep multiobject spectroscopy.

These goals together make the greatest demands on development of very large format, low background detector arrays for the near and mid infrared.

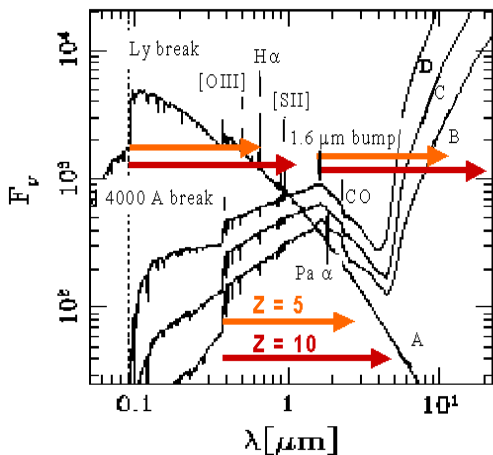


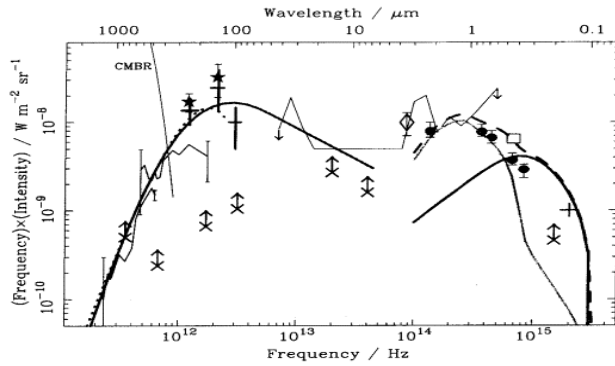
Figure 2

Even at modest redshifts, optical techniques only probe the rest frame ultraviolet. Interstellar

dust can absorb nearly all the UV in star forming galaxies. Although [Figure 2](#) suggests that the rate of massive stellar formation can be determined well in the rest frame ultraviolet, reddening has been found to make such estimates uncertain by an order of magnitude. In the best-studied starburst galaxies such as M82, a debate raged for more than a decade regarding how to correct even the near infrared emission for the effects of interstellar extinction. Consequently, there are significant uncertainties in the star forming rate for $z > 1$.

These uncertainties could be removed by measuring the far infrared emission emitted by dust heated by young stars in these galaxies. The importance of this approach is underlined by the Cosmic Background Explorer (COBE) discovery of a background in the submm with an energy density comparable to that of the visible light cosmic background (see [Figure 3](#)). This

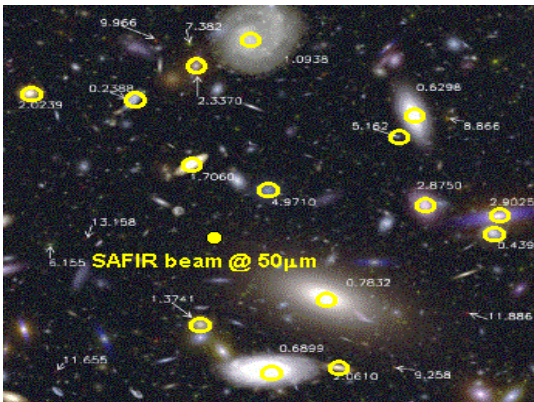
background has been partially resolved by ISO in the very far infrared and SCUBA near 1mm and is thought to arise from starburst galaxies at $z = 1$ to 3. A 10-m or larger telescope with detection limits of 0.1 mJy or less would resolve most of this high redshift background into individual galaxies.



[Figure 3](#)

Ultradeep optical images (e.g., Hubble Deep Field) reveal many galaxies too faint to contribute significantly to the submm diffuse

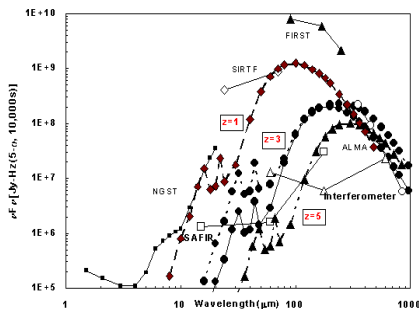
background, but which we need to study to probe early star formation. The infrared emission of these “normal” starbursts should dominate over infrared cirrus emission between about 15 and 80 m m. At $z \geq 4$, it will begin to become possible to measure this emission with the Millimeter Array (MMA). However, for $z < 4$, the MMA only probes the cool dust and infrared cirrus emission that may not be a reliable indicator of the recent star formation. The rate of star formation for $1 < z \leq 5$ can be determined through high sensitivity imaging from 20 to 70 mm. As illustrated in [Figure 4](#), angular resolution of about $1''$ (10-m telescope at 50 m m) will be adequate.



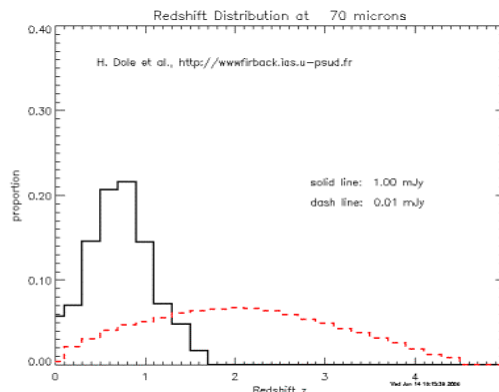
[Figure 4](#)

[Figure 5](#) shows that the sensitivity of a 10-m telescope will allow detecting a far infrared L^* galaxy to $z \sim 5$. In fact, the sources detected by a 10-m

far infrared telescope would span well the redshift range $0 < z \leq 5$, as shown in [Figure 6](#).

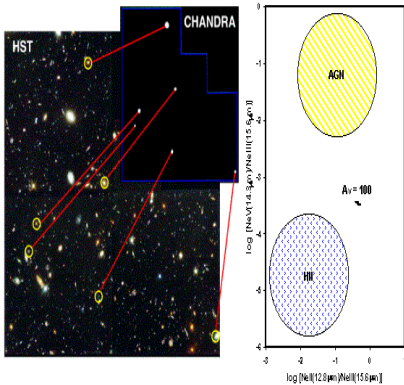


[Figure 5](#)



[Figure 6](#)

Chandra has detected a large number of compact sources that are likely to be active galactic nuclei at high redshift. [Figure 7](#) shows the deep Chandra image and the identifications of the detections in the HDFN. The sources are not prominent in the HST image, possibly because they are in dusty galaxies and are heavily obscured. The mid-infrared fine structure lines can provide a nearly extinction-free and extinction-independent indication of the slope of the UV source, as shown in the right panel of [Figure 7](#).



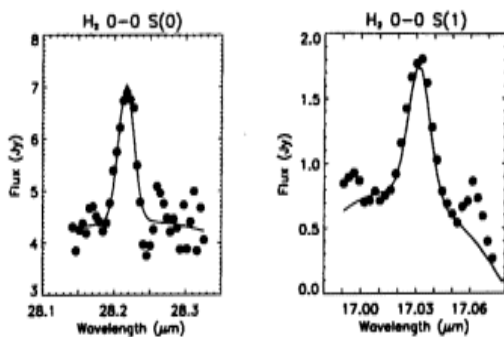
[Figure 7](#)

All of these objectives will be served by development of large format far infrared imaging

arrays and their use on large-aperture telescopes. The largest telescopes used routinely in the far infrared are less than 1 meter in aperture. No true imaging array has been used with them; the first true imaging array for the far infrared is scheduled to be launched with SIRTF.

How do the first gas clouds form? What chemical processes occur within them and how do their characteristics change as the first traces of metals are injected into them by stellar processing?

The low-lying H₂ lines at 17 and 28.2mm are one of the few conceivable ways to study molecular gas prior to the formation of metals (and to determine if molecules can even form during this epoch). ISO has demonstrated that these lines can be detected in the interstellar medium (see [Figure 8](#)). In this case, fits to their absolute and relative strengths require a molecular gas temperature of about 100K and a density of about 3000 cm⁻³. However, these lines are undetectable from the ground until z > 20 (particularly since both need to be measured for physical interpretation of temperatures and densities).



[Figure 8](#)

Once even traces of metals have formed, the C⁺ line at 157 mm becomes very bright. Its

luminosity in nearby spiral galaxies is typically a few tenths of a per cent of the entire bolometric luminosity of the galaxy. Although this line is partially accessible in the poor

atmospheric windows between 300 and 700mm, it will be routinely observed from the ground only at $z \geq 4$, when beyond 800mm. Study of the molecular hydrogen and C⁺ emission of gas clouds in the early Universe and as a function of redshift promises to reveal many of the processes occurring in the gas clouds that collapse into the first galaxies.

Space-borne observations in the FIR/Submm using both incoherent detector arrays in spectrometers and also high frequency heterodyne techniques will enable this study.

2. Birth and Evolution of Stars and Planetary Systems

Stars are born in cold interstellar cloud cores that are so optically thick they are undetectable even in the mid infrared. In about 100,000 years, a young star emerges, ejecting material along powerful jets and still surrounded by a circumstellar disk. The subsequent evolution is increasingly well studied, but the star formation event has occurred hidden from view. How does the cloud core collapse? How does subfragmentation occur to produce binary stars? What are the conditions within protoplanetary disks? When, where, and how frequently do these disks form planets?

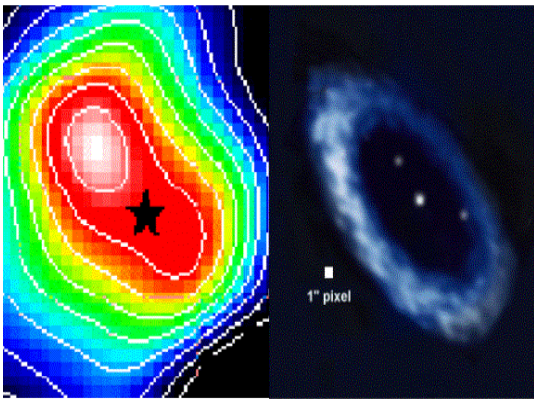
The birth of stars and planets can be probed thoroughly at FIR/Submm wavelengths. A far infrared 10-m telescope provides a resolution of ~ 1 arcsec at 50 mm (≤ 100 AU for the nearest star forming regions), so imaging could probe the density and temperature structure of these ~ 1000 AU collapsing cores on critical physical scales. In addition, 100 AU resolution would reveal the steps toward binary formation. Resolutions of 0.1 to 1 AU (1 to 10 km baseline interferometer at 50 m m) are required to probe circumstellar disk structure in the regions of terrestrial planet formation, searching for disk gaps and measuring the sharp thermal and compositional gradients that are predicted as a consequence of planet growth. Far infrared polarimetry is a powerful probe of magnetic field geometries, both for studying core collapse and mapping the fields that must play an important role in accelerating and collimating jets.

FIR/Submm spectroscopy can determine when and where flows begin that evolve into jets and can probe the physical conditions in the cold core. The gas in the core is warmed until its primary transitions lie in this spectral region. Spectroscopy in molecular lines such as H₂O and the J>6 high series lines of CO, as well as in FIR atomic lines of OI, C⁺, and NII, can probe the conditions in the collapse. Ceccarelli, Hollenbach, & Tielens (1996) have predicted the spectrum of a collapsing cloud core. The OI lines have narrow components from the infalling envelope and broad ones from outflow shocks. They are the main coolant of the gas in the intermediate regions of the cloud. Bright H₂O lines between 25 and 180m m are the dominant coolant in the inner cloud, where a broad component is expected from the accretion shock and a narrow one from the disk. The CO lines from 170 to 520m m are the main coolant for the outer cloud; warmer CO from within the cloud can also be studied because of velocity shifts due to the collapse. These studies are among many examples of the application of high frequency heterodyne receivers.

The Infrared Astronomy Satellite (IRAS) discovered debris disks around Vega, β Pic, and other stars, with evidence for inner voids that might have resulted from planet formation. Although far less prominent, the Kuiper Belt is similar in many ways to these systems and

should be interpreted as the debris disk of the solar system. The most prominent example, β Pic, is thought to be only about 20 million years old. Transient and variable absorptions by the CaII H&K lines in its spectrum have been interpreted as the infall of small bodies from the debris system. This system contains fine grains that heat sufficiently to be detected in the mid infrared and scatter enough light to be seen at shorter wavelengths. Because it should be drawn into the star quickly, this fine dust may be produced in recent collisions between planetesimals. Thus, this system and others like it demonstrate the potential of examining the early, violent evolution of debris disks and the infall of comets.

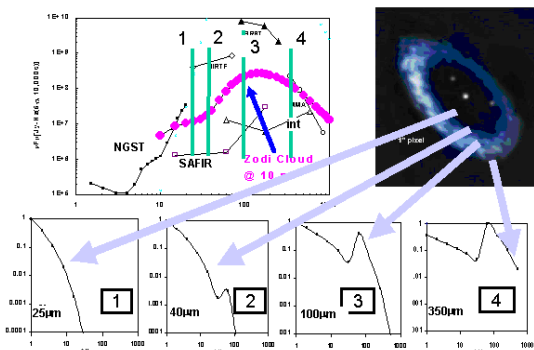
Debris disks are bright in the far infrared, where they can be imaged to identify bright zones due to recent planetesimal collisions, as well as voids. [Figure 9](#) illustrates the potential advances with a large FIR telescope and imaging array. Giant planets similar to Jupiter and Saturn could be detected to compare their placement with the debris disk structure. Similar views of very young planetary systems forming in the nearest molecular clouds could be achieved with an interferometer baseline of about 200 meters.



[Figure 9](#)

To study debris disks in detail requires measurements of their structures over a range of wavelengths. This point is illustrated

in [Figure 10](#). The spectrum of the debris disk is based on a model of the solar system zodiacal cloud plus the Kuiper Belt, placed at 10pc to represent what might be seen around a nearby star and increased in density. The calculation has been normalized to allow 100 resolution elements over the disk at each wavelength, the minimum which would give good information on the structure. Detailed models of the radial profile of the thermal emission at four fiducial wavelengths are shown in the lower panels. They emphasize that the shorter wavelengths will probe the inner portions of the system, for a solar-like system the zodiacal cloud. The longer wavelengths progressively probe increasing distances from the star; in the case of a solar-like system, 350 mm would be a good choice to study the parts of the system at a 100 or more AU radius. By combining observations at all the wavelengths, a detailed model of the system could be derived.



[Figure 10](#)

Spatially resolved spectroscopy with such a telescope, illustrated in [Figure 11](#), could probe the mineralogy of the

debris disks in the 20 - 35 mm region where the Infrared Space observatory (ISO) has found a number of

features diagnostic of crystalline and amorphous silicates. It could locate the zone of polyaromatic hydrocarbon (PAH) emission, of interest because the carriers should be so small that they can have only very short lifetimes within the system. Finally, it could also find ice through its 63 mm emission feature, indicative of a zone responsible for comets.

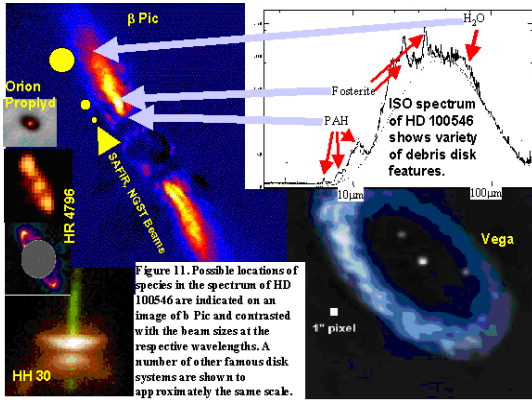


Figure 11

3. Discovery Potential

To compare the discovery potential of different missions operating over the same spectral region, the Bahcall Committee developed a figure of merit they called “Astronomical Capability.” This parameter is defined as the lifetime times the efficiency times the number of pixels / the sensitivity squared. It scales the amount of data that can be obtained in given mission, if all other things were equal such as optical parameters defining the projection of the pixels onto the sky. Compared with our current knowledge about the far infrared sky (from ISOPHOT between 20 and 100mm) and what could be achieved with the best currently available detector arrays on a 10m cold telescope, the gain in Astronomical Capability is about a factor of 10^9 ! With improvements in detectors, a factor of well over 10^{10} should be possible. These gains are illustrated in Figure 12.

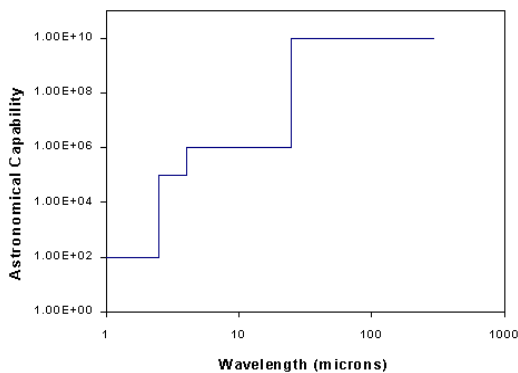


Figure 12

To compare the discovery

To place these gains on a more familiar scale, the improvement from the work of Shapley on the size and shape of the Milky Way to the Hubble

Deep Field represents a gain of about 10^7 in Astronomical Capability. Thus, our ability to predict what will be found in future FIR/Submm missions is probably no better than Shapley would have done in predicting the contents of the HDF.

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