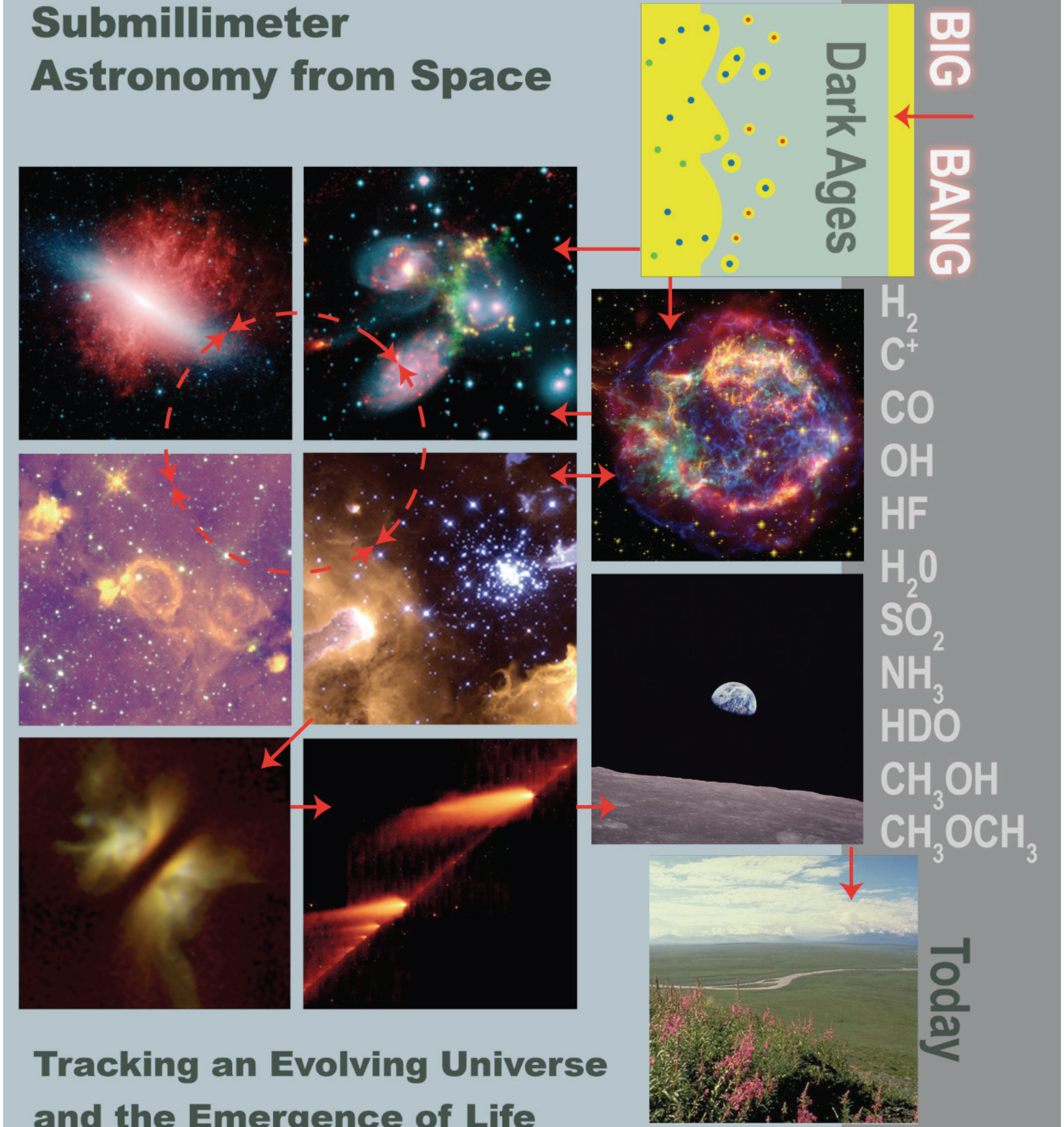
Far-Infrared / Submillimeter Astronomy from Space



Tracking an Evolving Universe and the Emergence of Life

Recommendations for The Astronomy & Astrophysics Decadal Survey of 2010

Far-Infrared/Submillimeter Astronomy from Space

Tracking an Evolving Universe and the Emergence of Life

A White Paper and Set of Recommendations for

The Astronomy & Astrophysics Decadal Survey of 2010

This white paper was conceived at a workshop on Far-Infrared /Submillimeter Astronomy from Space held in Pasadena, CA, May 28 – 30, 2008. A Special Session held at the January 2009 AAS meetings provided additional recommendations from the wider astronomical community. The individuals listed below were contributors to the 2008 workshop or are FIR/SMM astronomers who helped to formulate a program intended to reflect our community's consensus plans and priorities for the years ahead.

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Cover Plate: A brief history of the Cosmos: Baryons cycle into and out of clusters, galaxies, the interstellar medium, stars, and planetary systems. Where, when, and how did chemical abundances and complexity arise to generate life?

Far-Infrared/Submillimeter Astronomy from Space

Tracking an Evolving Universe and the Emergence of Life

Executive Summary

We outline a program to trace the dynamic and chemical evolution of the Cosmos that led to the emergence of life. Our two-part plan takes advantage of an exciting near-term opportunity, while laying the groundwork for future progress.

1. The US has an unparalleled opportunity to participate in the Japanese-led Great-Observatories-class mission, SPICA, to be launched in 2017. SPICA will have a cryogenically cooled 3.5-m telescope and thus unsurpassed Far-Infrared/Submillimeter sensitivity. The astronomical insights enabled by a highly sensitive, background-limited spectrometer on this mission will profoundly affect our understanding of cosmic evolution. US participation, at a fraction of the SPICA mission total cost, is also a logical step toward two other more advanced missions, previously recognized in the 2000 Decadal Review.(40)

2. We propose a dedicated effort, during 2010 – 2020, to advance several technologies essential to these two other powerful next-generation missions to be launched between 2020 and 2035. The 10-m class cryogenically-cooled Single Aperture Far Infrared Telescope, SAFIR, and a Michelson spatial interferometer, both of which are natural successors to SPICA and all other ongoing efforts, will probe the Universe to greater distances and earlier epochs, with far higher sensitivity and spatial resolution than ever possible before.

With these two steps, we will be able to begin answering many long-standing questions:

- What is the chemical history of the Universe? Does it mirror the energy generation history?
- How did chemical evolution affect quasar, galaxy, star and planet formation over the eons?
- Where and when did life originate?

The Far-Infrared spectral regime is the repository of half the electromagnetic energy released in the evolution of stars and galaxies. Properly read, this stream of radiation will reveal great episodes in the history of the Cosmos:

- How and when the first heavy elements formed at redshifts $z > 10$ will be conveyed through the far-infrared/submillimeter atomic and ionic fine-structure transitions that identify them.
- How and where the great surges in star formation occurred will be discerned in deep spectro-photometric surveys with exquisitely sensitive detectors and high spatial resolution.
- The dynamic processes at play in dust-shrouded star and planet formation will reveal themselves in the spectra of atomic or molecular coolants promoting gravitational collapse.
- The origins of life beyond the Solar System may become apparent through the infrared, submillimeter, and radio signatures of molecules that served as biogenic precursors.

The Far-Infrared/Submillimeter space efforts we propose will permit us to pursue these goals.[*]

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[*] If approved, we expect any of the missions proposed in this white paper to be competitively considered by NASA.

1. A Decade of Past Achievements: A Decadal Vision of Future Prospects

1a. A Decade of Achievements

The past fifteen years have revolutionized our understanding of the Universe we inhabit. Using the Infrared Space Observatory (ISO) and the Spitzer Space Telescope (Spitzer), we:

- Detected massive galaxies undergoing rapid enrichment of chemical elements as early as redshift z ~ 5–7, corresponding to the first billion years in the existence of the Cosmos;(1)
- Discerned the striking evolution of galaxies and their energetics over the past 8-10 Gyr, and clarified the relation between starbursts, active galactic nuclei, and galaxy mergers;
- Accounted for roughly ¾ of the cosmic infrared background radiation at wavelengths as long as 160 μm through number counts of extragalactic sources;
- Unveiled giant intergalactic shocks radiating almost solely in H_2 emission lines and X-rays, with luminosities as high as $L_{H2} \sim 8 \times 10^{41}$ erg s^{-1};
- Peered into dust-shrouded molecular clouds to locate myriad protostars and distinguish their evolution in isolation or as influenced by more massive, more luminous neighbors;
- Together with the Submillimeter Wave Astronomy Satellite, SWAS, established the ubiquitous presence of water vapor and clarified the roles that H_2O and other chemical constituents play in the formation of giant molecular clouds, in the collapse of their cores to form stars, in the evolution of planet-forming disks, and in the formation of planets;
- Obtained the first evidence for water vapor in the atmosphere of an extrasolar planet, suggesting the existence an abundance of planets potentially capable of sustaining life;
- Tallied the distribution of Solar System minor planets, whose existence in such large numbers had not been anticipated, and measured their albedos and diameters; and
- Followed the fragments of a comet, ten years after its initial break-up, to trace the subsequent evolution of its many components; a similar break-up of planetesimals is believed to play a significant role in the evolution of planet-forming disks.

All these and many other striking advances were made possible by the exceptional sensitivity afforded by cryogenically cooled telescopes, with surprisingly small apertures by modern standards --- 60 cm on ISO and 85 cm on Spitzer! However, none of these discoveries would have been fully assimilated into the astrophysical landscape were it not for additional observations obtained with radio, visual, X-ray and gamma-ray telescopes.

This second factor reflects a major development of the past decade: The joint efforts of the Great Observatories family of telescopes, have convincingly demonstrated that important gains are made when complex astrophysical phenomena are investigated with powerful telescopes spanning the entire electromagnetic spectrum. Figure 1 provides an example of this synergy.

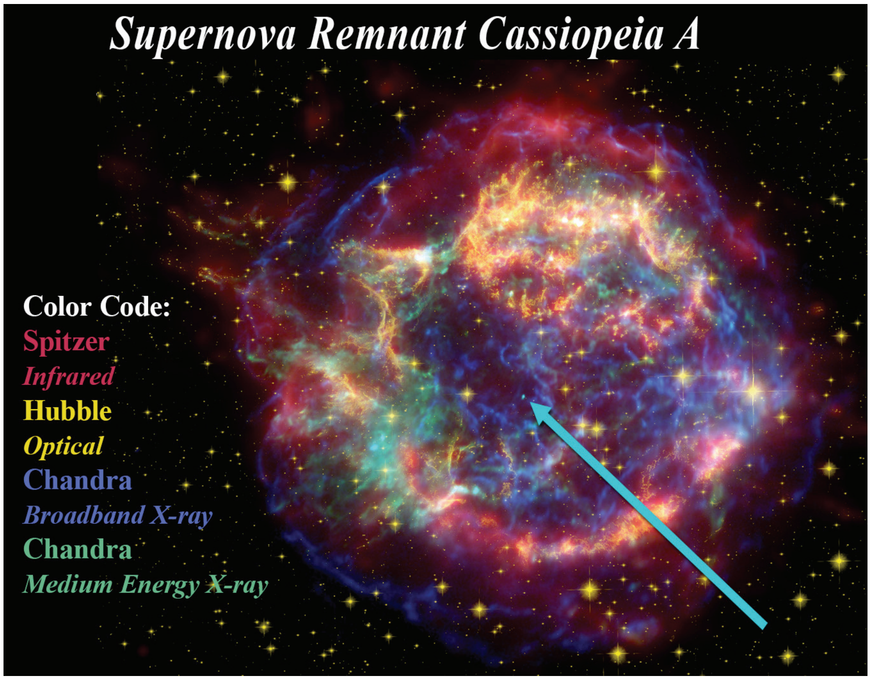

Figure 1. The synergy of observations conducted over the widest possible spectral energy domain: The Supernova remnant Cassiopeia A is shown as imaged with three of the Great Observatories. Regions imaged in blue were obtained with Chandra's broadband detectors covering low to high X-ray energies; regions shown in green are Chandra observations at intermediate X-ray energies. The HST observations recorded in yellow were obtained at 9000 Å. The HST and Chandra emission, respectively, trace shocked gas at ~10^4 *and* 10^7 *K as the outflow impinges on surrounding gas. Spitzer data shown in red were acquired at 24 μm and trace radiation from an outer shell of cooler dust and gas. The small turquoise dot at the center indicated by the arrow is the remnant's pulsar. The infrared radiation appears to be due to a light echo from a relatively recent outburst by a central remnant magnetar.*(3)

1b. A Vision of Future Prospects

Drawing from the consequences of these two factors --- the ability of cryogenically cooled infrared observatories to provide major new insights, and the deeper understanding that results from observations covering the widest ranges of the electromagnetic spectrum --- we conclude that a clear and urgent strategy for astronomy today is to pursue a two-pronged Far-Infrared/Submillimeter, FIR/SMM, instrumental program: (i) to enhance observational capabilities along lines that have led to great success in the recent past and are critical to future progress; (ii) to bring FIR/SMM instrumental capabilities to a level where our ability to study the sky is roughly balanced across the whole electromagnetic spectrum, and a successful strategy of gaining insight through comprehensive multi-wavelength observations can be pursued. Both of these strategies lead to identical requirements --- the construction of cryogenically cooled telescopes with background limited sensitivities and similarly cooled interferometers in space to provide improved maps with high spatial and spectral resolution.

1c. The Major Astronomical Questions We Expect to Investigate

Three major classes of astronomical questions speak to the importance of bringing FIR/SMM capabilities up to a level available in other wavelength bands:

1. *Evolution of Galaxies from Early Times to the Present:* Half of the electromagnetic energy emitted by stars and galaxies now is observable solely in the far-infrared. In the local Universe, this is largely due to the dusty regions that permeate and shroud most luminous regions. At great distances across the Cosmos, a competing effect is the systematic redshift of radiation to ever longer wavelengths. How much of this energy was injected at different epochs and redshifts? How does this correspond to the increasing abundance of heavy chemical elements? Molecular hydrogen appears to have been the prime coolant in the birth and explosive death of the first massive stars at redshifts $z > 15$. At later epochs, atomic fine-structure, molecular line, and dust radiation dominated cooling. But we do not yet know when these different cooling phases set in. FIR/SMM observations may well be the sole means for identifying when these changes set in.(3)

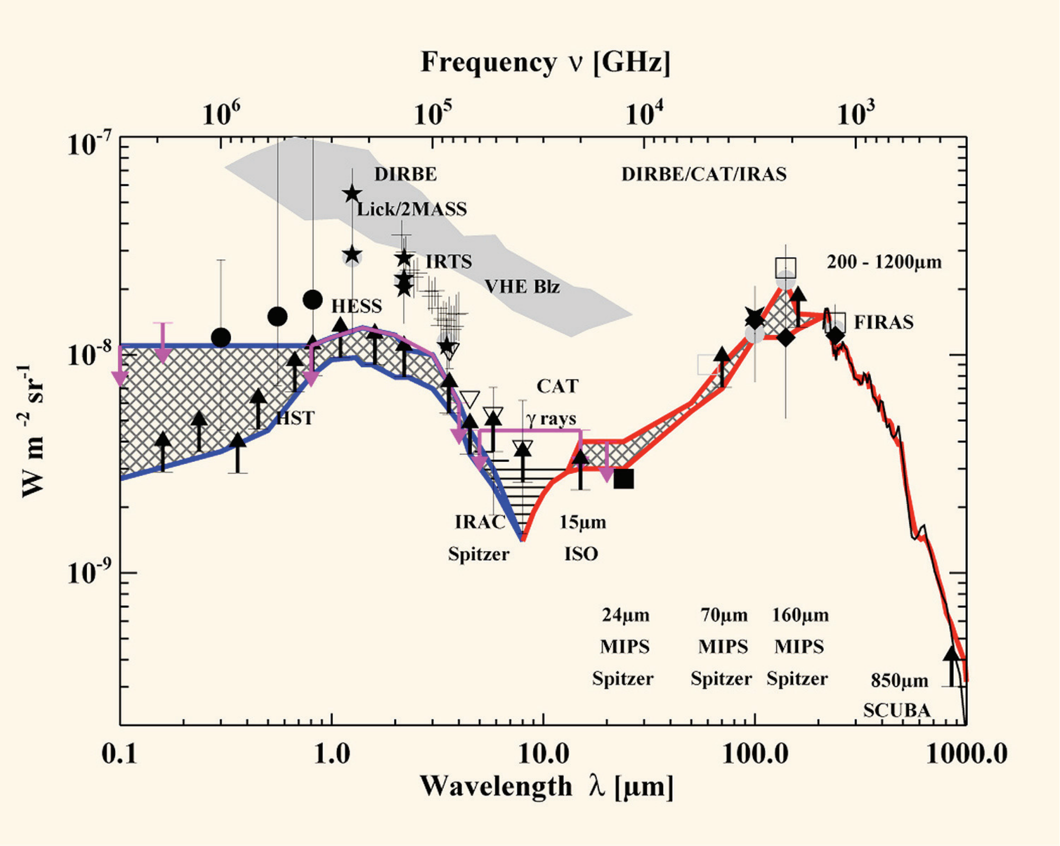

Figure 2. Roughly half of the electromagnetic energy emitted in the Universe since the formation of stars and galaxies resides in the FIR/SMM spectral range, as indicated by the spectral energy distribution, λF(λ), of the cosmic infrared background radiation. Black arrows represent lower limits. Purple arrows and lines are current upper limits. Intermediate background radiation levels are indicated by the crosshatched areas. A variety of older upper limits derived from various sources are also shown.(4)

2. *The Obscured Universe: Dust –Shrouded AGN Tori and the Formation of Stars and Planets:* Our current understanding of Active Galactic Nuclei, AGNs, shrouded by massive tori of gas and dust is hampered by an inability to directly view the central engine that powers these nuclei. FIR/SMM spectroscopy with sub-arcsecond angular resolution is needed to obtain a clear view of the processes at work. Similarly, in today's Universe, stars and planetary systems begin their lives in densely obscured cores of giant molecular clouds. To understand how the stars and their planet-forming disks originate, we must penetrate these clouds. Only FIR/SMM wavelengths meet this challenge; shorter wavelength radiation lacks the penetrating power. We still lack detailed insight on how the dynamics of protostellar collapse affects ambient chemistry, and the extent to which the changing chemical constituents, in turn, promote or hinder cooling and further collapse. Insight on these and other heavily obscured processes will be gained only through FIR/SMM observations made at high spatial and spectral resolution and high sensitivity.

3. *The Chemical Evolution of the Universe --- The Origins of Biogenic Molecules:* To trace the onset of life in the Universe, arguably one of the most ambitious but potentially also one of the most rewarding programs astronomy is on the threshold of pursuing, we need to understand the chemical evolution of the Cosmos and build-up of the molecular components that enabled life to spring up on our planet and perhaps elsewhere as well. We will need to establish a comprehensive program, concentrated on observations in the mid-infrared, FIR/SMM, and millimeter wavelength ranges, where molecular radicals, molecules, and macromolecules can be spectroscopically identified. Within the inner regions of forming planetary systems, FIR/SMM efforts will help us establish the conditions and define the environment that may have led to the formation of life. The study of meteorites shows that amino acids and other sizeable molecules formed early in the history of the Solar System. But we will need to study nascent planetary systems around other stars to determine how and where these molecules first formed. Ultraviolet radiation tends to destroy macromolecules. Evidence for the existence of biogenic molecules, and insight on how life may have originated beyond the Solar System, is thus likely to emerge from observation of dust-shrouded regions accessible only through observations in which FIR/SMM and radio spectroscopy will play an essential role.

Well over a hundred large molecules and their isotopologues have by now been identified through centimeter, millimeter and submillimeter spectroscopy from the ground. The recent millimeter-wave discovery of the sugar glycolaldehyde, CH_2OHCHO, in the dusty hot core of a molecular cloud within $\sim 10^4$ AU of a protostar, is particularly important. Glycolaldehyde combines with the similarly-sized molecule propenal, CH_2CHCHO, to form ribose, a central constituent of ribonucleic acid, RNA, linked to the origin of life.(5)

ISO and SWAS provided insight on the ubiquity of water, and the presence of many radicals that form the building blocks of larger molecules. In the mid-infrared, polycyclic aromatic hydrocarbons (PAHs) have been identified by Spitzer in planet-forming disks, star-forming cores in the Milky Way, in powerful starbursts in the nuclei of distant galaxies, and in a host of other astrophysical environs. The Heterodyne Instrument (HIFI) on Herschel, the ESA/NASA FIR/SMM mission to be launched in 2009, will provide a new view of the chemical makeup of sources across its operational wavelength range from 157 to 625 μm, and the Atacama Large

Millimeter Array, ALMA, will have superb angular resolution for studying the spatial distribution of some of these molecules. Until SPICA is launched, the Stratospheric Observatory for Infrared Astronomy, SOFIA, will be the sole observatory carrying out spectroscopic observations in the 27 – 60 µm spectral range. By flying out of airports distributed across the globe, SOFIA will also be able to observe eclipses, explosions, and other rare phenomena at times of peak interest that Herschel and other space observatories might be unable to pursue because of time-dependent sun-angle avoidance and other constraints that do not apply to SOFIA. After Herschel ceases operations, around 2014, SOFIA will still provide high spectral resolution FIR/SMM data with its heterodyne instruments.

The James Webb Space Telescope, JWST, will excel at many tasks. Among many other projects, JWST will seek to trace the history of biogenic molecules by studying the molecular constituents of planet-forming disks and detecting PAHs out to redshifts ~3, beyond which their strongest spectral features at ≥ 6.2 µm successively shift out of the JWST spectral range, to be picked up at greater redshifts by Herschel and the Space Infrared telescope for Cosmology and Astrophysics, SPICA, a Japanese-led international mission expected to be launched in 2017. Among all these cited FIR/SMM facilities only SPICA will have a sensitivity matching that of JWST and ALMA!

1d. Currently Available Sensitivity

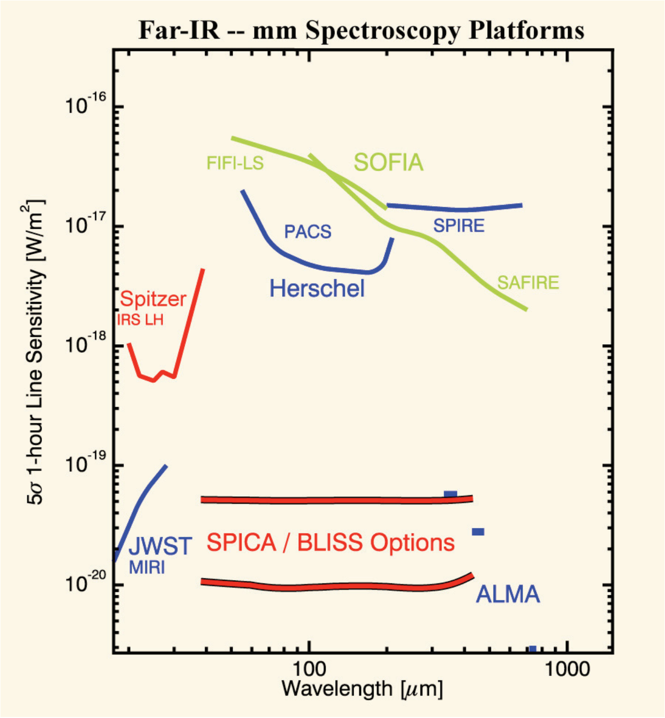

Figure 3. The sensitivities of currently-planned or active FIR/SMM spectroscopic facilities emphasize the great gains possible with the fully cooled 3.5m SPICA optics combined with sensitive detector arrays. Smaller values represent more sensitive measurements. Figure 19 on page 30 shows gains achievable in extragalactic astronomy. The three small rectangles on the lower right indicate the sensitivity of the ground-based Atacama Large Millimeter Array, ALMA.

As Figure 3 shows, JWST, operating at wavelengths below ~27 µm, and ALMA, operating through a number of submillimeter atmospheric windows as well as beyond ~650 µm, will have sensitivities at least 100 times higher than Herschel spanning the intervening 60 - 650 µm wavelength range. Herschel, ALMA, SOFIA and JWST, all are currently scheduled to start operations within the next few years. Ideally the results obtained with them should dovetail, but the disparity in sensitivity will make it difficult to directly compare their findings for faint sources like those at high redshifts. Only SPICA will provide the requisite two-to-three orders of magnitude increase in sensitivity that will bring FIR/SMM sensitivity into line with those of JWST and ALMA.

The lower curve shown in Figure 3, for a Background Limited Infrared/Submillimeter Spectrometer, BLISS, approaches the fundamental sensitivity limits of a spectrometer on a cold telescope, determined by photon noise from zodiacal and Galactic dust emission. The new discoveries to be made with SPICA and the synergies to be achieved with JWST and ALMA are staggering, as detailed in Section 3, below.

Thus, the highest priority for the US FIR/SMM community in the decade of 2010 – 2020 is significant participation in the Japanese-led SPICA mission, through contribution of a FIR/SMM spectrometer with a highly sensitive background-limited detector array, to enable a scientific program of astronomical investigations at compatible sensitivities over the entire spectral range from the near infrared out to the millimeter regime with JWST, SPICA and ALMA. The US contribution to SPICA should be coupled to meaningful support for the US scientific community to access and exploit the mission's scientific data.

1e. Currently Available Spatial Resolution

Investigations of cosmic chemical evolution and the origins of biogenic molecules, will ultimately require not only dramatic advances in sensitivity, but also significantly improved FIR/SMM angular resolving power, as urgently as increased sensitivity. But this improvement calls for greater investments and thus longer-term planning: None of the space observatories built to date have had apertures significantly exceeding 1 meter. As a result, ISO and Spitzer have offered a diffraction-limited angular resolving power at 160 – 200 µm, of the order of an arcminute. This is comparable to the resolution that Tycho Brahe attained, at visible frequencies with the naked eye, more than four centuries ago. Herschel and SOFIA, with respective apertures of 3.5 and 2.5 m, will provide an angular resolution comparable to that made possible at visible wavelengths by Galileo's spyglass --- fortuitously on the four hundredth anniversary of his momentous discoveries of 1609. The highly productive, 15-m-aperture James Clerk Maxwell Telescope operating at wavelengths around 1 mm, has a comparable angular resolving power. The sensitive 40-cm aperture Wide-Field Infrared Survey Explorer (WISE) to be launched in 2009, an all-sky-mapping observatory preparing the way for JWST, will have a similarly limited angular resolution at its longest wavelengths ~ 23 µm. In contrast X-ray, visual, and radio telescopes or interferometers provide respective angular resolving powers in the sub-arcsecond, milli-arcsecond, and micro-arcsecond ranges. To overcome this disparity, a longer-term FIR/SMM program needs to be pursued.

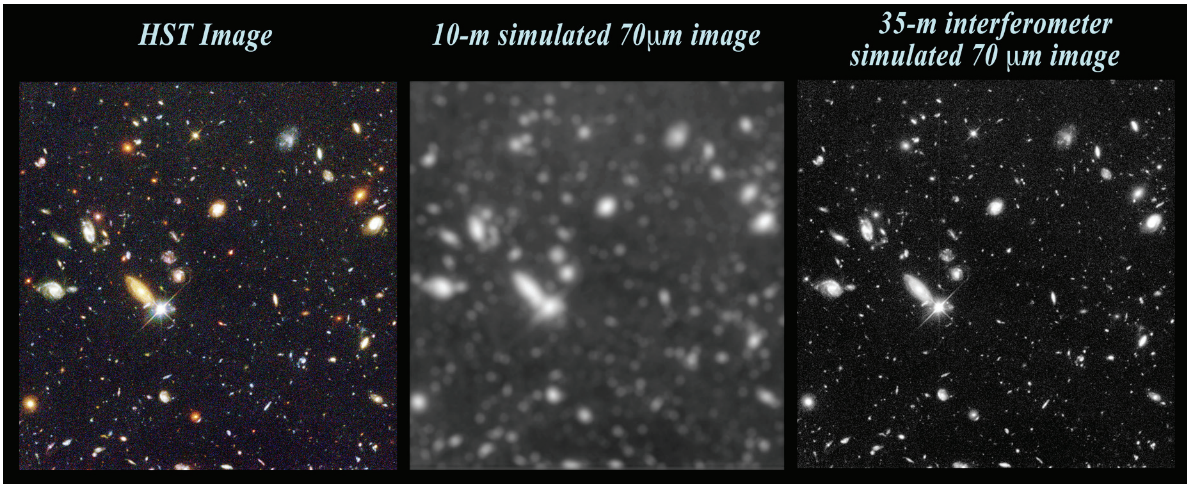

Figure 4. The urgent need for improving the spatial resolving power and image quality of far-infrared observatories. Studying star formation in distant galaxies at FIR/SMM wavelengths is hampered both by limited angular resolution and limited light-gathering power. Shown are a portion of the Hubble Deep Field as resolved by HST (left); a simulated image that a 10-m aperture telescope will provide at 70 µm (center); and the simulated image a 35-meter-baseline spatial interferometer will produce at 70 µm (right). (Courtesy of George Rieke).

We need to implement a program of sensitive spectroscopic observations capable of resolving small scale cosmic structure across the entire electromagnetic spectrum. This will require both the light-gathering power of a 10-m class cryogenically cooled telescope in space and a similarly cooled FIR/SMM spatial interferometer with angular resolving power matching that of JWST around 25 µm and ALMA at submillimeter wavelengths. Both the Single Aperture Far-Infrared Telescope (SAFIR) and a space-based infrared interferometer (currently exemplified by the SPIRIT mission concept) received recognition in the 2000 Decadal Review and will satisfy these requirements.[†]

To construct these two observatories in the era of 2020-2035, we propose (i) to prepare the technical prerequisites in the 2010 – 2020 decade and (ii) to conduct phase-A studies of both SAFIR and SPIRIT before the end of the decade, to provide the 2020 Decadal Review with a strong recommendation on which of these two missions has greater immediate astronomical promise and higher readiness for early launch in the 2020 – 2035 era.

It is important to emphasize that both an interferometer and a large filled aperture will ultimately be required. A large filled aperture can never have the angular resolution of a spatial interferometer with a larger baseline. But an interferometer with a smaller light collecting area will be more limited in sensitivity.

[†] The Year 2000 Decadal Report states, "A rational coordinated program for space optical and infrared astronomy would build on the experience gained with NGST to construct SAFIR, and then ultimately, in the decade 2010 to 2020, build on the SAFIR,TPF, and SIM experience to assemble a space-based, far-infrared interferometer." (40)

We know from past experience that order-of-magnitude advances in both sensitivity and improved angular resolving power have predictably led to new discoveries at all wavelengths. The prospects of similar gains in the FIR/SMM spectral range, where so much has already been achieved with merely 1-meter-class telescopes, are tantalizing.

2. SPICA: An Unparalleled Opportunity to Advance Far-Infrared Astronomy

2a. A Brief Description of SPICA

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a 3.5-meter telescope actively cooled to below 5 K. The Japanese Aerospace Exploration Agency (JAXA) plans to launch SPICA into an Earth-Sun Lagrangian-point L2 orbit in 2017. By the time SPICA is launched, both the Spitzer and Herschel missions will have run their course determined by the lifetime of their respective liquid helium charges.

Over nearly a decade of studies, planning for the SPICA project has reached a high level of maturity through extended series of component level tests in the laboratory. As part of this effort, JAXA has invested heavily over the past 5 years to develop and verify closed-cycle 4-K and 2-K cryocoolers to enable the 5-year primary SPICA mission. Further experience has been gained with the agency's FIR/SMM all-sky cryogenically cooled Akari survey launched in February 2006.

In addition to JAXA, the European Space Agency (ESA) and Korean astronomers also are involved in the construction of SPICA. JAXA has recently embarked on a pre-phase-A study of SPICA and its mid-IR coronagraph and imaging spectrometer, jointly conceived with the Korea Astronomy and Space Science Institute (KASI).

A unique capability on SPICA will be the mid-IR camera and high-resolution spectrometer operating in the 5 – 38 μm range. This instrument also comprises a long-slit grating spectrometer with an integral field unit and a high spectral resolving power, R ~ 30,000 or ~ 10 km s^{-1}, an order of magnitude higher than available on JWST. Although SPICA's aperture is smaller than JWST's its cryogenically cooled primary provides a sensitivity comparable to that of JWST, i.e. ~ 1 μJy (5σ- 1hr) in photometric mode, albeit with angular resolving power a factor of ~2 lower. SPICA will thus complement JWST in reaching out to longer wavelengths, at higher spectral resolution.

ESA is providing the 3.5 meter telescope that JAXA will actively cool to cryogenic temperatures. Concurrently, European scientists are studying an imaging FIR Fourier-transform spectrometer for the mission, the Spectrometer for Astronomy in the Far Infrared (SAFARI).

The current complement of SPICA instruments lacks a highly sensitive FIR/SMM spectrometer for extragalactic research at high redshifts with spectral resolving power R ~ 1,000. A US contribution is compelling because the planned FIR/SMM spectrometer will require highly sensitive, far- IR-submillimeter detector arrays for which the US is the world leader and is thus best poised to make this astronomically important contribution. Our aim is to build BLISS to operate in the spectral range of ~ 30 – 430 μm separating JWST and ALMA, and capable of conducting a broad program of cosmological investigations. If this thrust is approved, we expect that NASA will widely compete implementation of a spectrometer of the type BLISS represents.

With its matched family of instruments, the SPICA mission will advance astronomy along lines of broad current interest. The combination of SPICA's cryogenically cooled telescope and highly sensitive U.S. detectors promises a 2-orders of magnitude increase in sensitivity and 4 orders-of magnitude-improvement in speed over any other planned facilities for spectroscopy.

Table 1. The SPICA Instrument Suite --- A Set of Matched Capabilities

Instrument	Contributor	Description/Capabilities
Mid-IR Imager/ Spectrometer	JAXA/KASI	4 channels from 5 to 38 μm. 1k x 1k Si:As and Si:Sb arrays. Imaging and R~200 grism spectroscopy with 100-400 arcsec field of view. Spectroscopy mode:long slit, R=3,000 at 20-30 μm, R=30,000 at 5-15 μm. Tip-tilt mirror shared with coronagraph.
Mid-IR Coronagraph	JAXA/KASI	5-27 μm core range, contrast > 10^5. Inner working angle 2-5 λ/D. Outer working angle, 10-30 λ/D.
SAFARI	European national agencies	30-200 μm imaging Fourier-transform spectrometer (IFTS), 2'x2' FOV. R variable from 10 to few x 1000. Detectors TBD Ge photoconductors or bolometers. Ref: Swinyard et al. 2008
BLISS	NASA	Grating spectrometer optimized for rapid spectral surveys. Sensitive bolometers at 50 mK. Range: 38-433 μm.

Notes: JAXA = Japanese Aerospace Exploration Agency / KASI = Korea Astronomy and Space Science Institute

BLISS will provide the first FIR/SMM capability for routine spectroscopy of galaxies at redshifts z > 2, where many galaxies reach their highest luminosities. A NASA contribution of BLISS to SPICA will provide U.S. scientists access to the full capabilities of this flagship-class observatory at a fraction of the mission's full cost. Because SPICA will be entirely cooled by cryo-motors its lifetime will not be limited by expendables and may well extend beyond a nominal 5 years. During this time, SPICA will be the only FIR/SMM facility spanning the wavelength range separating JWST and ALMA and operating at comparable sensitivity.

2b. The SPICA Timeline

Following proposal submission in September 2007, JAXA conducted a primarily scientific Mission Definition Review of SPICA, leading to approval in March 2008. This was followed by a management-oriented Project Preparation Review which, in turn, led to approval by the board of directors at JAXA/HQ, on July 8, 2008. With this last step, SPICA entered a "pre-project phase", roughly corresponding to a NASA Phase-A phase, as of July 8. This phase comprises two stages, a "concept design" and a "system definition" stage. At the end of the concept design phase, which will define requirements for the entire system specified in the Mission Definition Review, a System Requirements Review will take place, most likely in the second half of 2009. This is expected to be followed in early 2011 by a System Definition Review, following which a further Project Go/No-go review --- a management review --- is anticipated in 2011 to determine whether SPICA is ready to graduate to phase-B and subsequent stages. Successful completion of these steps is expected to lead to the launch of SPICA in 2017.

In 2003, NASA commissioned JPL to conduct an Origins Probe concept study of BLISS. As part of this effort, the U.S. study team worked with colleagues in Japan to specify the instrument and define clean, readily implemented interfaces. Close relations at the working level have since then assured a common understanding of what BLISS on SPICA will be able to achieve, and the steps required to move ahead.

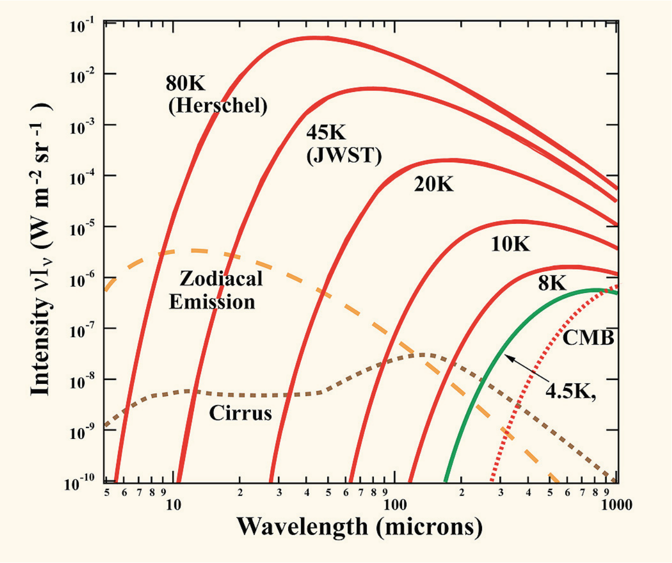

Figure 5. Sensitivity limitations due to telescope and background temperatures. In the FIR/SMM range, cooling a telescope to 4.5 K (green curve) suffices to limit astronomical observations by natural backgrounds due to zodiacal cloud emission (long dashes), Galactic cirrus (short dashes), and the cosmic microwave background (fine dots) (Courtesy, Dr. Takao Nakagawa).

2c. The SPICA Vision and its Prospects for Science

SPICA's large, cold aperture combined with BLISS will directly address two of the four targeted questions in NASA's 2007 Science Plan: “How do Planets, Stars, Galaxies and Cosmic Structures Come Into Being?” and “When and How Did the Elements of Life in the Universe Arise?” JAXA's key study areas for SPICA are similar to NASA’s: “1) The birth and evolution of galaxies, 2) the chemical evolution of the Universe, and 3) the birth and evolution of stars and planets.” This agreement on fundamental aims bodes well for close international collaboration.

Participation on the SPICA mission, to be launched around 2017, after both Spitzer and Herschel will have ceased operation, will provide the US far-infrared community access to the powerful capabilities of a world-class space observatory in return for a single contributed instrument. Participation on SPICA is also a logical preparatory step leading to the two larger missions we propose for the era beyond 2020. The current schedule in Japan is extremely tight. To keep US options open, NASA should soon initiate steps for potential US participation, while awaiting the recommendations of the Decadal Review.

3. Cosmic Evolution, Planetary Systems & Origins of Life: Three Science Goals

3a. The New Challenges

In this section, we will enumerate a wide range of problems that FIR/SMM astronomy will tackle in the decade ahead. Not all of them will be fully solved with Herschel, or SPICA. Some will have to await the higher sensitivities and angular resolving powers of SAFIR and SPIRIT later on. But the sheer variety and number of these topics should provide an indication of the excitement and sense of expectation that the observatories we propose to build have raised. Whether one's priorities are to better understand the Universe, to know how planetary systems come into being, to learn how and where life originated, the instrumentation onboard the missions we propose to launch will yield rich rewards. This is what the present section is hoping to demonstrate. We begin with the birth of the Universe and work ourselves on to the present.

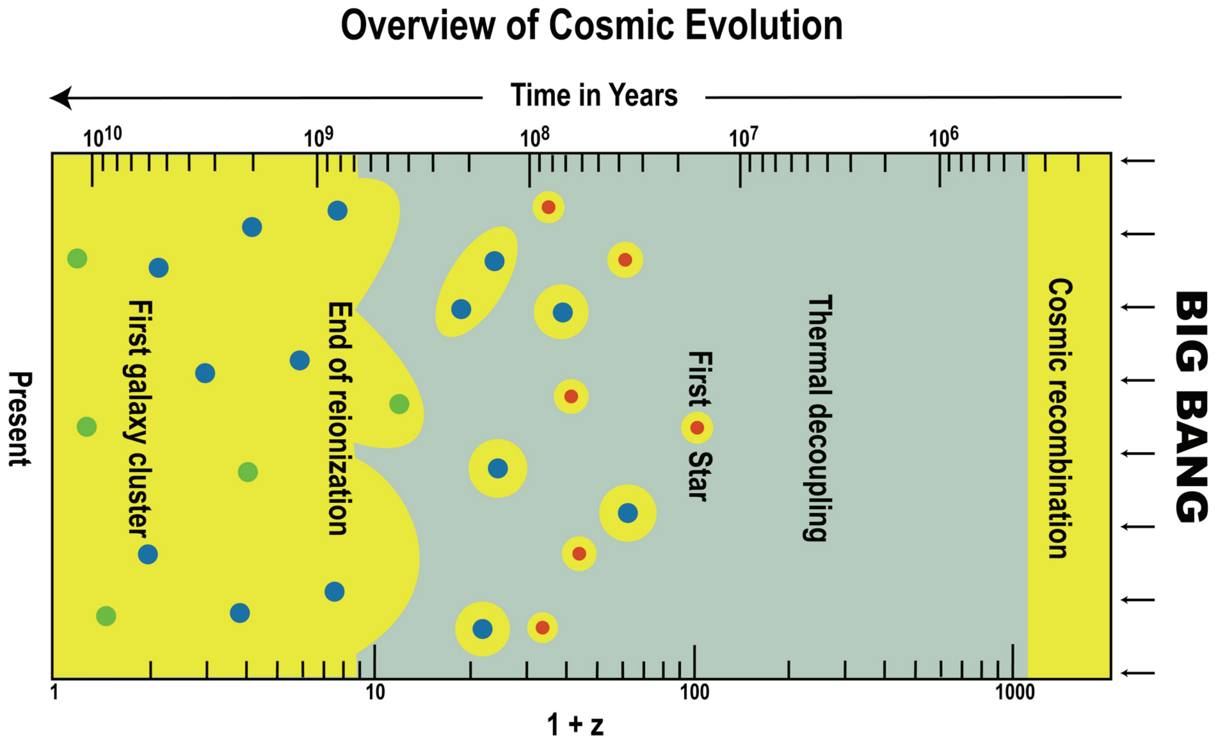

Figure 6. Evolution proceeds from right to left. Following recombination, the Dark Ages stretch from z ~1,000 to ~100. The first Population III stars are currently believed to have formed around redshift z ~ 20, or even earlier. Yellow is the region where most of the hydrogen is ionized. Dark matter concentrations shown in red, blue and green, respectively, denote concentrations with sizes 0.1, 1, and 200 kpc. FIR/SMM observations will contribute to our understanding of most of these evolutionary phases. (After R. Barkana.(6))

As the intensely hot early Universe rapidly expanded, its temperature dropped by a half for every doubling of expansion. Roughly a minute into cosmic time, the temperature had dropped to a billion degrees, sufficient to permit primordial protons and neutrons to combine to form nuclei of deuterium, helium, beryllium, and lithium. The entire process took no more than three minutes. Production of the heavier elements without which planet Earth could never have formed had to wait another few hundred million years. Each step in this nucleochemical sequence and each step in a parallel chain of molecular evolution has left an archaeological imprint that FIR/SMM spectroscopy can help us unveil to reconstruct a history of cosmic chemical evolution.

3b. Our Motion Through the Universe and the Motion of Galaxy Clusters

The Planck survey to be launched in 2009 will probe the cosmic background radiation to wavelengths as short as the 300 – 400 μm band. The mission will define the precise location and intensity of the peak background emission, to determine the direction into which Earth is moving through the Cosmos, with an accuracy of 1.7 arc minutes, while registering the speed with an accuracy of ~ 0.4%. (7) This motion reflects the locally inhomogeneous cosmic mass distribution.

In collaboration with ground-based millimeter wave measurements, FIR/SMM observations with Herschel, BLISS and later with SAFIR will enable determination of similar motions, on larger scales far out in the Universe, through detections of the kinematic Sunyaev-Zeldovich effect. This effect sorts out the line-of-sight motion of galaxy clusters at great distances, by observing the Doppler shift of cosmic microwave background radiation scattered off ionized cluster gases. The effect is greatest at millimeter wavelengths, but observations at FIR/SMM wavelengths help to sort out the effects of thermal dust emission in the clusters.(8, 9)

3c. Tracing Cosmic Evolution Through Recombination and the early Dark Ages

Recombination of hydrogen and helium at redshifts $z \sim 1000 – 7000$ imprints a faint emission spectrum on the FIR/SMM background radiation. This is produced by Lyman-α transitions and two-photon 2s – 1s decay of atomic hydrogen and the corresponding emission lines of He I and He II. Together, these transitions are expected to give rise to two broad spectral emission peaks observable today at ~170 and ~370 μm.(10) While these will be challenging to observe, in view of strong Galactic foregrounds (Figure 5), detecting them should be facilitated by the spatial correlations of the 170 and 370 μm components and the differences in spectral energy distribution, spatial distribution, and polarization characteristics between Galactic foreground emission and this remnant from the recombination era. The importance of these measurements lies in the reassurance they may provide that we correctly understand cosmic evolution during recombination and the early Dark Ages --- an epoch which may yield few other clues except perhaps through equally-challenging 21-cm observations of the later phases of the Dark Ages.

3d. Formation of the First Stars

Studies of the formation of Population III stars are still in their infancy. But agreement is emerging that at least indirect evidence for their existence will be found through FIR searches for red-shifted rotational emission of H_2 surrounding these stars. These rotational transitions, at 28, 17, and 12 μm in the rest frame of the gas but highly redshifted at $z > 10$, will be largely excited through $H – H_2$ collisions in turbulent shocks radiating outward from HII regions surrounding the newly-formed massive stars.(11) Rovibrational emission will also be induced at ~2 μm in the rest frame following Lyman and Werner band absorption.(12) Massive first generation stars will explode as supernovae, injecting the first heavy elements into their surroundings. Cooling of gas leading to the formation of second generation stars will then be dominated by infrared rest-frame fine-structure line emission of [O I], [Si II], Fe II] and [C II] once metal abundances reach a critical level ~ 10^{-4} times solar. Santoro and Shull have carried out calculations of cooling rates due to these fine-structure transitions at the critical abundance levels and higher for redshifts 20 > z > 5, when the age of the Universe ranged from ~ 0.2 – 1.2 Gyr.(11)

3e. Tracing Early Chemical Enrichment

Among the impressive achievements of the Spitzer mission is the detection of galaxies at redshifts between z = 5 to 7, as evidenced by the 3.6 and 4.5 μm data points in Figure 7. The spectral energy distribution indicates continuum emission by a dusty interstellar medium. The data raise the question "How did heavy chemical elements and dust form so early --- within only a few hundred million years after creation?" One suggestion is that the dust is created in the explosion of a first generation of massive stars in the ~140 - 260 $M_\odot$ range that produce pair-instability supernovae.(13) In these stars the central temperature rises until colliding photons produce electron-positron pairs at low velocities, thus suddenly reducing the pressure and leading to a collapse which may convert ~15 – 30% of the progenitor mass into heavy elements.(14) The ensuing supernova explodes these out of the star to form circumstellar Mg_2SiO_4 and SiO_2 silicate dust.

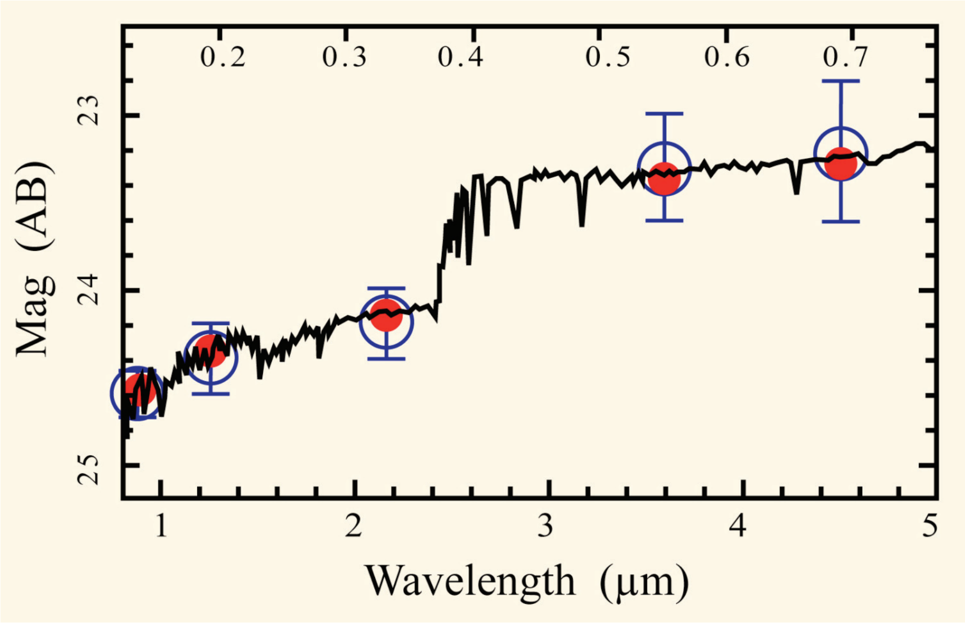

Figure 7. The starburst galaxy BD38 at z = 5.51 observed with Hubble and Spitzer. The five data points have been fitted to a Bruzual & Charlot spectral energy distribution, in which the Balmer jump at a rest-frame wavelength of 0.4 μm is shifted to ~ 2.5 μm. The spectrum suggests a stellar population with solar abundances at a cosmic age ~ 1 Gyr.(1, 52) *The lower wavelength scale shows the observed wavelength; the upper is the rest-frame wavelength.*

This suggestion may be partially confirmed by X-ray observations of excess silicon ejected by first-generation stars into the hot intergalactic medium of massive galaxy clusters. But direct FIR/SMM observations of the dust or elemental constituents at high redshifts will more firmly establish a convincing history of the rise of chemical enrichment.(16 – 18) The next generation of

FIR/SMM, radio, and X-ray observatories should help shed light on the linked questions of early star formation, the initial mass functions of the first stars, their explosive disruption, the evolutionary influences of quasars and AGNs, and the rise of heavy element abundances. From these, we will also learn whether it was massive stars or quasars that played the leading role in ionizing the intergalactic medium at red-shifts around z ~ 6. SPICA and later SAFIR and SPIRIT may be expected to play significant roles in clarifying these questions.

3f. Cosmological Surveys and the Confusion Limit

Cosmological surveys are conducted to determine evolutionary trends. They enable unambiguous interpretation only when individual galaxies can be securely identified and studied. A major hindrance arises when confusion, the uncertainty about whether one is dealing with one galaxy, or possibly several unresolved galaxies, comes into play. Deep surveys in the 24 μm band on Spitzer showed that 80% of the infrared background in this band is accounted for with sources brighter than 60 μJy. Assuming a similar source distribution at 200 μm implies a probability P ~ 0.5 of finding a source in any broad-band 200 μm diffraction-limited beam of SPICA. The telescope will thus be confusion limited in this wavelength range. BLISS will, however, compensate for this confusion by identifying the spectral lines due to powerful [OI], [OIII], and [CII] fine-structure lines emitted by individual galaxies at rest-frame wavelengths 63, 88 and 158 μm. Because the redshifts of these lines will vary from source to source within a field of view, a clear set of identifications will emerge. Some of the FIR/SMM fine structure lines are highly luminous in the local Universe. In many galaxies the 158 μm [C II] line emits > 0.3% of the total radiant power. In others the [O I] line at 63μm the [O III] line at 88 μm and occasional molecular absorption features can be comparably striking (Figure 8). At least two of

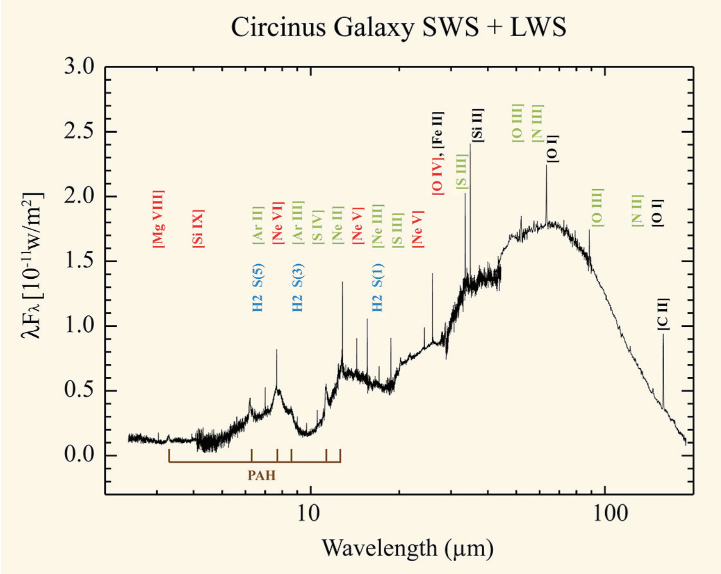

Figure 8. The Circinus Galaxy observed with the Short- and Long-Wavelength Spectrometers on the Infrared Space Observatory ISO.$^{(19)}$

the spectral lines will generally fall in the BLISS-covered band for all redshifts. Their frequency ratios immediately identify the lines and will fix the redshift for each galaxy.

3g. Contributions to the Cosmic Infrared Background

To understand the contribution of these galaxies to the cosmic infrared background (CIB), SPICA/BLISS will conduct a survey of a few thousand high-z galaxies, to provide a statistically significant measure of their properties. Based on the sensitivity estimates shown in Figure 3, that survey will require less than one hour per galaxy, on average, and verify whether our current indications, based on observations by ISO and Spitzer --- namely that galaxy luminosities peaked around z ~2 --- are correct or need significant modification. This is important, because it is not clear whether the dusty galaxies which produced the CIB, have undergone the same energy release history as visually-selected populations. Mounting evidence indicates that they have not.

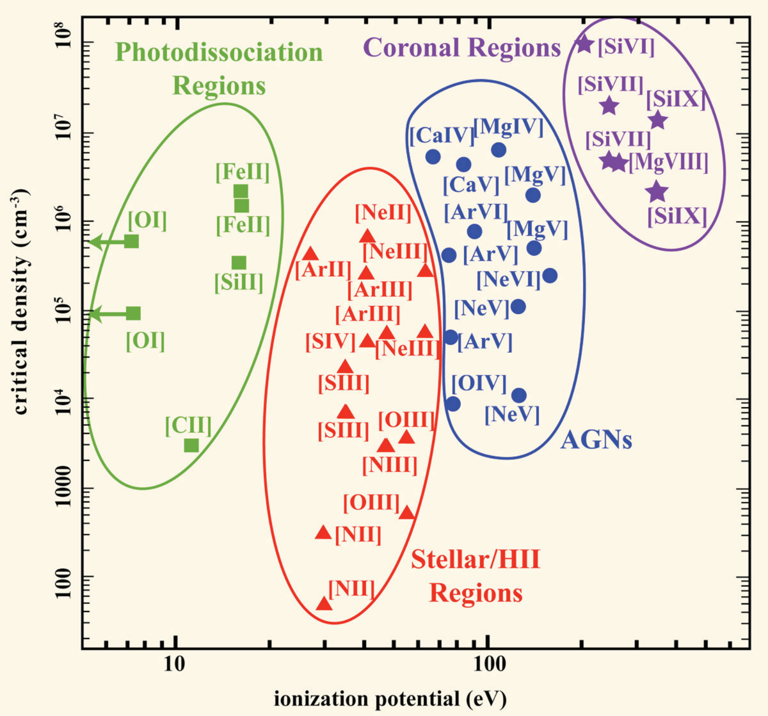

Figure 9. Key diagnostic fine-structure lines serving as tracers of excitation conditions in stellar coronae, photo-dissociated regions (PDR), Strömgren spheres, and AGNs as well as quiescent and starburst galaxies. Relative line strengths serve as diagnostics for temperature, density and ambient radiation fields. In extragalactic sources the strongest of these lines can provide direct measures of redshifts otherwise not readily available.

Luminosities based on UV/blue fluxes and colors underestimate the total luminosities of a sample of LIRGs and ULIRGS, Luminous and Ultraluminous Infrared Galaxies, by factors of 3 to 75, and the UV/visual light often comes from regions hundreds of parsecs from the major luminosity sources. Mid-IR spectra of heavily obscured luminous AGNs indicate that a considerable fraction of their FIR/SMM luminosity results from absorption of X-rays emanating from around the central black hole. This luminosity provides a measure of the radiation released by matter impinging on the black hole rather than generated in stars.

3h. Studies of Nearby and Distant Galaxies

BLISS will be sensitive to spectral emission from H II regions, photo-dissociation regions (PDRs), the radiation produced by AGNs, and will be able to distinguish these components through analyses of the hardness of the radiation fields, discerned from ratios of fine-structure line strengths obtained for individual elements, e.g. ratios of [OIII] & [OIV]; [NII] & [NIII]; or [NeII] or [NeIII] & [NeV]) (see Figure 9). BLISS will have the sensitivity to make these kinds of measurements on LIRG-class galaxies out to redshifts z ~ 5, when the Universe was <10% its current age. In dense neutral regions, it will also obtain spectral information about CO, particularly in shocked domains where rotational transitions from states excited to quantum levels J = 8 – 15 will be apparent as long as they are not redshifted out of the BLISS wavelength band. In the dense torus around an AGN, where temperatures reach ~1000 K, Krolik and Lepp estimated that an individual CO line (e.g. J = 40→39 at 70 μm) can radiate up to 1% of the incident X-ray flux from the central active nucleus.(20) If this prediction holds, BLISS will detect such intense lines out to redshifts z ~ 2. The J-value of the peak radiating rotational levels will further indicate whether the radiating gas is UV- or X-ray-excited.

3i. Vast Regions of Shocked Intergalactic Molecular Hydrogen

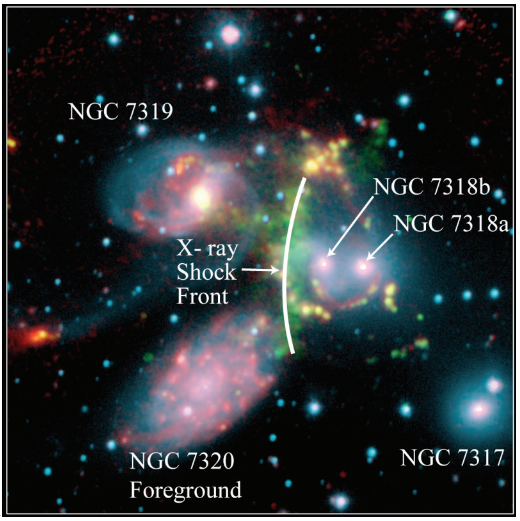

Figure 10. Stephan's Quintet showing a diffuse arc of atomic hydrogen emission, indicated in green, roughly coincident with a shock front observed in the X-ray domain. Spitzer observations reveal powerful H_2 *emission originating from the center of this* 10^3 *km* s^{-1} *shock.* (21)

Powerful H_2 emission has been observed from a number of source, including Stephan's Quintet, Figure 10. In the radio galaxy 3C326 housing a quasar the integrated emission summed over all the H_2 rotational lines is 8 x 10^{41} erg s^{-1}, amounting to an astonishing 17% of the 18 – 70 μm luminosity of this quasar and galaxy. The estimated mass of just this warm, mid-infrared-emitting molecular hydrogen component is $10^9\ M_\odot$. The H_2 appears to be shock-heated as it falls into the galaxy in a tidal accretion flow from a nearby companion galaxy.(22) We now have evidence for up to 10^{10} $M_\odot$ of warm (T>150K) molecular gas associated with galaxy interaction, gas accretion, and feedback. Newly discovered luminous H_2 sources include AGNs, cooling flows, star-burst winds, colliding galaxies and mergers. The SAFARI and BLISS instruments on SPICA (see Table 1) will be able to study such powerful emitters of H_2 out to considerably greater distances than Spitzer and elucidate how these shocks originate.

3j. Tracing Later Chemical Enrichment

What kinds of stars, in what kinds of galaxies promote chemical enrichment today? Spectroscopy with ISO provided a first sampling of molecular, ionic, and atomic processes in extragalactic sources.(23, 24) In addition to observing molecular emission of H_2, OH, and H_2O, as well as PAHs, ISO detected a wealth of fine-structure lines due to relatively abundant constituents such as argon, carbon, magnesium, oxygen, nitrogen, neon, silicon and sulfur. As Figure 9 indicates, these lines serve as reliable diagnostics of interstellar plasmas over a wide range of temperatures, allowing us to reconstruct physical conditions in complex regimes, such as the those in the Circinus galaxy (Figure 8). However, because stars of different masses eject different mixtures of chemical elements into the ambient interstellar medium at the end of their lives, and because some of this material can be explosively ejected from the parent galaxy, we still lack certainty about precisely how and where different elements and their isotopes are most abundantly produced, or where grains of different mineralogical composition originate. By penetrating highly obscured regions FIR/SMM spectroscopy is able to provide answers to such questions. SAFARI and BLISS on SPICA will be able to resolve many of these questions out to

Figure 11. Outflow from the galaxy M82. Shown in red is the outflow of PAHs embedded in a gaseous wind propelled out of the galaxy by hot stars in the stellar disk (blue). In this image obtained with Spitzer, starlight (measured at 3.6 μm) has been subtracted from 5.8 μm and 8 μm images to enhance the visibility of the PAH features.(25)

increasing extragalactic distances. SOFIA will study some of the brightest among these sources with its sophisticated complement of instruments.

3k. The Complex Interplay of Dynamics and Chemistry

Astrophysical processes frequently take place at supersonic velocities. Interactions between converging flows result in shocks that raise temperatures and produce chemical reactions. The newly-formed molecules and molecular ions often dominate local heating and cooling rates that, in turn, dampen or act to maintain the flow dynamics. The spectrometers on Herschel and SPICA will help us resolve the interplay of dynamics, or more precisely magnetohydrodynamics, and chemistry. Table 2 lists many of the leading infrared diagnostics that will serve this purpose. Molecular lines in cold domains may be observed in absorption.

Table 2. Leading MIR and FIR/SMM Diagnostic Spectral Features

Species	Wavelength [μm]	I.P. [eV]	fM82	fA220	Diagnostic Utility
			Ionized Gas Fine Structure Lines		
Ne V	14.3, 24.3	97.1			Primarily AGN
O IV	25.9	54.9			Primarily AGN
S IV	10.5	34.8	2.1×10^{-5}		Probes gas density
Ne II	12.3	21.6	1.2×10^{-3}	7.5×10^{-5}	and UV field hardness in star formation HII regions.
Ne III	15.6, 36.0	41.0	2.05×10^{-4}		"
S III	18.7, 33.5	23.3	1.0×10^{-3}	7.3×10^{-5}	"
Ar III	21.83	27.6	9.1×10^{-6}		"
O III	51.8, 88.4	35.1	1.3×10^{-3}		Diffuse HII regions
N III	57.3	29.6	4.2×10^{-4}		
N II	122, 205	14.5	2.1×10^{-4}		
			Neutral Gas Fine Structure Lines		
Si II	34.8	8.2	1.1×10^{-3}	7.7×10^{-5}	Density and temperature
O I	63.1, 145		2.2×10^{-3}	-6.8×10^{-5}	probes of photodissociated-neutral gas interface
C II	158	11.3	1.6×10^{-3}	1.3×10^{-4}	between HII regions and molecular
C I	370		6.2×10^{-6}	1.2×10^{-5}	clouds and around AGN
			Molecular Lines		
H_2	9.66, 12.3, 17.0, 28.2		2×10^{-5}	3×10^{-5}	Mass of warm (few 100K) molecular gas
HD	37, 56, 112				D/H ratio
LiH	112, 135, 169, 225, 338				Li/H ratio
CH	149			-4×10^{-5}	Ground state absorption, gives column and abundance.
OH	34.6, 53.3, 79.1, 119		-2×10^{-6}	-2×10^{-4}	
OH	98.7, 163			5×10^{-5}	Emission → temperature & density
H_2O	73.5, 90, 101, 107, 180			$\pm 5 \times 10^{-5}$	
CO	~2600/J = 130, …, 217,				High-J, T > 200K molecular gas, e.g. torus
CO	237, … 260, … 325, 372		3×10^{-6}	(1×10^{-5})	Mid-J, 50K < T < 200K mol. gas
			Dust Features		
Silicate	9.7, 18				Dust tracer, also seen in QSO emission
PAH	6.7, 7.7, 8.5, 11.3,				Small transiently-heated grains

Note: The fM82 and fA220 are the ratios of the line luminosity to the total bolometric luminosity in those sources.

The heterodyne spectrometer on Herschel will resolve the spectral shape of a large number of emission or absorption lines for one and the same atomic, molecular or ionic species to analyze complex regions consisting of many different density and temperature regimes along a single line of sight. The high-resolution mode of the Mir-IR Imager/Spectrometer on SPICA (see Table

1) will partially fulfill a similar role at shorter wavelengths. Observations of isotopic species with greatly varying abundances and hence also optical depths, will often resolve ambiguities on density distributions along these sight lines.

3l. Galactic Investigations

The SAFARI imaging Fourier-Transform spectrometer contributed to SPICA by the European consortium of astronomers will expand by factors of 30 to 10^3 the volume over which FIR/SMM observations of Galactic and nearby extragalactic sources becomes possible. By employing a new generation of improved detectors cooled to 50 mK, the sensitivity of SAFARI in the wavelength range of 30 - 210 μm will surpass by one or two orders of magnitude the sensitivity of the imaging spectrometers onboard Herschel (see Figure 3). This will enable the identification of a vast range of chemical species and their abundance gradients across the Galaxy, with similar gradients observable across nearby galaxies. We will be able to compare the outflows of different types of stars to determine where grains of different mineral composition originate or are processed. With BLISS we will be able to pursue similar investigations of fainter, more distant Galactic and extragalactic sources. With complementary JWST and SOFIA observations, we will be able to probe how and where most of the polycyclic aromatic hydrocarbons (PAHs) filling interstellar space arise, whether in winds emanating from carbon-rich post-Asymptotic-Giant-Branch stars, in interstellar shocks, or possibly elsewhere.(26)

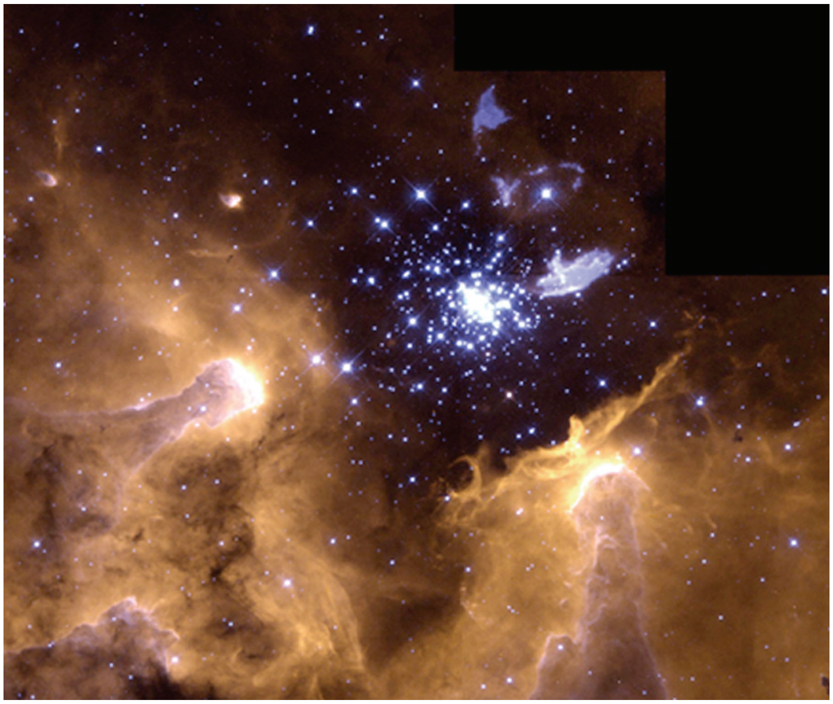

Figure 12. The star-forming region NGC 6303, showing a cluster of stars already born and regions about to give birth.

3m. Star Formation

The past decade has abundantly shown that understanding the chemical evolution of dense gas as it collapses to form a star is key to understanding star formation. Observing molecular emission offers the only method of tracing not only the dynamics but also the chemical changes that take place within a collapsing cloud. Species like N_2H^+ and CN are better tracers of the innermost cloud core while CO traces the surrounding envelope. Chemistry also retains a temporal memory, most notably shown by the timescales on which H_2 ortho-para transitions occur.(27) Thus spectroscopy with Herschel and SPICA should improve our grasp of both the dynamics and timescales of star formation.

As clouds of atomic gas initially fall into dark-matter haloes, or collide in the merger of galaxies, fine-structure transitions of singly-ionized carbon [C II] at 158 µm cool the atomic medium to temperatures where molecular hydrogen begins to form. Spectrometry on Herschel will help to elucidate the role of turbulence in this process by tracing the kinematics of C^+ at high spectral resolution. Ultimately we want to spatially resolve star-forming dynamics with sufficient angular and velocity resolution to trace the turbulent magnetohydrodynamic dissipation scale. Here, as elsewhere observations with SPICA at wavelengths ≤ 430µm will complement ALMA work.

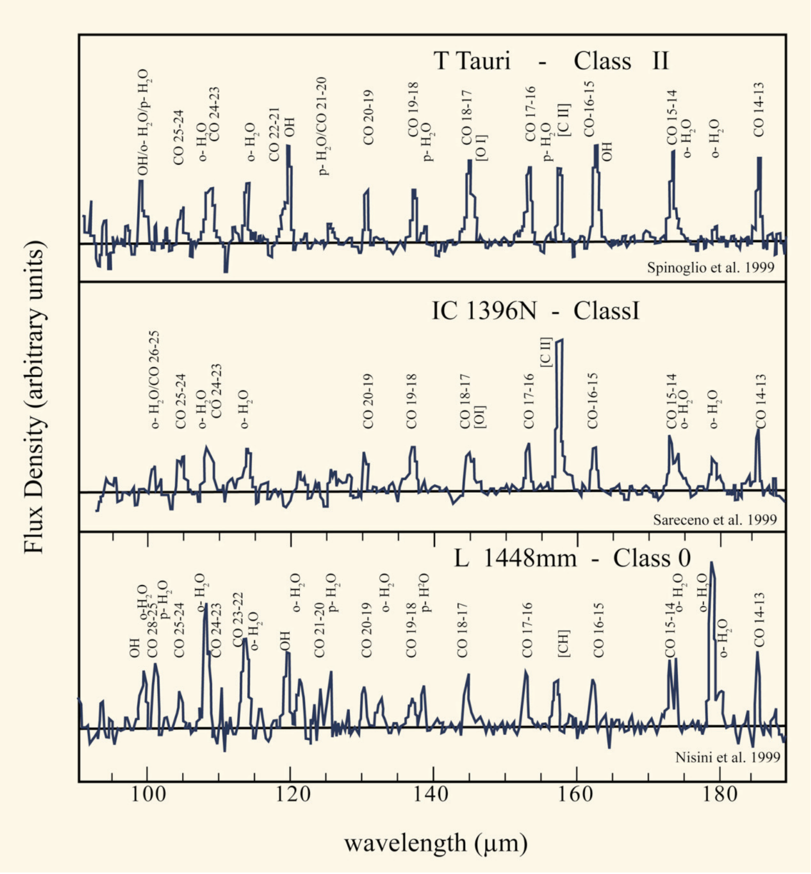

Figure 13. Spectra of Different Classes of Protostars obtained with ISO at a spectral resolving power of R ~ 300. (Reassembled from Spignoli et, al., Saraceno et al., and Nisini et al.)(28-30)

Both atomic and molecular hydrogen radiate inefficiently at low temperatures. Most of the cooling of star-forming clouds involves trace constituents like CO, H_2O, or the FIR/SMM fine-structure transitions of abundant atomic interstellar species, O, C and C^+. Herschel's spectroscopic observations of these emissions, at line-of-sight velocity resolution better than a kilometer per second, will portray the kinematics of the clouds and the constant interplay between evolving chemical species and turbulent, supersonic, magnetohydrodynamic flows.

While ground-based radio astronomy has carried out similar studies, FIR/SMM observations reveal cooling by H_2O, C^+ and many other species not accessible from the ground. And with a six-fold larger aperture than SWAS or ISO had, Herschel and SPICA will be able to image regions at six times higher diffraction-limited angular resolving powers. Ultimately, the launch of the FIR interferometer SPIRIT in 2020-2035 will map, at high spatial resolution, the distribution of chemical species and potential coolants produced in protostellar shocks. For infrared astronomy to play this intended role, it will have to provide observations with the same high spatial resolution that millimeter-wavelength interferometers bring to bear on, say, 2.6 mm emission of CO, an especially effective coolant of giant molecular clouds.

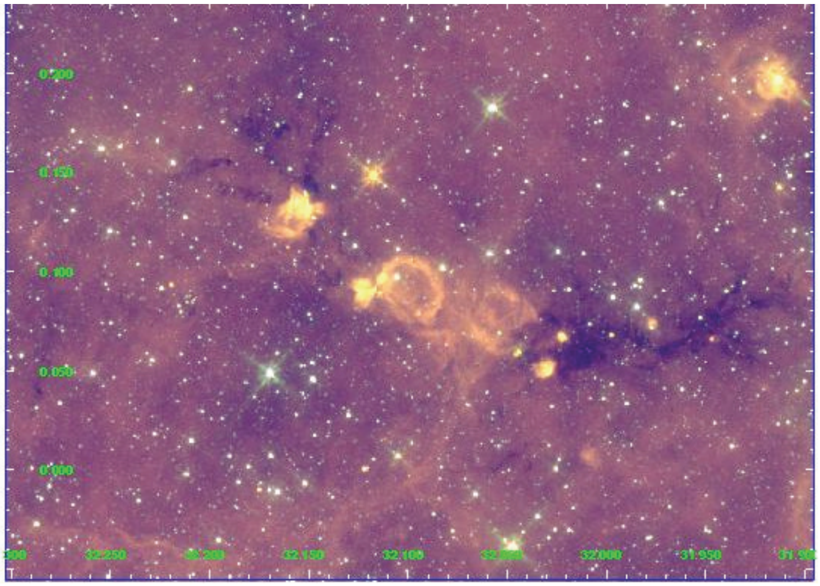

Figure 14. Spitzer observations of outflows from young massive stars interacting with the ambient interstellar medium. (Courtesy E. Churchwell.)(31)

This FIR/SMM capability will be particularly important for understanding the evolution of young stellar objects by resolving the regions in which their bipolar outflows are accelerated. To gain added insight on the dynamic interplay between accretion disks and outflows, we will need to also trace the temperature, velocity, and density structures both of the outflows and the disks.

3n. The Chemistry of the Interstellar Medium

The chemistry of the interstellar medium is complex. Abundant gas-phase molecules and radicals are CO, H_2CO, HCN, NH_3, all observed through their readily detected FIR/SMM emission lines.

The wide variety of physical conditions requires that multiple transitions throughout the FIR/SMM be observed to determine accurately the abundance of these species and thus to unravel the chemistry taking place on grain surfaces as well as in the gas phase.

A number of chemical cycles are particularly important: Atomic oxygen in the cold neutral medium is instrumental in forming water vapor through gas-phase reactions (Figure 15). H_2O also forms as ice on grains during cloud core formation at temperatures of 10 - 20 K. Laboratory studies show that, if the carbon-to-oxygen ratio on grain surfaces is sufficiently high, complex organic molecules can form through ultraviolet processing or through grain-surface catalytic --- Fischer – Tropsch --- reactions.(32) Some of this organic matter finds its way into disks during pre-stellar collapse to be eventually incorporated in planetesimals. Some of the oxygen ultimately is returned into space in atomic form. Both ground-based and space observations will be required to trace the evolving chemistry of oxygen and water throughout a cloud core during star formation and, subsequently, during incorporation of matter in planets. Following the ortho/para ratio of water, and the deuterium/hydrogen ratios in H_2O and HDO, will provide added information on the chemical constituents and physical conditions in star- and planet-forming regions. Herschel will have studied some of these processes at higher velocity resolution, but SPICA will be able to trace less abundant constituents with its higher sensitivity.

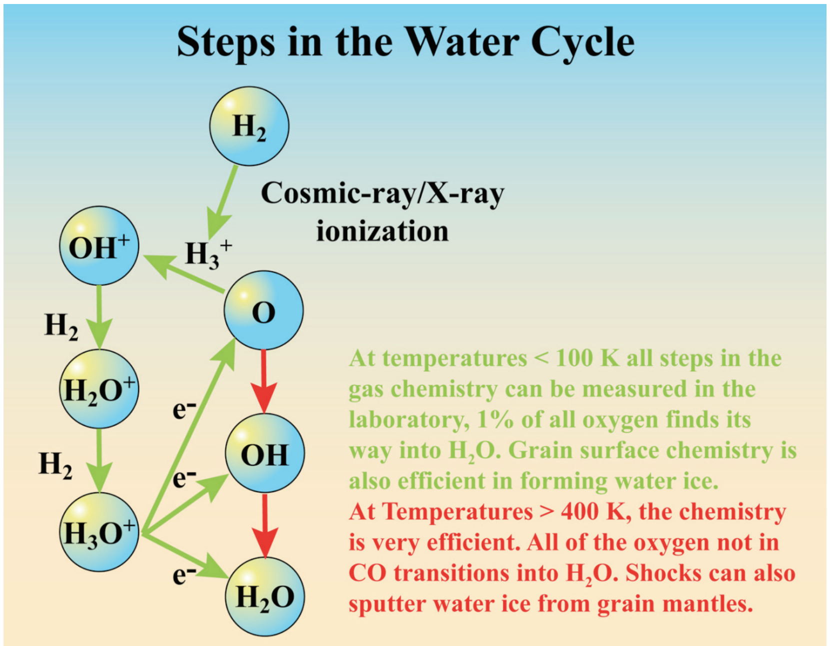

Figure 15. The water cycle, indicating the complex series of gas-phase reactions leading to the formation of water. All of the gas-phase reaction rates are measured in the laboratory, providing considerable analytic insight. Water also forms on grain surfaces. [Courtesy E. Bergin.]

Current interstellar chemical models cannot predict how or where the complex molecules on which life depends may form. Theory and observations will thus need to jointly advance.

3o. The Classes of Planetary Disks(33)

The JAXA/KASI coronagraph on SPICA will provide greatly improved images of protoplanetary disks, debris disks, and the immediate environs and outflow of stars, all of which will be imaged with a 1k x 1k Si:As array with 0.1 x 0.1 arcsec^2 pixels. Gaps and spiral density waves in star-forming disks will be more clearly imaged and help to determine whether giant planets preferentially from through core accretion or gravitational instability. Spectroscopic imaging with SPICA will further identify the distribution of different mineralogical or chemical constituents and regions where phase transition occur, such as the potential snow line at disk radii beyond which water vapor freezes. The mid-IR coronagraph will thus powerfully complement the capabilities of JWST's coronagraph, by operating out to longer wavelengths ~ 27 μm, a circumstance of especial significance since SPICA and JWST will be in simultaneous operation for many years. Although SPICA's aperture is smaller than that of JWST, the cryogenically cooled primary leads to a sensitivity comparable to that of JWST, i.e. ~ 1 μJy (5σ- 1hr) in photometric mode --- albeit at an angular resolving power a factor of ~2 lower.

Planetary disks divide into three classes. *Primordial disks* are rich in gas, optically thick, and composed of relatively unprocessed interstellar material left over from star formation. Within a few million years, they evolve into *transitional* disks as their inner regions begin to clear. As Spitzer has shown their outer regions beyond 10 or 20 AU remain intact far longer. The disks' gas content appears to control the formation of the planetary system, by circularizing planetary orbits and controlling the migration responsible for the hot Jupiters, giant planets observed orbiting close to their parent stars. Because these planets could not have formed in situ, they must have spiraled inward. And because they are largely gaseous they must have formed before the circumstellar gaseous disk dissipated. We do not yet understand the rates at which these processes take place. Herschel will spectrally resolve [CII] emission at 158 μm, [O I] emission at 63 and 146 μm, as well as a number of FIR water vapor lines, all of which will serve as tracers of disk dissipation and typical lifetimes. But we will require the larger aperture of SAFIR and ultimately a FIR/SMM interferometer like SPIRIT to spatially resolve and image these disks.

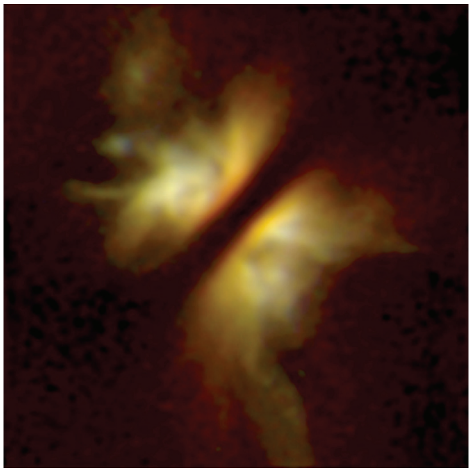

Figure 16. The evolving planet-forming disk IRAS 04302+2247

The oldest observed disks, the *debris disks*, are younger, denser versions of the asteroid and Kuiper belts formed through destructive collisions of planetesimals. Currently, Beta Pictoris is the only debris disk for which we have a nearly complete inventory of the elemental abundances of mid-plane gas.(34) Curiously, most observed elements have solar abundances, as does the central star. But the gaseous C/O ratio has 18 times the solar value, which calls for explanation. Further studies of debris gas in this and many other disks, with the high spectral resolution of Herschel and the much higher sensitivity of BLISS on SPICA will shed light on the composition of young planetesimals and provide comparative information on the formation of the atmospheres of primitive terrestrial planets. We expect also to learn much more with ALMA, which should be sufficiently sensitive to detect gas emission from a larger number of debris disks.

3p. Water in Disks

A question of major interest is how water finds its way onto planets. Although initial indications suggested that terrestrial water arrived through comet impacts, delivery through comets may not play the most important role. The source of water may, instead, be the impact of icy planetesimals from the outer asteroid belt or the impact of bodies composed of hydrous minerals. With high angular resolution the FIR/SMM bands of hydrated silicates will be discerned to determine where they from in a disk. Most of the water in a planet-forming disk is in the form of ice. ALMA will observe HDO and $H_2{}^{18}O$ vapor and compare their abundances to those of cometary and terrestrial isotopologues of water. But whereas ALMA cannot observe $H_2{}^{16}O$ or the $^{16}O/^{18}O$ ratio, which may vary across the disk, Herschel and SPICA will be able to provide this requisite information.

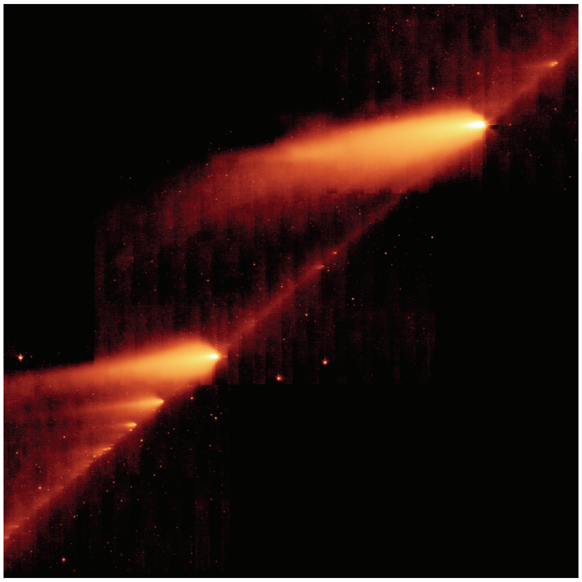

Figure 17. An image obtained with Spitzer at 24 μm, shows the fragments of Comet 73P/Schwassman-Wachmann 3, in the wake of the comet's break-up in 1995. The debris ranges in size from pebbles to large boulders, and stretches along the comet's orbit around the Sun. This image was taken from May 4 to May 6, 2005.

3q. Solar System Studies

To understand extra-solar planetary systems, we will need to further investigate our own Solar System. Spitzer's study of the breakup of comet Schwassman-Wachmann 3 (Figure 17) may shed light on the break-up of planetesimals in planet-forming disks. Spitzer has also gathered valuable information on myriad trans-Neptunian bodies in the outer Solar System, measuring their albedos and dimensions. Both high- and low-albedo surfaces are observed. High albedos are presumed to be associated with ices, low albedos surfaces are generally thought to be darkened by aliphatic and/or polycyclic aromatic hydrocarbon molecules, but additional, more sensitive spectroscopic observations should help to discern the actual composition.

A quite different type of infrared study concentrating on identification and cataloguing of near-Earth asteroids will provide forecasts of collisions with Earth and perhaps enable ways of dealing with impending catastrophes. A wide variety of observations dedicated to such searches are planned, including contributions from the Spitzer extended mission, JWST, SOFIA, Herschel and SPICA.

3r. The Seeds of Life

Half a century ago, Stanley L. Miller and Harold C. Urey showed that passing a discharge through a mixture of primitive molecules, H_2, H_2O, CH_4, and NH_3, produced molecules such as glycene, amino acids like alanine, as well as glycolic and lactic acid in significant numbers. (35) Similar biogenic molecules have been produced with ultraviolet and other energetic irradiation. The same irradiation, however, can also destroy these molecules. Some measure of protection is thus needed for biogenic molecules to both form and survive. Such regions, quite possibly, are the interfaces between regimes characterized by energetic irradiation and adequate shielding --- dense molecular clouds irradiated by massive stars or impacted by supernova remnants; the surfaces of comets or planets; and planetary atmospheres pierced by lightning. Such an interface is precisely what the recent observations of glycolaldehyde, CH_2OHCHO, in the dusty hot core of a molecular cloud appear to show.(5) The glycolaldehyde is observed within $\sim 10^4$ AU of a massive forming star. Particularly tantalizing is the potential for glycolaldehyde to combine with the similarly-sized molecule propenal, CH_2CHCHO, to form ribose, a central constituent of ribonucleic acid, RNA, linked to all primitive forms of life.

In the Solar System, traces of amino acids and hydrocarbons are found in carbonaceous chondrites, a type of meteorite containing spherical chondrules having the appearance of frozen droplets. The chondrules, are thought to have been formed early in the history of the Solar System, and more generally in the planet-forming disks around T Tauri stars, during their phase of X-ray-flaring, which may induced flash melting followed by freezing. Sensitive infrared, submillimeter and radio spectroscopic mapping offer a way of probing this hypothesis through observations of the chemical preconditions in the T Tauri disks that could give rise to the observed chondrules.

Within the Solar System, the surfaces of comets may be the simplest locales to search for biogenic molecules. Cometary surfaces are subject both to ultraviolet irradiation and protective dust shielding. If biogenic molecules are found there, they may be compared to those found in meteorites. But we have no reason to believe that biogenic molecules will be found solely in planetary systems, so that broader surveys may yield striking new results. For example, the environs of planetary nebulae offer similar combinations of ultraviolet irradiation and dust shielding expected to produce complex molecules. At the very least, such regions deserve scrutiny to the extent that they could serve to discriminate between conditions that are necessary and those that are sufficient for forming biogenic molecules.

3s. Planets Orbiting Other Stars

In addition to its many other achievements, Spitzer has succeeded in measuring the infrared radiation from hot Jupiters. (36) Observations show the first spectrophotometry of planets undergoing primary and secondary eclipses as they orbit their parent stars in planes seen edge on. The spectral signature of water vapor, a main requirement for the existence of life, is particularly striking in the atmosphere of the extrasolar hot Jupiter planet HD 189733b .(37) The larger FIR/SMM telescopes coming on line in the next few years, will enable the study of many more planetary atmospheres to determine the prevalence of habitable planets and, in particular, smaller Earth-like planets.

The brightness contrast of stars and their planets quickly diminishes at increasing wavelengths. Planets emit a significant fraction of their thermal radiation in the 5 – 27 µm mid-infrared, where the radiation emitted by their parent stars rapidly declines with increasing wavelength. The mid-IR coronagraph jointly pursued by JAXA and KASI will operate in this wavelength range and

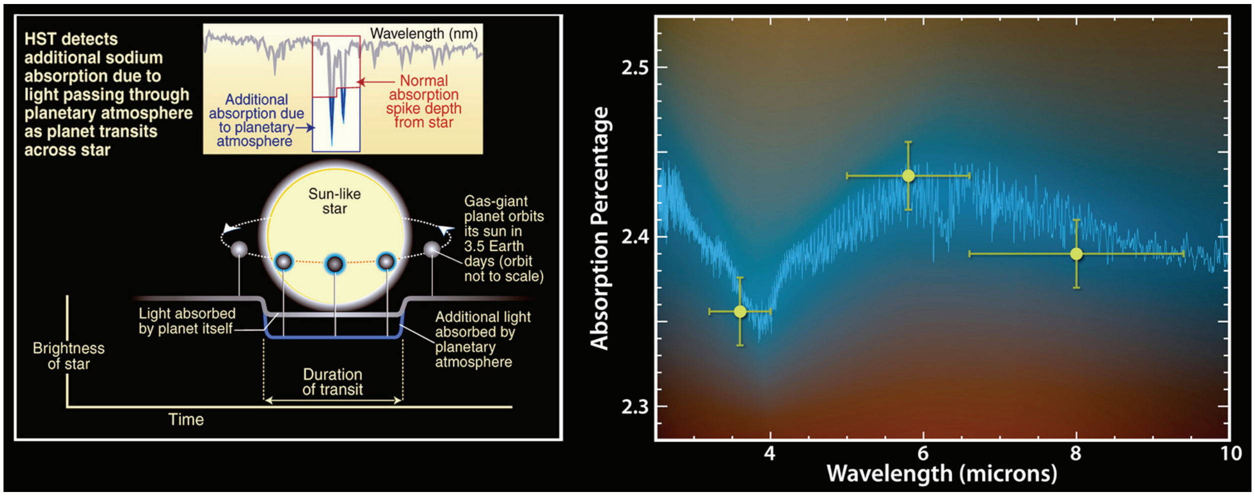

Figure 18. Heuristic diagram to show how primary and secondary eclipses provide information on an exoplanet's atmosphere (left). Spitzer data on size vs. wavelength indicates absorption by abundant water vapor in the atmosphere of the exoplanet HD 189733b (right). This figure re-emphasizes the importance of joint observations at different wavelengths --- here provided by HST and Spitzer.(37)

directly detect and image giant planets a factor of 10^6 fainter than their parent stars. SPICA's on-axis Ritchey-Chretien optics enable the coronagraph to provide an inner working angle ~ 2 to 5 λ/D, corresponding to a separation of 6 – 15 AU at 5 µm for stars at distances of 10 pc. This will provide a greatly improved census of giant planets around nearby stars, particularly planets in distant orbits, which are difficult to detect by conventional means because their gravitational tug on the parent star is considerably weaker than that of hot Jupiters in close passage by the star. The instrument's spectral resolving power of R ~ 200 will uniquely enable mineralogical and chemical analyses, particularly of planetary atmospheres in this spectral range rich in molecular features and potential indicators of biological activity. Molecular features of particular prominence are those of H_2O at ~ 6-8 µm, O_3 at ~9.6 µm, silicate clouds at ~10 µm, NH_3 at ~10.7 µm, CO_2 at ~15 µm, as well as less abundant hydrocarbons and sulfur- or nitrogen-bearing species.

4. A Coherent Technological Program to Attain The Cited Scientific Goals

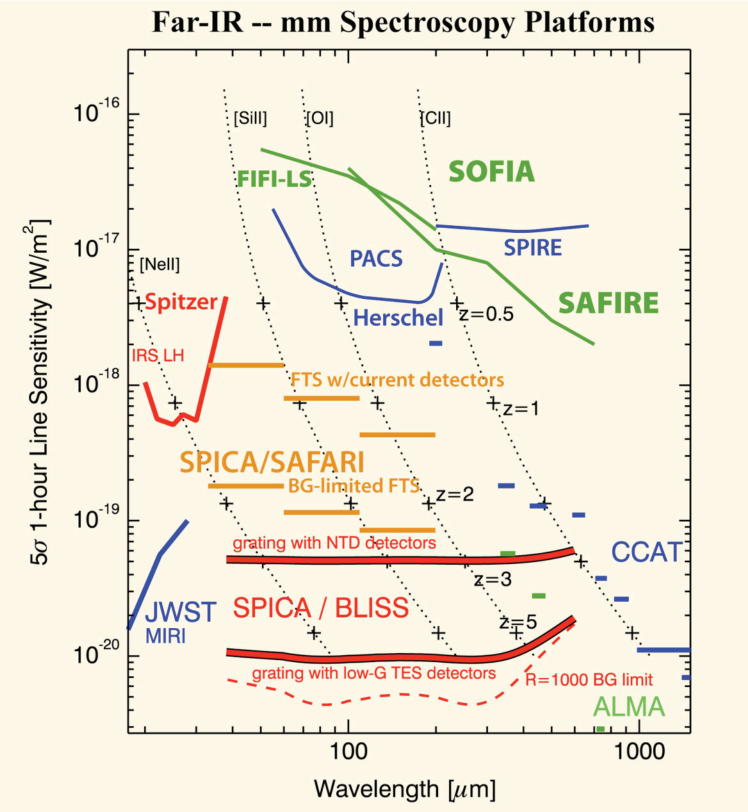

Figure 19. Anticipated performance of the Background Limited Infrared/Submillimeter Spectrometer (BLISS) on the Japanese-led SPICA mission. Most of the gains come from the cryogenic optics and very sensitive detectors. The lower BLISS curve assumes detectors with noise equivalent powers ~ 5 x 10^{-20} W $Hz^{-1/2}$. With this sensitivity and complete spectral coverage from 38 – 433 µm, we will be able to observe the red-shifted [Si II] 34.8 µm and [O I] 63.1 µm fine-structure lines in distant galaxies out to z ~ 5, enabling study of the chemical evolution of, and the engines and processes within, these early galaxies.

4a. SPICA

SPICA has been conceived to provide insight on the many different problems described above. The coronagraph is specifically meant to meet the needs of exoplanetary research. SAFARI is intended primarily for Galactic studies and investigation of relatively nearby galaxies. However, an additional, superbly sensitive, mid-resolution spectrometer capable of analyzing faint local sources and extremely distant extragalactic objects will be needed to carry out many of the promising investigations described in Section 3, above. For this we will require a background-limited spectrometer working at the forefront of current capabilities summarized in Figure 19.

In 2003, NASA commissioned JPL to conduct an Origins Probe concept study of BLISS. As part of this effort, the U.S. study team worked with colleagues in Japan to specify the instrument and define clean, readily implemented and maintained interfaces. If BLISS is recommended for implementation participation on the project is expected to be widely competed.

In seeking participation on SPICA, the US FIR/SMM community will be pursuing a cost-effective strategy adopted more than a decade ago, first with our participation on ESA's ISO mission as a minor partner, and currently as a minor partner on ESA's Herschel mission to be launched in 2009. On ISO, NASA's primary contribution was data downlink recovery at its ground station at Goldstone, CA, whenever the spacecraft was obscured by Earth from the primary downlink station at Villafranca in Spain. In return, hundreds of US investigators obtained ISO observations enabling them to author or co-author many of the ~1500 refereed

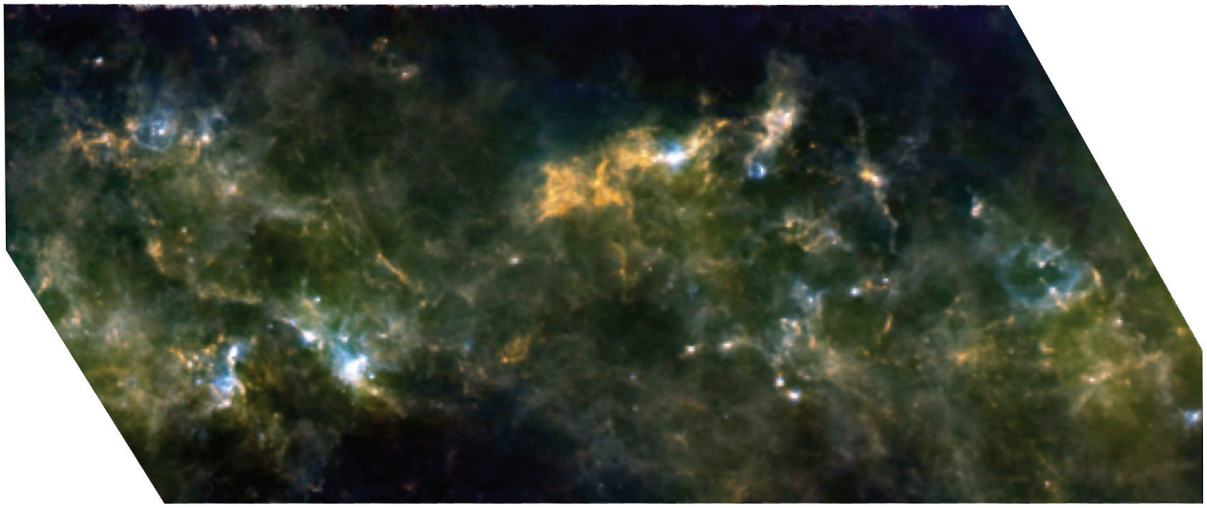

Figure 20. A 50 square degree map of the Galactic plane in the Vela region observed with the Balloon Large Aperture Submillimeter Telescope (BLAST), a 2-meter aperture telescope operating at 250 μm (blue), 350 μm(green) and 500 μm (red), revealing previously undetected cold dust and registering dust temperatures as low as ~12 K. The spectrophotometer on board is based on that of the SPIRE instrument on Herschel, which is expected, among many other projects, to provide maps of the coldest Milky Way clouds with roughly twice the angular resolving power of BLAST and significantly greater sensitivity. (Courtesy the BLAST Team.)

scientific ISO publications on record. US participation on Herschel and SPICA is expected to be similarly cost-effective. On Herschel, NASA expenditures through hardware and software contributions, data analysis, end of active mission, and archiving are budgeted at $270M, a relatively modest sum considering that it provides the US scientific community full access to a Great-Observatories-class mission.

4b. A Balloon-Borne Far-Infrared Interferometer(38, 39)

A balloon-borne far-infrared interferometer could serve as a precursor and test-bed for critical technologies anticipated for SPIRIT. This has led to the proposal for a FIR/SMM balloon-borne double-Fourier interferometer, i.e. an interferometer capable of both spatial and spectral interferometry. The sensitivity of balloon-borne telescopes is apparent from Figure 20.

Use of a fixed ~ 8-meter boom will enable mapping at an angular resolution of 0.5 arcsec at 40 µm. The ~ 220 K ambient temperature optics outside the cryostat at float altitudes, and two ~50-cm aperture siderostats would suffice to spatially resolve many of the myriad IRAS sources with fluxes exceeding 1 Jy. Many of the technical prerequisites for such a program already exists. A series of flights with such a balloon borne interferometer will probe the astronomical landscape at high spatial resolution in the FIR/SMM and simultaneously test all significant optical and metrological components required for a space-based double-Fourier interferometer.(39)

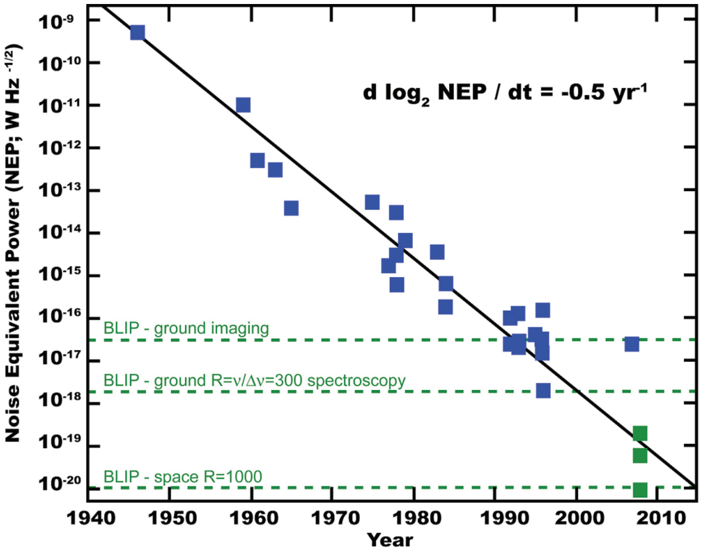

Figure 21. Improvement in detector sensitivity over the past 70 years. "Richard's Law" predicts an average doubling of sensitivity every two years. The horizontal green lines show the photon-background-limited noise equivalent powers entailed for ground-based and space-based detectors. Currently available detectors satisfy the background limit for ground-based imaging and spectroscopy. But a grating spectrometer on a cold telescope in space requires detectors two orders of magnitude more sensitive than for a similar instrument on the ground or on a sub-orbital observatory. Blue symbols indicate performance of detectors currently operating in the field, green points indicate laboratory measurements of test devices. (After Jonas Zmuidzinas.)

4c. Detector Development:

A major US contribution to the Herschel mission has been the development and production of sensitive detectors --- bolometers for the Spectral and Photometric Imaging Receiver (SPIRE) and high-frequency heterodyne receivers for HIFI. Any US participation on SPICA will similarly involve improved detector production, as would any significant steps toward realizing SAFIR or SPIRIT. The US has consistently maintained its world leadership in detector technology, and maintaining this lead is essential to enable our making cost-effective contributions to major international collaborations.

Detector development is at the heart of all current plans. Steady progress on bolometers has followed (Paul) Richards' law, improving pixel sensitivity by nine orders of magnitude over the past 50 years. The development of pixel arrays has been comparably revolutionary. Over the past two decades, development on submillimeter pixel arrays has followed Richards' second law, producing detector arrays with pixels now numbering in the thousands. Combining these two trends, on telescopes appreciably larger than those flown in space to date, we confidently expect a steady increase in overall observing efficiency, which by now has reached factors in the range of 10^{12} in comparison to capabilities available in the early 1960s.

A variety of new classes of detectors are currently under development and promise further improvements, including photon counting devices sensitive to single photons. These range over transition edge bolometers, in which the photon energy sufficiently heats a superconducting bolometer to destroy its superconductivity; quantum capacitor detectors in which photon absorption changes device capacitance; kinetic inductance detectors; and quantum well devices.

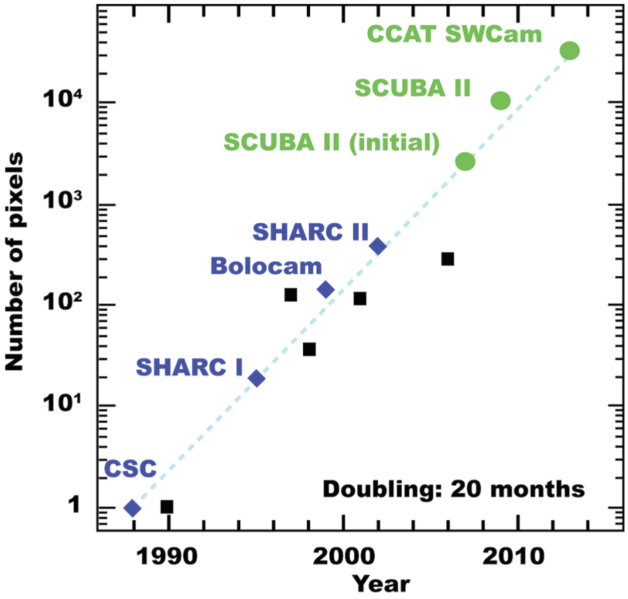

Figure 22. The Revolution in SMM Array Technology and Imaging: Richards' Second Law. Blue symbols show accomplishments. Green symbols indicate current expectations.(Courtesy Jonas Zmuidzinas.)

Each of theses classes of devices has a different advantage and characteristics and serves varying purposes offering exciting opportunities. Detector development, however, also requires sustained long-term funding.

4d. Steps toward SAFIR and SPIRIT

Realization, in space, of a single aperture 10-m class cryogenically cooled FIR/SMM telescope, SAFIR, and a similarly cooled spectra/spatial Space Infrared Interferometric Telescope, SPIRIT, will also require further cryo-cooler and cryo-mechanism development to enable longer-lived, lighter-weight, and thus more cost effective and increasingly reliable missions in space. Mechanical systems will need to be refined. Optical components, thermal modeling, automated metrology to maintain required alignment, and a number of other components and capabilities will also have to be pursued to bring all the required technical prerequisites to technology readiness level 6 (TRL 6), where phase-B design studies for either the interferometer or the large aperture telescope can be contemplated. Most of these requirements are common to both SAFIR and SPIRIT. Advances in many of these technologies will be inherited from JWST,

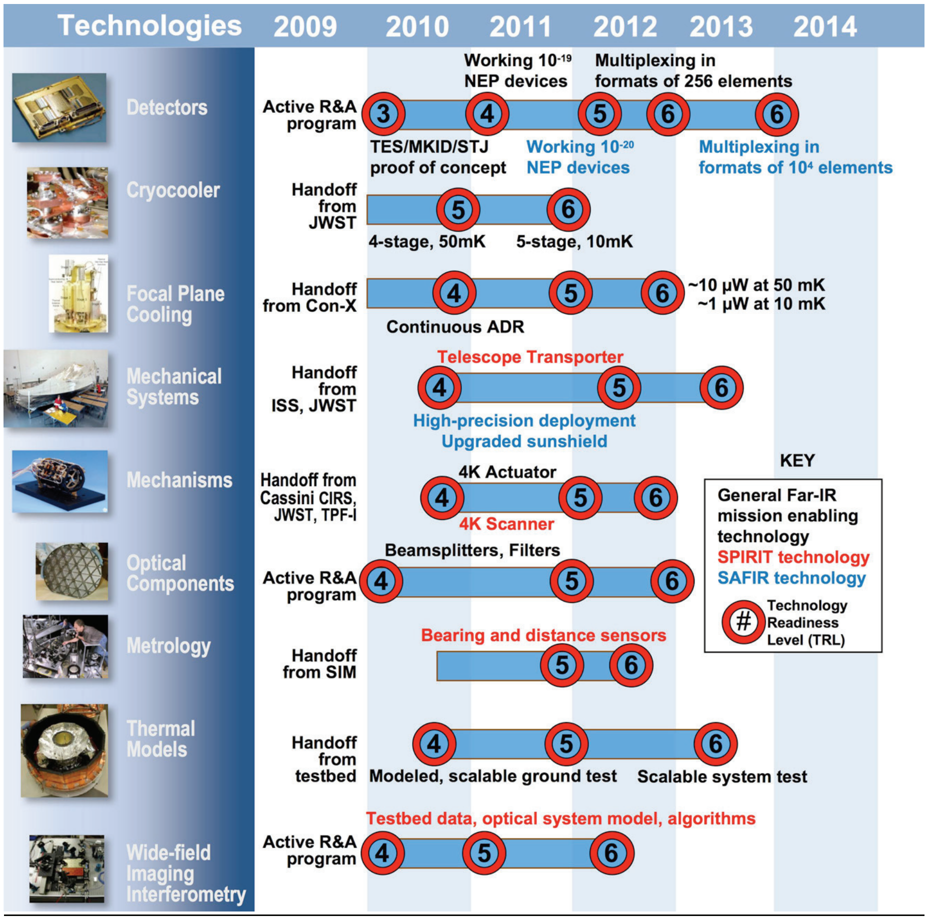

Figure 23. Technology development path leading to technological readiness level TRL 6 for both SPIRIT and SAFIR.

Constellation-X, and other NASA programs, but considerable investments will nevertheless be required in the decade ahead.

NASA commissioned a Vision Mission study of SAFIR completed in 2005, and an Origins Probe study of SPIRIT carried out that same year. Both studies addressed the technical prerequisites to enable these missions. A variety of costing studies have also been conducted on each.

To advance both these FIR/SMM astronomical observatories, we propose a long-term, phased program that seeks completion in the next twenty-five years of both these facilities.

(i) Timing:

Having conducted and completed comprehensive investigations of SAFIR and SPIRIT during the past several years, our community realizes it is unlikely that either of these two missions will be launched within the decade of 2010-2020. However, to launch them in the 2020 – 2035 era, we need to embark today on a coherent long-term program defining the way forward, even as we continue to increase our understanding of the Universe with FIR/SMM facilities that are both affordable and available in the immediate decade ahead, 2010 – 2020.

(ii) SAFIR: Several concepts for a telescope in the SAFIR class have been proposed. Most recently JPL has studied in considerable depth the Cryogenic Aperture Large Infrared Space Telescope Observatory (CALISTO), a very high efficiency telescope with an elliptical primary.

The CALISTO realization of the SAFIR concept adopts an off-axis, unblocked telescope, which has the important attribute of dramatically reducing stray light from the Galactic Plane and zodiacal dust in our Solar System. This allows SAFIR to achieve astronomical-background-limited sensitivity over a large fraction of the sky, which is essential to achieve the demanding scientific goals for this mission. An unblocked aperture also increases the light-gathering efficiency of a telescope by approximately 25 percent. JPL has studied the costs of a version of CALISTO built around a 6 x 4 m elliptical primary that could fit fully deployed into the shroud of existing launch vehicles. If the proposed Ares V launch vehicle comes on line, larger versions of SAFIR could be launched, potentially at lower payload cost by avoiding the challenges of more complex deployment. With pursuit of the technical prerequisites during 2010 – 2020, launch of a SAFIR class facility will be enabled by 2020 – 2035.

(iii) SPIRIT: We envisage the design, development, and launch of a Space Infrared Interferometric Telescope (SPIRIT) with a baseline of 40 m, also between 2020 and 2035.

SPIRIT with a baseline of 40 m will improve on the angular resolution of SAFIR by an order of magnitude, since the angular resolution of an interferometer operating at wavelength λ is $\lambda/2D_I$ in place of $1.2\lambda/D_A$ for a single dish. Here D_I, is the maximum interferometer baseline and D_A the single dish aperture. For a star-forming region at 140 pc, the angular resolution of SPIRIT will be ~15 AU at 40 μm, adequate for studying the cold outer regions of imaged disks around young stars and mapping their spectral line and continuum emission. For planetary systems at 50 pc, a planet at 5 AU is resolved from its parent star at the same wavelength. The Goddard Space Flight

Center has studied the implementation and cost of this interferometer, and defined the technical prerequisites that need to be developed in the 2010 – 2020 decade to enable launch into space in 2020 – 2035. An 8-meter-baseline precursor to SPIRIT carried aloft by a balloon will be able to test all technical aspects of this effort by demonstrating the ability to map astronomical sources with unmatched FIR/SMM spatial resolution.

(iv) Development of Technical Prerequisites:

As part of these efforts, we plan to further develop cryo-coolers and cryo-mechanisms to enable longer-lived, lighter-weight, and thus more cost-effective and increasingly reliable FIR/SMM astronomical missions in space. These and refined mechanical systems, automated metrology to maintain correct alignment of optical components, and a number of other technologies will need to be brought to Technical Readiness Level 6 (TRL 6), in the 2010 – 2020 decade, so that detailed design studies for SAFIR and SPIRIT can be completed. Many of these technologies are common to both missions; several will be inherited from JWST, Constellation-X, and other NASA programs.

(v) Phase-A Studies for SAFIR and SPIRIT:

Finally, we propose to conduct Phase-A studies of both SAFIR and SPIRIT before the end of the 2010 - 2020 decade to provide the 2020 Decadal Review with a well-reasoned and documented recommendation on which of these two missions should be launched first in the 2020 – 2035 era. This recommendation will be influenced both by priorities of the larger astronomical community around the years leading up to 2020 and by technological readiness and anticipated cost.

Successful completion of the SPICA mission is likely to be a prerequisite for both SAFIR and SPIRIT. Both missions will have to build on technical experience gained in constructing a fully cooled telescope with an aperture larger than Spitzer's 85 cm telescope, the largest fully cryogenically cooled telescope constructed to date. SPICA will also shape the astronomical landscape which the next generation of instruments will aim to further explore.

(vi) Continuity of a Successful Venture

In the context of these plans, we recall that the Decadal Review of 2000 recommended that "A coordinated program for space optical and infrared astronomy would build on the experience gained with NGST [now JWST] to construct SAFIR and then ultimately, in the decade 2010 to 2020, build on the SAFIR,TPF, and SIM experience to assemble a space-based far infrared interferometer.(40)

The acronyms for the missions may have changed, and we obviously lag far behind the schedule anticipated ten years ago, but the rationale for our long term program continues to be valid, as attested to by the cascade of successes achieved by infrared astronomy in the ten years since that last Decadal Review. We believe our vision remains sound, and that the support we are requesting for the next ten years is both cost-effective and affordable.

5. Summarizing Conclusion

1. The highest priority for the US FIR/SMM space community in the decade of 2010 - 2020 is significant participation in the Japanese-led SPICA mission. Contribution of a US FIR background-limited spectrometer with a highly sensitive detector array, will enable a broad astronomical program, with JWST, SPICA and ALMA, covering the spectrum from the near infrared to the millimeter range, all at comparable sensitivities. Japan's schedule for SPICA is extremely tight. To keep US options open, NASA should soon initiate steps for potential US participation, while awaiting the recommendations of the Decadal Review.

2. Our long-term goal for the 2020-2035 era is a program of sensitive imaging and spectroscopic observations capable of resolving small-scale cosmic structure across the entire FIR/SMM range. This will require both (i) the light-gathering power of a 10-m class cryogenically cooled telescope in space to allow us to resolve the Extragalactic Infrared Background at 100 – 200 µm the way Spitzer resolved it at 24 µm, and (ii) a similarly cooled FIR/SMM spatial interferometer with angular resolving power matching that of JWST around 25 µm and ALMA in the SMM range. This combination will allow us to study the sky with balanced capabilities across the electromagnetic spectrum.

3. To realize this goal we will need, in 2010 – 2020, to: (i) prepare the scientific and technical prerequisites and (ii) conduct full phase-A studies of both a 10-m class cryogenically cooled Single Aperture Far-Infrared Telescope, SAFIR, and a similarly cooled Space Infrared Interferometric Telescope, SPIRIT, before the end of the decade. These activities will allow the Decadal Review of 2020 to recommend which of these two missions best meets the scientific priorities and is technologically ready at that time. Our priority would be that one of these missions be launched before 2030, the other before 2035.

Both an interferometer and a large filled aperture will ultimately be required. A large filled aperture lacks the angular resolution of a spatial interferometer with a longer baseline. But an interferometer with a smaller light collecting area will be less sensitive. Both SAFIR and a space-based infrared interferometer (now exemplified by the SPIRIT mission concept) were recognized in the 2000 Decadal Review and have been intensively studied since then.[‡]

4. The program we propose for the decade 2010-2020 is both scientifically farsighted and technologically responsible. It is critical for the realization of a dedicated thrust in the era of 2020-2035 to bring far-infrared/submillimeter capabilities in space to a level where some of the deepest scientific questions of all time will be answered: How did the first cosmic structures form? Where and when did the heavy chemical element abundances begin to rise? How did they influence the dynamics of stellar system and black hole formation? Where did the biogenic molecules, the seeds that led to the appearance of life, originate?

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[‡] The Year 2000 Decadal Report states, "A rational coordinated program for space optical and infrared astronomy would build on the experience gained with NGST to construct SAFIR, and then ultimately, in the decade 2010 to 2020, build on the SAFIR,TPF, and SIM experience to assemble a space-based, far-infrared interferometer." (40)

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Acronyms:

AGN	Active galactic nucleus – also a galaxy with such a nucleus
ALMA	Atacama Large Millimeter Telescope
BLAST	Balloon Large Aperture Submillimeter Telescope
BLISS	Background Limited Infrared/Submillimeter Spectrometer
CALISTO	Cryogenic Aperture Large Infrared Space Telescope
CCAT	Cornell Caltech Atacama Telescope
CIB	Cosmic Infrared Background
CMB	Cosmic Microwave Background
COBE	Cosmic Background Explorer
CGRO	Compton Gamma Ray Observatory
ESA	European Space Agency
FIR	Far-infrared
FIR/SMM	Far-Infrared/Submillimeter
HIFI	Heterodyne Instrument for the Infrared on the Herschel space mission
HST	Hubble Space Telescope
IRAS	Infrared Astronomical Satellite
ISO	Infrared Space Observatory
JCMT	James Clerk Maxwell Telescope
JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
LIRG	Luminous Infrared Galaxy
NEP	Noise equivalent power
PAH	Polycyclic Aromatic Hydrocarbons
PDR	Photodissociation Region
SAFIR	Single Aperture Far Infrared Telescope
SMM	Submillimeter
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPIRE	Spectral and Photometric Instrument for the Far-Infrared on Herschel
SPIRIT	Space Infrared Interferometric Telescope
SWAS	Submillimeter Wave Astronomy Satellite
TRL	Technological Readiness Level
ULIRG	Ultraluminous Infrared Galaxy
WISE	Wide-Field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe