THE SUBMILLIMETER FRONTIER: A SPACE SCIENCE IMPERATIVE

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Abstract

A major goal of modern astrophysics is to understand the processes by which the universe evolved from its initial simplicity, as seen in measurements of the Cosmic Microwave Background (CMB), to the universe we see today, with complexity on all scales. The initial collapse of the subtle seeds seen in the CMB results in the formation of galaxies and stars. The formation of the first stars marks the beginning of heavy element nucleosynthesis in the universe, which has a profound effect on the formation of subsequent generations of stars. The density fluctuations in the CMB from which all this structure grows are primordial. The development of these fluctuations into progressively more complex systems is the history of the universe; galaxies from seed structures, clouds from uniform interstellar gas, stars from clouds, elements from the initial hydrogen and helium, molecules from elements, dust from molecules, and planets from dust. These processes have resulted, at least on Earth, in the remarkable range of physical, chemical, and biological systems we see around us.

While the diffuse background measurements of COBE reveal the importance of the far infrared and submillimeter in early galaxy and star formation, the understanding of the development of complex structure requires high resolution imaging and spectroscopy. It is clear
Formation of stars from primordial material and
galaxies from pre-galactic structures
Evolution of galaxies and structures
History of energy release, nucleosynthesis, and dust formation
Feedback effects of Population III stars on those that came later

Table 1: SPECS will enable detailed astrophysical studies of the early universe.

from COBE observations of the far infrared background that much of the luminosity emitted in the critical initial phases of structure formation is emitted at far infrared wavelengths. Dust, which is responsible for the far infrared emission, hides much of the activity in the early universe from optical and near infrared study.

We present a concept for an instrument that will enable us to observe the dominant far infrared and submillimeter emission from the epoch of structure formation. The instrument, called the **Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)**, will produce high resolution images and spectroscopic data, allowing us our first clear view into the hidden environments where the structures in the universe developed. These observations will become powerful new tools to understand this crucial phase in the development of complex structures in the universe. SPECS will also open up new realms of discovery in the local universe. For example, individual star forming regions in a wide variety of nearby galaxies can be studied in detail, showing how the star formation process is affected by variable conditions such as metallicity and interstellar radiation field intensity. Such information will further improve our understanding of galaxies in the early universe.

SPECS is not only scientifically exciting, it is technically feasible. If a concerted effort is made to advance and test the required technologies during the next decade, it will be possible to build the SPECS observatory in the succeeding years.

1 Introduction

One of the most remarkable understandings developed by modern astrophysics is that the very complex local universe evolved from an earlier hot phase of almost perfect uniformity. Observations of the CMB reveal density fluctuations of only a few parts in $10^5$ at $z \sim 1000$. By the time we see the distant universe of galaxies in the Hubble Deep Field ($z \sim 1 - 3$), these density fluctuations have developed into isolated galaxies and clusters in mostly empty space, with a whole array of shapes and sizes. The **primary goal of SPECS is to provide a definitive observational basis for understanding the history of and the processes that drive the development of complex structure from the homogeneous early universe.** While simple observations are sufficient to characterize simple systems, the rich complexity of this era of galaxy formation requires observations with sufficient spatial and spectral resolution to characterize the total luminosities, physical conditions, and morphological characteristics of these developing systems.

Observations with HST, ISO, Keck, JCMT and other large Earthbound telescopes have
resulted in the identification of a large number of galaxies at redshifts out to $z > 3$, and have begun to produce a consistent picture of cosmic evolution. The optically selected samples of galaxies show a rapid increase in star formation rate, hence luminosity, as a function of redshift, peaking at about 10 times that in the local universe at $z \sim 1.5$ (Madau, Pozzetti & Dickinson 1998). The far-infrared/submillimeter extragalactic background measured by the DIRBE and FIRAS instruments on COBE (Hauser et al. 1998; Fixsen et al. 1998) requires a similarly high rate of star formation at $z \sim 1.5$ (Dwek et al. 1998).

Conclusions regarding the earlier history of star formation are more tentative; the star formation rate may remain near the elevated rate seen at $z \sim 1.5$, or it may decline significantly. The background measurements provide a weak constraint on the star formation at $z \gtrsim 1.5$. Ground based submillimeter observations from the SCUBA camera on the JCMT and measurements with ISOCAM on ISO have recently revealed high $z$ galaxies with very high star formation rates. These galaxies are completely undistinguished in an optical survey. Observations of the Hubble Deep Field at 450 and 850 $\mu$m suggest that optically faint galaxies undergoing massive starbursts may be responsible for 50% of the cosmic infrared background seen by FIRAS and DIRBE, and that as much as 80% of the luminosity of the early universe may be emitted in the far infrared (Hughes et al. 1998). Apparently most of the nucleosynthesis and its associated energy release, the motive force behind galactic evolution, occurs in environments that in optical studies are shrouded in dust. Indeed, extinction by dust is an important and ill-quantified source of systematic error in many cosmological surveys.

Thus we should strive to obtain a detailed view of the optically obscured star forming systems in the early universe; we need the ability to measure the luminosities, redshifts, metal abundances and morphologies of galaxies back to the epoch of their formation. SPECS achieves this goal with sensitive submillimeter interferometry and spectroscopy. As outlined in Table 4, SPECS provides high sensitivity and HST-like angular resolution in the far infrared, a wide field of view, and spectral resolution $\sim 10^4$. Since submillimeter radiation from the early universe is faint, cryogenic telescopes with background-limited direct detectors are required. The angular scales of the relevant structures are very small, so interferometric baselines ranging up to $\sim 1$ km are required.

Here we present a program of development that can, by late in the next decade, open the era of galaxy formation to detailed study. The emission from stars from this era is redshifted into the near infrared spectral region, where it can be studied by NGST. When combined with NGST observations, SPECS observations will provide direct measures of the total luminosities of forming and young galaxies by measuring their fluxes in the two spectral regions where the bulk of their energy is emitted.

SPECS will help answer several key questions about the basic characteristics of the universe:

1. When was “first light”? Did the first generation of stars form in early galaxies or before such systems existed?
Table 2: Parameters of SPECS, Submillimeter Probe of the Evolution of Cosmic Structure

| Parameter                          | Value                                                                 |
|------------------------------------|----------------------------------------------------------------------|
| Three Telescopes                   | $D_t = 3 \text{ m aperture}$                                         |
| Telescope temperature              | 4 K                                                                  |
| Maximum baseline, $b_{max}$        | up to 1 km                                                           |
| Detectors                          | Six $N_{\text{pix}} \times N_{\text{pix}} = 100 \times 100$ detector arrays |
| Detector type                      | Superconducting Tunnel Junction or bolometer                         |
| Spectrometer                       | Michelson Interferometer                                             |
| Wavelength range                   | 40 - 500 $\mu$m                                                     |
| Spectral resolution                | up to $10^4$                                                         |
| Angular resolution                 | $\lambda/b_{max}, 0.05''$ for 250 $\mu$m and 1 km                   |
| Field of view                      | $N_{\text{pix}} \frac{\lambda}{2D_t}, 14'$ for 250 $\mu$m, $N_{\text{pix}} = 100$, Nyquist sampling |
| Typical image size                 | $\sim 17000 \times 17000$ resolution elements                      |
| Typical exposure                   | 1 day                                                                |
| Typical sensitivity                | $\nu S_\nu \times 10^7$ Hz-Jy, $10^{-19} \text{ W/m}^2$ at 100 $\mu$m, 1 $\sigma$ |

2. What is the history of energy release and nucleosynthesis in the universe? How did carbon, oxygen, other heavy elements, and dust build up over time? What mechanisms were responsible for dispersing the metals?

3. Did the process or rate of star formation change over the course of cosmic history? How might any change in the star formation process be attributed to the gradual enrichment of the interstellar medium with heavy elements, or other factors still unknown?

4. What are the processes of structure formation in the universe? Were these processes hierarchical? What is the role of collisions between clouds and galaxy fragments? When and how did the first bulges, spheroids and disks form? How, ultimately, did the galaxies in today’s universe form?

In addition to these primary objectives, SPECS will provide unprecedented observations needed to understand the formation of stars and planets and the interaction of stars, at birth and death, with the interstellar medium.

In this paper, we argue for the necessity of a sensitive submillimeter interferometer for spectroscopic and imaging studies of the development of structure in the universe and the enrichment of the universe with heavy elements over cosmic time. Section 2 provides a theoretical and observational context in which gaps in our understanding are evident and the niches to be filled by SPECS are identified. Section 3 relates the physical processes that yield far-IR and submillimeter emission to the astrophysical systems that produce the emission, and illustrates how the SPECS observations can be used to address the scientific questions mentioned above. A technical concept for the SPECS observatory is presented in §5. We show that many of the technologies required for its realization exist, or are being developed as a part of the NASA program (§4). We identify the new technologies required (§5.3), and outline an incremental scientific program in which they can be developed during the next decade (§5.4).
2 Cosmic Evolution - Current Understandings and Observational Context

The canonical picture of the evolution of the universe given below provides a framework for discussion of the need for an instrument like SPECS. As they are currently understood, the major developments were as follows:

- $z \gg 10^7$ – The expanding universe begins in a hot, dense Big Bang, including a period of cosmic inflation that produced a smooth distribution of matter over the scale of our horizon and the density fluctuations, a part in $10^5$, seen in the cosmic microwave background radiation. A few minutes later, nucleosynthesis results in the production of H, D, He, Li, Be, and B from the initial protons and neutrons. Observed abundances are consistent with this picture. Dark matter, perhaps both cold and hot, begins to move under its own gravity as soon as the distant universe came within the causal horizon.

- $z \sim 1000$ – The decoupling of radiation from matter allows baryonic matter to cluster around the dark matter. The universe becomes transparent, leaving behind the microwave background radiation observed by COBE. We know the statistics of the density field at this time, and believe that a linear theory describes the growth of density fluctuations. This is the basis of the claim that the cosmic microwave background fluctuations can measure the main cosmic parameters. The MAP (2000) and Planck (2007) missions, and many ground based measurements, will do this.

- $z \sim 20$ – The first luminous objects form in fluctuations of greatest density enhancement ($> 3\sigma$). They must cool off as they collapse, emitting spectral lines from H$_2$ and H. Such lines would be extremely weak (of the order of pico-Janskys) and are not expected to be observable. However, the first star-forming systems might be detectable; whereas the binding energy, only $\sim 1 - 10$ eV/nucleon, is released during cloud collapse, nuclear fusion releases a few MeV per nucleon. In this epoch massive stars (Population III?) form and begin to ionize the intergalactic medium, and some expel heavy elements in supernova explosions and stellar winds. These objects are entirely hypothetical, but we know that something ionized the intergalactic medium by a redshift of 5. With SPECS we will be able to find and characterize the first stars even if our view is obscured by dust, learn when these objects produced heavy elements, and determine when the first dust formed. At a redshift of 20, Ly$\alpha$ is observable by NGST. The redshifted Brackett lines could be observed by SPECS, as could the near IR emission from cool stars, continuum emission from dust in H II regions, and several important diagnostic fine structure lines from heavy elements (see §3). The [C II] 158 $\mu$m line is redshifted to 3.3 mm and could be seen with the Millimeter Array (MMA), along with thermal emission from dust associated with the neutral phases of the ISM.
• \( z \sim 3 - 20 \) – Secondary structure formation. Cloud cooling is enhanced by the inclusion of newly synthesized heavy elements. Galaxies grow by collisions and absorption of smaller fragments, with a rate governed by the statistics of the primordial density fluctuations and their growth. Many are very dusty, with star formation obscured by very local dust from young hot stars and supernovae. Interstellar shocks reprocess the dust. Some heavy elements enrich the newly ionized intergalactic medium, driven by high pressures and outflows from small galaxies with insufficient gravity to retain the debris. Gas liberated from the galaxies by collisions is heated and radiates X-rays. Deep potential wells form in clusters and gravitational lenses allow far IR measurements of even more distant objects. SIRTF will count the galaxies and measure their luminosity functions. NGST will observe the stars in the galaxies, and the obscuration by dust. \textbf{SPECTS will observe the dust luminosity directly, allowing the inference of the hidden stellar luminosity.}

• \( z \sim 1 - 3 \) – Star formation peaks with frequent collisions of galaxies and fragments. Cooling flows allow hot gas to fall to the centers of galaxy clusters and disappear from view, possibly forming stars (O’Connell and McNamara 1991). In many galaxies Active Galactic Nuclei (AGN) form in dense cores with accretion disks of infalling material and produce jets observable from radio to X-ray. These AGN have strong effects on their host galaxies. SIRTF establishes the relationship between AGN and the ultraluminous infrared galaxies first seen by IRAS. HST reveals the morphologies and colors of young galaxies and tells us that collisions are common. NGST sees the stars and, depending on its long wavelength coverage, part way into the dense cores of AGN. SPECTS sees into the dense cores, penetrating the opaque dust and seeing its emission. A number of \( \text{H}_2\text{O} \) lines, which are important diagnostics of star forming molecular clouds (Harwit et al. 1998), will be visible to SPECTS. \textbf{The combination of NGST and SPECTS allows us to distinguish the emission from individual star forming regions and learn whether and how much star formation is driven by collisions of galaxies, spiral density waves in existing galaxies, feedback from other star formation, or other causes.}

• \( z \sim 0 \), the local universe – Galaxy mergers have nearly ceased. Nearby galaxies allow us the maximum visibility into star formation processes, which now occur presumably under very different densities and radiation fields than at higher redshifts. NGST and SPECTS are complementary, and both are necessary for a complete picture. \textbf{In the Milky Way and more than a hundred nearby galaxies, SPECTS allows us to see inside dusty clouds where stars and planets are forming. The high angular resolution provides a new dimension of information.} Studies of the carbon, water, nitrogen, and oxygen lines show the cooling of the warm phase of the interstellar gas at high spatial resolution. Protostellar disks in local star forming complexes can be resolved in these lines, enabling the development of more detailed astrophysical models of protostars.
In cosmology, the far IR and submillimeter region is centrally important. A plot of the luminosity of a typical spiral galaxy (the Milky Way, Figure 1) has just two large bumps, one from 0.2 to 2 µm from the luminosity of stars, and one nearly as large from 50 - 400 µm, from the energy absorbed and reradiated by dust. These two terms dwarf all the others, but only one has been widely observed; the far IR emission from most galaxies is barely detectable with present techniques, and very few galaxies can be resolved into parts. Early galaxies tend to be even more profuse infrared emitters than typical galaxies in the local universe, as illustrated here by the spectrum of a representative starburst galaxy (Figure 2). It seems likely from direct measurements of high redshift galaxies (Blain et al. 1998; Barger et al. 1998) and from measurements of the cosmic far infrared background (Hauser et al. 1998; Fixsen et al. 1998) that much of the luminosity of the early universe has been hidden by dust absorption and is reemitted in the far infrared. The history and even the list of constituents of the universe is presently quite incomplete. There is a huge uncharted far IR universe awaiting the first discoverers with adequately sensitive instruments.

To summarize, an instrument like SPECS is needed to fill a gap in observational capability at far infrared and submillimeter wavelengths that translates directly into an inability to solve some of the greatest mysteries currently recognized in astronomy. The SPECS observations would be complementary to those of the NGST and MMA. A triad of observatories consisting of these three would allow us to take the next leap forward in our understanding of the universe.

3 Physical Processes in Submillimeter Emission

The purpose of this section is to relate the observational capabilities envisioned for SPECS (Table 2) to the primary scientific objectives (Table 1). To make this connection one must consider the physical processes that give rise to the observable emission.

The main processes known to produce far infrared radiation are thermal emission from interstellar dust, fine structure line emission from interstellar atoms and ions, rotational line emission from molecules, and synchrotron and bremsstrahlung radiation from hot electrons in dense regions like active galactic nuclei. Atomic and molecular features that play key roles in the collapse of star-forming clouds and in the energy balance of the interstellar medium are unique to the far IR. The line emission allows detailed investigation of physical conditions such as temperature, density, chemical composition, and ionization state. Very small dust grains emit “PAH features” and nonthermal radiation as they spin at many GHz rates. Condensed objects (stars, planets, asteroids, and comets) all emit at far infrared wavelengths, and if they are cold enough (< 40 K) they have no other emission. In addition, rest frame near- and mid-IR emission from high-z galaxies appears in the far infrared, making this the relevant spectral window for observations of hydrogen Brackett line and cool star emission from such galaxies. A wide range of phenomena are uniquely well observed in the far IR.
Figure 1: Milky Way spectrum in photon units (top) and $\nu L_\nu$ units (bottom). Spectral lines at $\lambda > 100\,\mu m$ are shown with 2% spectral resolution. The C$^+$ 158 $\mu$m line, which cools the interstellar medium, is the brightest. Most of the Galaxy’s photons are in the far-IR.
Starburst galaxies like NGC 6090 are much more luminous in the far-IR than at UV and visible wavelengths, and the dominance of the far-IR bump in photon units is even greater. The NGC 6090 data sources are Acosta-Pulido et al. 1998 (ISO), Soifer et al. 1989 (IRAS), and the NASA Extragalactic Database (UV - visible).
3.1 Structure in the Early, Metal-free Universe

Since the heavy elements responsible for the cooling and collapse of gas clouds in the present universe are not available for the formation of the first generation of stars and galaxies, the detailed physical mechanisms of initial formation must be very different. SPECS will provide us with a unique view of the first galaxies and protogalactic systems. For example, assuming that molecular hydrogen clouds were the progenitors of the first stars, the redshifted H$_2$ 17 and 28 $\mu$m rotational lines could be observable. SPECS will resolve a hypothetical $z = 10$ object at the 100 pc scale in the 17 $\mu$m line. If stars formed as early as $z = 20$, then SPECS would detect the Br$\alpha$ and Br$\gamma$ lines at the redshifted wavelengths 85 $\mu$m and 45 $\mu$m, respectively. From SPECS observations it will be possible to learn whether the first stars formed in pre-existing galaxies, or if stars formed earlier in pre-galactic clouds.

3.2 The History of Energy Release and Nucleosynthesis

What produces the cosmic far infrared background? It is usually said that the far IR emission comes from starburst activity (e.g., Haarsma & Partridge 1998) and (in combination with the UV-optical emission) reveals the nucleosynthesis history of the universe. However, it would be more accurate to say that the far IR background reveals the luminosity history, since we do not know whether the luminosity comes from starbursts or from AGN. Some have argued, combining ISO, SCUBA, and X-ray data, that much of the X-ray and far IR background comes from AGN sources associated with and partially obscured by intense nuclear starbursts (Almaini, Lawrence, and Boyle 1998; Almaini et al. 1998; Fabian et al. 1998; Genzel et al. 1997; Lutz 1998; Lilly et al. 1998). The actual nature of the far IR sources detected with the SCUBA array (Hughes et al. 1998; Barger et al. 1998) is unknown.

There are several ways to investigate such far IR objects. Many have far IR luminosities that exceed those at other wavelengths by an order of magnitude, so it is clearly important to observe this dominant luminosity as well as possible. Low spectral resolution photometry over the entire wavelength range from X-ray to far IR is required to get the luminosity; extrapolations from wavelengths that are conveniently observed are not really sufficient. Those objects that are not too heavily obscured can be seen with HST, and high resolution UV images might reveal star clusters or compact disks. Hard X rays (> 3 keV) can penetrate high column densities of obscuring material, directly revealing a non-thermal source. Mid IR (5 - 30 $\mu$m) spectroscopy (preferably spatially resolved) can observe the 5 - 12 $\mu$m AGN/starburst diagnostic lines and dust features found by ISO (Genzel et al. 1997), with the observable spectra depending on the depth of obscuration and on the redshift. Long wavelength high angular resolution imaging (e.g., with the MMA or a space interferometer) is also required, to locate the sources precisely and determine their spatial structure. Very high spatial resolution is required to measure the diameter of a compact source at the core, if there is one, calling for a millimeter array or a far IR space interferometer with very long baselines.

SPECS would fill a very important gap. The objects seen with SCUBA are at the
milliJansky level at 850 $\mu$m, and are considerably brighter (though less easily seen from the ground) at shorter wavelengths. The SPECS sensitivity is of the order of 10 $\mu$Jy (see §3), two or three orders of magnitude below the SCUBA source brightness, and it would have the combined spatial resolution and sensitivity to resolve the SCUBA sources into hundreds of pixels. In the end, we would know how and where most of the cosmic energy in the whole X-ray to far IR range is liberated, something we can not know today.

In normal spiral galaxies, the [C II] line at 158 $\mu$m is often the brightest emission line at any wavelength, dominating the cooling of the Warm Neutral Medium. In typical spirals, the line can have a total luminosity about 1/3% of the total system luminosity (Stacey et al. 1991). Although a deficit is seen in the 158 $\mu$m line emission from ultraluminous infrared galaxies, suggesting that perhaps high redshift galaxies show weak [C II] emission (Luhman et al. 1998), the line still may prove to be a useful marker for such galaxies. SPECS observations of galaxies over a wide range of redshifts in the [C II] and other fine structure lines from oxygen and nitrogen will enable us to trace the buildup of heavy elements in the universe over time. Moderate spectral resolution ($\sim 10^3$ - $10^4$) will be needed to detect the line emission. High angular resolution is required to examine the mechanisms responsible for dispersing the metals in a large number of galaxies.

3.3 The Evolution of Galaxies and Structures

High spectral and spatial resolution observations will yield both kinematic and morphological information about the structures in the universe. We would like to know how these structures interacted and developed over time into the $z = 0$ galaxies. What were the progenitors of halos, bulges and disks, and galaxy clusters and superclusters, and when did these structures form? Did galaxies form from the “top down,” or were they assembled from bits and pieces? How did the different galaxy morphological types develop? The broad and continuous spectral coverage provided by NGST, SPECS and the MMA, will enable us to follow the development of structure from $z = 10$ to $z = 0$ in a fixed set of spectral lines and features.

3.4 Galaxies as Astrophysical Systems

Following the initial phase of nucleosynthesis in the universe, the dominant cooling and diagnostic lines are in the far IR region, and are not accessible to detailed study from the ground (except at very high redshift). This spectral region includes the fine structure lines of [C II], [O I] and [N II], which dominate the cooling of and reveal the physical conditions in neutral and ionized gas clouds. These elements are also the building blocks of life, and it is important to know when and where they are produced and turned into planets.

Molecular lines in the far IR from CO and H$_2$O dominate the cooling of dense molecular clouds and are thus critical players in the formation of stars. Additional diagnostic lines, such as those of the hydrides (OH, CH, FeH, etc.) are also found in this spectral region. Thus spectral line measurements will allow us to probe dense, cold material in dark clouds,
providing insight into the details of cloud collapse in star formation. Longer wavelength studies with ground based telescopes of other less energetically important lines have been remarkably successful, but we are seriously limited at present by our inability to observe the lines that dominate the energy balance.

In addition to the far IR fine structure lines mentioned above, many galaxies are luminous sources of mid IR fine structure emissions from Ne II (12.8 µm), O III (52, 88 µm), Ne III (15.6, 36.0 µm), Ne V (15.6, 36.0 µm) and several other ions that result from photoionization by radiation shortward of the Lyman limit (e.g., Moorwood et al. 1996). Even at moderate redshift, all of these important diagnostic lines are shifted longward of even the longest wavelengths contemplated for NGST. The mid IR lines provide unique probes of the metallicity and gas density in ionized regions, as well as the spectral shape of the ionizing radiation field (e.g., Voit 1992). These transitions have several important advantages over the optical wavelength lines traditionally used to probe H II 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. The availability of noble 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 spectral bump characteristic of thermal dust emission (see Figures 1 and 2) will be evident in galaxies dating back to the first epoch of dust formation. Recent observations of an individual galaxy indicate that dust existed at z = 5.34 (Armus et al. 1998). Extinction effects become important as soon as there is dust.

SPECS will spatially resolve individual galaxies and allow us to study them in the spectral lines that dominate the energy balance of the interstellar medium, cloud collapse, and star formation, and in the spectral features that signify the presence of dust. We can expect to observe changes in the physical properties of the interstellar medium, and the star formation rate or process, as a function of redshift. It might be possible to infer, for example, the effects of increasing metallicity on molecular cloud cooling and the rate of star formation. In any case, clearly, such a rich data set would provide the basis for new and improved astrophysical models.

In summary, observations of the early universe in the far infrared and submillimeter will allow us to:

1. Obtain a complete census of energy release in the universe as a function of cosmic time;
2. Probe physical conditions associated with star formation in the early universe, including metallicity and depletion in the interstellar media of high redshift galaxies;
3. Investigate the kinematics of the newly formed galaxies to help understand the role of collisions in the initiation of star formation and the growth of complex structure; and
4. Measure the relative importance of ionization by starlight and by active galactic nuclei in the high redshift universe.

Observations of star formation in the local universe are important in providing a detailed picture of this process in environments enriched with heavy elements.

If high sensitivity and angular resolution can be extended to the far IR/submillimeter, then new kinds of objects may be detectable. Old planets far from their parent stars, either in distant orbits or already escaped, could be numerous and detectable only in the far IR.

4 Submillimeter Astronomy Today, Opportunities for Tomorrow

To put our current submillimeter observational capability in perspective, we can compare the present facilities with the human eye. At a wavelength of 1 mm, even a large telescope like the 15 meter JCMT (James Clerk Maxwell Telescope) at Mauna Kea has an angular resolution only as good as a 7.5 mm diameter telescope at 0.5 µm; in other words, far IR astronomy now has the angular resolution of an ideal human eye. Had the Hubble Deep Field been observed at comparable resolution, most of the interesting information would have been missed. The far IR telescope and atmosphere are also glowing brightly, compared to the faint objects being observed. In one sense this is tremendously disappointing, but in another it is a tremendous opportunity.

To meet this opportunity, several major projects are planned or being built. The SIRTF (Space Infrared Telescope Facility), with an 0.8 meter telescope at 4 K, is now under construction. The Far IR Submillimeter Telescope (FIRST), an ESA Cornerstone mission with a US-contributed 3.5 meter telescope operating at a temperature of 70 K, will fly around 2007. The Japanese H2L2 mission is being planned for a launch in 2012 with a 3.5 m telescope at 4 K (Matsumoto 1998). These new telescopes represent a continuing series of more sensitive instruments, but they will be limited by angular resolution only a little better than the human eye. The images of distant objects obtained with these telescopes will be fuzzy and overlapping. We need a far-infrared telescope that can distinguish individual distant galaxies. On the ground, the MMA is to be built in Chile, an extraordinary facility with coherent receivers, upward of 40 dishes of 10 m aperture, and spacings up to kilometers apart. This equipment will provide excellent angular resolution, comparable to the HST. It will be limited in sensitivity by antenna spillover and atmospheric emission at ambient temperature, and in dynamic range by atmospheric fluctuations, but with long exposures will be able to find immense numbers of galaxies because of its huge collecting areas.

The science drivers for SPECS are derived from the considerations of the previous sections. We have already shown how several fundamental questions pertaining to the evolution of structure in the universe can be addressed observationally. **None of the existing or planned facilities will provide the combination of high sensitivity, high angular resolution, and large solid angle at far IR wavelengths that we believe is nec-**
ecessary to meet the scientific challenge. The obvious answer is a far IR space interferometer with cold, photon-counting array detectors.

The development of space interferometry was recommended by the HST and Beyond committee (Dressler et al. 1996) and by the Bahcall decade survey committee (Bahcall et al. 1991), although the emphasis in those reports was on shorter wavelengths. One reason for this emphasis is the strong desire to find and learn about planets around other stars, and the mid IR band (5 - 20 µm) contains the key spectral signatures of photosynthetic life (ozone, water, and carbon dioxide). Also, far IR astronomy is so far behind other areas that its potential can be hard to recognize. Acting on the Bahcall and Dressler Committee recommendations, NASA and ESA are both preparing for space interferometers at visible and near IR wavelengths, and the technological basis is under development.

The key new development that enables sensitive far infrared space interferometers is the detector system. The current generation of bolometric detectors is already good enough to be limited by the photon fluctuation noise of the cosmic infrared background light in wide bandwidths. Semiconductor bolometers can be made in arrays by two different techniques, and improvements using superconducting thermometers and amplifiers promise to reach the extreme sensitivities required for this mission (Irwin 1995; Lee et al. 1996, 1997; Lee et al. 1998). Another promising detector technology is direct detection with superconducting tunnel junctions. These devices convert far IR light directly into photocurrents that can be amplified and measured. The necessary superconducting electron counting amplifier design has just been developed (Schoelkopf et al. 1998), and there is every reason to be optimistic about continued improvements. For many applications, current direct detectors are already far more sensitive than even ideal ("quantum limited") amplifiers or heterodyne receivers, which suffer additional quantum fluctuation noise equivalent to receiving one photon per second per unit bandwidth and polarization, and can be orders of magnitude more sensitive for the SPECS application.

Photon detectors are preferred whenever the background photon rates are small compared with the detector bandwidths of interest. This is true for broadband systems at wavelengths shorter than about 1 mm, although for very high spectral resolution the coherent receivers are competitive down to about 300 µm wavelength. The sensitivity of an ideal photon detector and amplifier are shown in Figure 3 using the COBE DIRBE measurements of the brightness of the darkest part of the sky. Note that the sensitivity worsens as the wavelength increases, but longer observing times and slightly larger collecting areas can compensate.

An interferometer would have the sensitivity of a single dish with the same collecting area, but the angular resolution of a telescope with the full aperture. Considering the sensitivity improvements that are possible, it seems that the individual apertures could be relatively small (a few meters) while the maximum useful separation could easily be hundreds to thousands of meters. Even accounting for all the penalties of interferometry, such a device could map thousands of $10^{10} L_\odot$ galaxies at $z = 1$ in a very reasonable time.
Figure 3: The sensitivity of the ideal photon noise limited detector (solid curve) and amplifier (dashed line) for a bandwidth of 100% and a diffraction limited beamwidth ($A\Omega = \lambda^2$) and two polarizations. Bolometers already achieve sensitivities of $3 \times 10^{-18} \text{ W/Hz}^{1/2}$. 
5 The Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)

The SPECS that we envision has the characteristics outlined in Table 2. In particular, the science drivers (§3) are satisfied with several to 10 µJy sensitivity, several tens of milliarcsecond angular resolution, \( \sim 10^4 \) spectral resolution, and a 15’ field of view.

Below we describe the basic concepts and configurations to be considered.

5.1 Basic Concepts

The principle of operation of a spatial interferometer is to determine the two-point correlation function of the incoming waves, and from that to compute a map and spectrum. A monochromatic plane wave can be described as

\[
\psi(x, t) = \psi_0 \exp(i(\vec{k} \cdot \vec{x} + \omega t)),
\]

where \( \vec{x} \) and \( t \) are position and time, and \( \vec{k} \) and \( \omega \) are the wavevector (\( |\vec{k}| = 2\pi/\lambda \)) and frequency (\( \omega = 2\pi f \)). Its correlation function is

\[
C(\vec{x}, \vec{x}', t, t') = E(\psi(\vec{x}, t)\psi^*(\vec{x}', t')) = |\psi_0^2| \exp\{i(\vec{k} \cdot (\vec{x} - \vec{x}') + \omega(t - t'))\},
\]

where \( E \) is the expectation value function. For a steady sky signal, the correlation function depends only on the spatial separation \( \vec{x} - \vec{x}' \) and the time delay \( t - t' \) between the two points of observation. By custom the component of \( \vec{x} - \vec{x}' \) perpendicular to the central line of sight is labeled by \( (u,v)\lambda \). The component of \( \vec{x} - \vec{x}' \) parallel to the line of sight is absorbed in the time delay term.

If there are only two telescopes at \( \vec{x} \) and \( \vec{x}' \), and the time delay \( t - t' \) is fixed, then the angular response function of the correlation function is a simple cosine pattern with angular scale of 1 cycle per \( \delta\theta = 1/|(u,v)| \). If the two telescopes are moved around to measure more data points, the angular resolution of the deduced map is approximately \( \delta\theta = 1/\max|(u,v)| \). The number of observations at different values of \( (u,v) \) gives the maximum number of parameters of the map that can be deduced from the data. If the values of \( (u,v) \) are uniformly spaced in a square grid pattern, the algorithm to recover the sky map is a simple Fourier transform. Indeed, the Van Cittert-Zernike theorem says that the correlation function for a given \( \vec{x},\vec{x}' \) and an intensity distribution on the sky is just a Fourier component

\[
C(0) \propto \int \int I(\vec{s}) \exp(-2\pi i\vec{s} \cdot (\vec{x} - \vec{x}')/\lambda) d\Omega,
\]

where \( I(\vec{s}) \) is the brightness in the direction \( \vec{s} \), \( \vec{s} \) is a unit vector, and \( \Omega \) is solid angle. Here the \( C(0) \) notation refers to setting the time delay equal to zero, so that the waves being correlated are in phase.

Spectral resolution can be obtained either by choosing a narrow band filter, or by performing measurements of the dependence of the correlation function on the time delay. Some spectral resolution is required to support the spatial interferometry, because the angular resolution and the whole scale of the reconstructed Fourier transform image depends on
wavelength. In general the reciprocal spectral resolution \( R^{-1} \equiv \delta \lambda / \lambda \) should be significantly less than the ratio of the size of the synthesized beam \( \delta \theta \) to that of the primary beam (\( \lambda / D_t \)), or \( R > \max (|u, v| \lambda / D_t) \); otherwise the reconstruction is ambiguous.

We can now compare coherent and optical technologies. With coherent receivers, the wavefunction \( \psi \) is measured directly, amplified, and relayed to a central computer, and all the correlation properties can be computed electronically in a giant digital correlator. With optical methods, the correlation function is determined using square law detectors (photon or energy detectors) and beamsplitters. Assume a beamsplitter with transmission coefficient \( t \) and reflection coefficient \( r \) is used to combine two beams, one reflected and one transmitted. The output amplitude on one side is then \( \psi = r \psi_1 + t \psi_2 \), and the intensity is \( I = |r \psi_1|^2 + |t \psi_2|^2 + 2 \Re (r \psi_1^* t \psi_2^*) \), where \( \Re \) is the operator that finds the real part of a complex number. This last term contains the needed information about the correlation function of the two input waves.

With coherent receivers, it is convenient to measure the correlation function at many different time delays (lags) and to deduce the spectrum of the incoming radiation from the Fourier transform of this distribution. Since the waves have already been amplified, this can all be done simultaneously in a digital correlator. In the optical case, the equivalent is a grating or prism spectrometer, which performs the coherent transformations instantaneously and disperses the output photons across a detector array. This has the advantage that the photon fluctuation noise is also distributed with the signal, and is the ideal when it is possible to provide enough detectors. Optical technology offers another method as well, the Michelson spectrometer. In this method, the time delay is varied by a moving mirror, and an interferogram is measured. The Fourier transform of this interferogram is the desired spectrum, just as in the coherent case. The disadvantage is that the photon fluctuation noise affects all the computed frequency bins regardless of the input spectrum. On the other hand, the Michelson spectrometer can easily cover a wide field of view simultaneously. This offers many potential advantages for the SPECS mission.

The distribution of points in the \((u, v)\) plane governs the quality of the image that can be reconstructed, and there is a large literature on the question of ideal arrangements. With ground based interferometers the optimization favors a large number \( m \) (10-50) of separate antennas in a Y shaped or circular pattern. Then the rotation of the Earth changes the orientation of the array relative to the sky, and each of the \( m(m-1)/2 \) pairs of antennas produces a track in the \((u, v)\) plane. Adjustable delay lines (e.g., coax cables) compensate for the fact that the antennas are not located in a plane perpendicular to the line of sight. With enough pairs and enough Earth rotation, a large number of points can be measured in a day. To get more coverage, the antennas can be picked up and moved, but this is time consuming.

With a space optical interferometer, complexity grows rapidly with the number of telescopes, so the smallest possible number is favored. With three telescopes, there are phase closure relations among the observations that enable self-calibration of certain instrument properties (Pearson and Readhead, 1984). With four antennas, there are amplitude closure relations as well, and with five antennas there are enough combinations to make redundant
self-calibrations. We have not analyzed this question fully, but are hopeful that the number of telescopes can be kept down to three by careful use of the information from multiple pixels within each field of view, by careful calibration of the equipment response functions, and by depending on good long term stability. This is not generally done with ground based instruments because the complexity of the receivers favors the use of more antennas instead of more detectors. Also, on the ground, atmospheric fluctuations are very rapid, demanding the use of the self-calibration relations on a second-by-second basis. We hope this is not necessary in space.

With a space interferometer, there is a choice of methods of moving the telescopes in the \((u,v)\) plane. The large scale of the desired SPECS precludes the use of rigid physical structures, so there must be separated spacecraft flying in formation. These can be completely independent, or they can be tethered together to reduce fuel consumption. If they are tethered together, the entire collection of telescopes can easily spin at relatively high speed around the line of sight, producing observations of a circular set of points in the \((u,v)\) plane. If the tethers are played in and out together, the radius of the circle in the \((u,v)\) plane changes too, so it may be easy to produce a spiral pattern. It would be possible to sample the \((u,v)\) plane completely in 2 days with 1 km maximum baselines if the scanning mirror could be made to stroke at about 1 Hz. If the spacecraft are not tethered together, then a more natural scan pattern may be a simple raster, in which velocity changes are abrupt at the end of each sweep. Whether this is feasible depends on the details of the propulsion system.

An advantage of a space interferometer is that in principle all spacings are available. There is no need to move heavy, fixed antennas from one attachment fitting to another, an approach often used on the ground. Elaborate algorithms such as CLEAN and Maximum Entropy have been developed to handle the irregularly spaced data collected with ground-based interferometers. Although perfectly uniformly sampled data could be Fourier transformed directly to produce an image, adaptations of CLEAN and Maximum Entropy likely will be useful in the construction of SPECS images, and might allow us to produce high-quality images even if the \((u,v)\) plane is undersampled. Unlimited by atmospheric fluctuations, and with the freedom to position the light-collecting telescopes where they are needed, a space-based interferometer can achieve much greater dynamic range than a ground-based system.

There are important choices to be made about the spatial and spectral resolution to be used for each target. For unresolved sources, the sensitivity is determined primarily by the collecting area and the observing time, and is about the same as for a filled aperture telescope of the same area. Excess resolution beyond what is needed for the interesting features is a waste of observing time. For a space interferometer, the spatial resolution is controlled by the scan pattern of the moving remote mirrors. The spectral resolution should be chosen to match either the spatial resolution, or the intrinsically interesting spectral structure of the sources.
5.2 Interferometer Configuration

A typical far IR imaging interferometer concept would include the following features. At least three telescopes are required, to take advantage of the possibilities of self-calibration of the telescope positions with phase closure algorithms. They would be cooled to a low temperature, so that their thermal emission is less than the sky brightness and they do not dominate the noise, as shown in Figure 4. These temperatures are now achievable with radiation baffles and active coolers, in deep space.

![Figure 4: Required temperature for telescope (dashed curve, emissivity 0.01) and instrument package (solid curve, unit emissivity) for thermal emission to be less than the infrared sky brightness.](image)

One way to arrange the telescopes in a far-infrared interferometer is illustrated in Figures 5 and 6. There are three telescopes at the central beam combining station, each looking out sideways at a diagonal flat. The diagonal flats move in formation to change the location of the observing stations, and all are located equally far from their respective telescopes. This arrangement produces the least possible beam divergence between the telescopes and the diagonal flats, since the telescopes at the central station have the largest possible aper-
tures. It also allows the diagonal flats to be packed close together, providing low spatial
frequency information. The telescopes are conceived as off-axis Cassegrain afocal systems
with a magnification factor of about 10. Their output beams reflect from small diagonal
flats to become parallel to the original line of sight from the sky, as illustrated in Figure 6.

The telescope beams would be combined to measure the correlation functions, using
beamsplitters (as in the Michelson spectrometer) or geometrically (as in the Michelson stellar
interferometer). We suggest the beamsplitter approach, as that is the most similar to the
successful imaging interferometers done with microwave receivers, and the algorithms are
fully developed. In this case, the path difference between the input beams is modulated to
measure the spectrum of the coherence function. This is like the digital correlator for the
MMA, which determines spectra by correlating one input signal with another as a function
of time delay. It has been shown that in the photon noise limited case, all forms of beam
combination produce approximately the same sensitivity (Prasad and Kulkarni, 1989). With
$m$ telescopes, there are $m(m - 1)/2$ beam combiners, each with two output beams, so there
are $m(m - 1)$ focal planes. One such concept is shown in Figure 7. The numbers of reflections
are equal in each path, so that the images from different telescopes can be superposed exactly.

With the beamsplitter approach each focal plane can be a direct image of the sky, feeding
an array of detectors just as though it were at the focal point of a single telescope. The field
of view can be as large as the telescope aberrations and detector technology allow; we think
a field of 1/4 degree may be feasible. This is totally different from the standard microwave
array, in which each antenna feeds a single pixel receiver. As a result, the far IR version
can have a huge advantage in observing speed, proportional to the number of detectors.
Effectively there are now $N_{\text{pix}} \times N_{\text{pix}}$ separate interferometers operating simultaneously, each
with its own field of view of approximately $\Delta \theta = \lambda/D_t$, where $D_t$ is the diameter of each
telescope. Since this $\Delta \theta$ can be much smaller than the geometrical field of view of the
telescope, it is possible to provide a large number of pixels. This is in addition to the sensit-
ity advantage of each detector over a coherent receiver. With the beamsplitter approach,
all frequencies are modulated and observed simultaneously, much as they are in the digital
correlators. However, the digital correlators use amplified copies of the input signals and
therefore have different noise characteristics. Digital correlators have the advantage that
they can measure many different time delays simultaneously, partially compensating for the
lower detector sensitivity of coherent systems in low background conditions, but they can
not be used in photon background limited receivers.

The maximum spectral resolution achievable is governed by the beam divergence at
the beam combiner, because the path difference is multiplied by the cosine of the angle of
each ray from the central ray, and a range of angles corresponds to an apparent range of
wavelengths. With a large diameter system like that described here, there is no problem
achieving resolutions of the order of $R = 10^4$, although the path difference required becomes
large, approximately $R\lambda$. If this much spectral resolution is required, a more compact
spectrometer such as the Fabry-Perot filter would be favored, and would have the advantage
of reducing the photon noise from signals outside the bandpass of interest.

The spatial resolution obtained is governed by the maximum spacing of the mirrors. At
Figure 5: Telescope concept as seen from the perspective of the target of observation. Low spatial frequency information is obtained when the mirrors are closely spaced, as shown. There are three Cassegrain off axis telescopes, with mirrors seen edge on, each seeing the sky reflected from a large diagonal flat, which appears round in this perspective. Small circles are diagonal flats that feed the beams down to beam combining optics.
One of Three Telescopes

Figure 6: Telescope concept, side view. The distance between the large flat and the primary mirror is adjustable up to about 1 km.
Figure 7: Beamsplitting and spectrometer concept. The actual mirrors and beamsplitters are omitted from the drawing, which shows only the ray paths. Three beams come down from the telescopes above. Each is split into two parts at the first vertex, a transmitted beam continuing downwards and the other reflected sideways. The transmitted beam strikes a reflector and also goes sideways. Each beam is then sent to one of six Cat’s Eye retroreflectors. The Cat’s Eye is a concave reflector with a secondary mirror that returns the beam parallel to itself and sends it towards a beam combiner. In this figure, each “W” in the ray path represents a Cat’s Eye. At the beam combiner in the middle of each side of the triangle, one beam is reflected downward and then passes to a beamsplitter, while the other beam goes directly to the beamsplitter.
a wavelength of 0.5 µm, the HST mirror is 4.8 million wavelengths across. For the same angular resolution at 200 µm, the mirrors need to be 960 meters apart. This is clearly impossible with a rigid physical structure in space, but it could be achieved with formation flying. The technology to do this will be demonstrated with the DS-3, a New Millennium program mission scheduled for launch in 2002. The DS-3 is intended to achieve much higher positional accuracy and stability than are required for a far IR interferometer. Because the remote mirrors must be propelled in a pattern, it is desirable that their masses should be as low as possible. For this level of accuracy, it may be that a stretched membrane on a hoop could be made flat enough and controlled well enough with electrostatic forces. In any case the spacecraft engineering challenge is significant.

The minimum spectral resolution needed is governed by the number of pixels into which each point source may be resolved (i.e., the ratio of the primary beam diameter to that of the synthesized beam). Since the synthesized beam diameter $\delta \theta$ is wavelength dependent, the wavelength must be known to a certain tolerance. For a general image, the spectral resolution should be greater than the ratio of the mirror separation to the mirror diameter.

The stroke of the Michelson interferometer retroreflectors produces interferograms that are Fourier transformed to obtain spectra of the correlation function between two apertures. The spectral resolution $R$ obtained is governed by the path difference range, which must be approximately $R \lambda$ long. In the case of the wide field interferometer described here, each individual detector pixel has its zero path difference point located at a different part of the mirror stroke, and the total path difference range needed to cover the whole field of view is $\theta b_{max}$, where $\theta$ is the width of the field and $b_{max}$ is the spacing between the remote reflectors. Although this is much longer than the stroke needed for a single detector pixel, by a factor of the number of rows or columns of detectors in each array, the array is faster than a single pixel detector in proportion to the number of rows of elements. At $R = 10^4$, $R \lambda \sim \theta b_{max}$.

The necessary orbit for such an interferometer must certainly be in deep space, far from the Earth. Otherwise, the viewing geometry relative to the Sun and Earth is so variable that good radiative cooling is impossible, and the long observing times required are not achievable.

The telescopes would each be shielded from the Sun by a radiative baffle like that developed for NGST. Additional cooling would come from an active cooler, and at least four types are currently popular: the reverse Turbo Brayton cycle; the Stirling cycle; the pulse tube; and the sorption pump cooler. These coolers could reach temperatures of the order of 4 K with some effort. The detectors will certainly need to be colder, of the order of 0.05 to 0.5 K depending on the technology chosen. The additional cooling may come from adiabatic demagnetization, as developed for ASTRO-E, or from helium-3 dilution, as developed for FIRST.

The sensitivity achievable by such a system is shown in Figure 8. The sensitivity is $\delta(\nu S_{\nu}) = NEP R / (A \epsilon t^{1/2})$, where $\delta(\nu S_{\nu})$ is the 1σ uncertainty in the brightness, $R$ is the spectral resolution $\nu / \delta \nu = \lambda / \delta \lambda$, NEP is the noise equivalent power from photon noise, $\epsilon$ is the system efficiency including a sine wave modulation factor of $1/8^{1/2}$, and $t$ is the observing time. The NEP is for a single detector and must be calculated allowing for the loss of photons
Figure 8: Sensitivity of the far-IR interferometer described in the text, both at full spectral resolution (heavy solid curve), and with spectral smoothing (heavy dashed curve). The light dashed curve represents an ultraluminous (1000 L*) starburst galaxy at redshift z=4, taking NGC 6090 as a spectral template (see Figure 1). Such a galaxy would be readily detected by the interferometer. The C$^+$ 158 μm line would be redshifted to 790 μm. The spectrum of a 15th magnitude A0 star is shown with a dotted line. Light solid lines mark flux densities of 10 μJy and 1 nJy.
on the way to the detectors. The collecting area $A$ is for the entire system, including all $m$ apertures. The subtleties about the details of beam combination are embedded in the efficiency factor. For Figure 8, we have chosen three apertures of 3 m each, an efficiency of 10%, a background limited photon noise for a 100% bandwidth and that efficiency, and an observing time of $10^5$ seconds, about 1 day. We also assumed a spatial resolution of 0.05″, which implies a maximum mirror separation and a required spectral resolution. The plot shows two curves, one with the full spectral resolution, and one with the spectra smoothed to give a wide band image and gain a factor of $R^{1/2}$ in sensitivity. The sensitivity is easily adequate to reach the brightness of a high-z galaxy, and to resolve such a galaxy into much fainter sub-units.

At 450 μm, where Noise Equivalent Flux Density data are readily available (Hughes and Dunlop 1997), the sensitivity of SPECS would exceed that of the other major submillimeter facilities by factors of 50 (FIRST and the South Pole 10 m telescope), 150 (MMA), 200 (SOFIA), 700 (JCMT), or more.

We note that a smaller version of the SPECS could still have high enough sensitivity to match the Hubble Space Telescope if the detector NEP can be improved. This could be feasible with new technology detectors combined with dispersive spectrometers to limit the photon noise on each one.

5.3 Technology Requirements

Many items need to be developed to bring SPECS to fruition. Clearly an engineering study with a complete performance simulation is needed to define the detailed configuration. The major technology developments needed are: high sensitivity, large format arrays of detectors; cold, lightweight mirrors for the telescopes and remote reflectors; formation flying with tethers; position measurement for the multiple spacecraft; active coolers for telescopes and detectors; and a smooth, long-stroke mirror scanning mechanism. There are many design choices to consider as well. Narrow band filters can reduce the spectral bandwidth and the detector noise. Dispersive spectrometers with large detector arrays could be combined with the imaging Michelson spectrometer to obtain improved sensitivity. There is no guarantee that the suggested optical configuration is close to optimal.

There is also little practical experience with image reconstruction from far IR detectors and spectral-spatial interferometers like SPECS. Simple laboratory tests should be done to
wring out the problems in the analysis algorithms; those in use at the NRAO took decades of development, and although our requirements are similar, they are not identical.

We anticipate that the new generation of detectors will be some kind of superconducting device, either a superconducting transition edge (TES) bolometer with a multiplexed SQUID readout, or a superconducting junction, with photons converted to quasiparticles that can be collected and moved to the input of a single electron transistor. For the junction detectors, the following problems need to be addressed: finding efficient devices for collecting and converting photons to quasiparticles; transporting the quasiparticles to the amplifiers; running the amplifiers (current designs require RF excitation); multiplexing the detectors and electronics to enable large arrays; and building on-chip integrated circuitry. It is possible that an improved TES bolometer array will prove the best choice. In that case, developments to anticipate include: large format arrays, on-chip readout electronics using superconducting thermometers and SQUID readouts, and on-chip multiplexing electronics.

5.4 The Road Leading to SPECS

If a concerted effort is made to advance and test the required technologies (Table 3) during the next decade, it will be possible to build the SPECS observatory in about 15 years. A number of relevant efforts already underway (e.g., the DS-3 mission to test formation flying) require sustained support. Funding for efforts that require long lead times, such as advanced array detector and lightweight cryogenic optical system development, should be augmented as soon as possible. The investment needed to make the detectors a convenient and affordable reality is vital to the future of this subject. Early support will also be required for SPECS tradeoff and design studies.

A likely outcome of an evaluation of cost and risk is the recommendation to fly one or more “precursor” missions. The primary purpose of such missions would be to advance the technical frontiers in sensible increments toward the ultimate goal, SPECS. However, these missions would have potential scientific benefits as well. For example, a mission to test the detectors and cryo-coolers might conduct an unprecedented all-sky, confusion limited far IR/submillimeter survey. A dispersive spectrometer with a detector array could provide simultaneous spectra. A smaller version of the SPECS, say with 1 m mirrors, would still be remarkably sensitive, particularly if the photon counting detector arrays work out well and dispersive spectrometers are used to reduce the photon noise on each detector.

Also, the US should pursue relevant opportunities to partner with other nations. Japanese IR astronomers (Matsumoto and Okuda) have expressed interest in contributions to their H2L2 mission (see §4). The US could contribute, for example, improved detectors and a scanning Michelson interferometer, which could be used to conduct a deep spectroscopic survey at $R \sim 10^3$ (i.e., enough to reach the linewidths of typical galaxies). While this survey would still be confusion limited, objects at different redshifts could be distinguished by their spectral lines.

Any opportunity that arises to test technologies applicable to SPECS on a precursor mission required for NGST should also be exploited if it is deemed cost-effective.
6 Summary and Recommendations

A space-based far infrared/submillimeter imaging interferometer is needed to answer some of the most fundamental cosmological questions, those concerning the development of structure in the universe (§1). Such an instrument would be complementary to the already-planned Next Generation Space Telescope and the ground-based Millimeter Array (§2); it would allow access to a large number of important cooling and diagnostic spectral lines from ions, atoms, and molecules, and to the bulk of the thermal emission from dust clouds (§3). In light of recent technology developments, especially the possibility of background limited photon counting detectors in the far infrared, it is now practical to consider building the interferometer (§§4 and 5.2). The authors recommend that we set our sights on this goal and, over the course of the next decade, design, build and test the technology (§5.3) that will be needed to deploy a Submillimeter Probe of the Evolution of Cosmic Structure.

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Web site for SPECS:
http://www.gsfc.nasa.gov/astro/specs