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An Explorer−class Astrobiology Mission

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ABSTRACT

In this paper we describe a potential new Explorer−class space mission, the AstroBiology Explorer (ABE), consisting of a relatively modest dedicated space observatory having a 50 cm aperture primary mirror which is passively cooled to T<65 K, resides in a low−background orbit (heliocentric orbit at 1 AU, Earth drift−away), and is equipped with a suite of three moderate resolution spectrographs equipped with first−order cross−dispersers and large format (1024×1024 pixel) near− and mid−IR detector arrays cooled by a modest amount of cryogen. Such a system would be capable of addressing outstanding problems in Astrochemistry and Astrophysics that are particularly relevant to Astrobiology and addressable via astronomical observation. The observational program of this mission would make fundamental scientific progress in each of the key areas of the cosmic history of molecular carbon, the distribution and chemistry of organic compounds in the diffuse and dense interstellar media, and the evolution of ices and organic matter in young planetary systems. ABE could make fundamental progress in all of these areas by conducting an approximately one year mission to obtain a coordinated set of infrared spectroscopic observations over the 2.5−20 μm spectral range at spectral resolutions of R ? 1000 of approximately 1000 galaxies, stars, planetary nebulae, and young star planetary systems.

Keywords: Astrobiology, infrared spectroscopy, Explorers, interstellar organics, telescope, spectrometer

1. INTRODUCTION

The field of Astrobiology, the study of the origin, evolution, and future of life in the universe, has received considerable attention in recent years. One of the principal overlaps between astrophysics and astrobiology is in the area of quantifying the role that interstellar materials may play in the origin of life. Tremendous strides have been made in our understanding of interstellar material over the past fifteen years thanks to parallel developments in observational astronomy and laboratory astrophysics. Dust in the diffuse interstellar medium (ISM) is now known to consist largely of cold refractory materials comprised of amorphous and crystalline silicates mixed with an amorphous carbonaceous material containing aromatic structural units and short, branched aliphatic chains. In the dense ISM, these cold dust particles are coated with mixed molecular ices, of which the major constituents are known. Lastly, the signature of carbon−rich polycyclic aromatic hydrocarbons (PAHs) is widespread throughout the ISM. These organics and ices play a central role in the chemistry of dense, dark molecular clouds−with the ices acting as both reservoir and reaction center for the species detected in the gas and, together with the organics, setting the stage for the chemistry that occurs when stars, planets, and ultimately life form.

This great progress has only been made possible by the close collaboration of observers with laboratory experimentalists, all with the goal of applying their combined skills to astrophysical problems. We are now poised to take deep, insightful looks into the chemistry of the cosmos, a vision which will bear directly not only on fundamental astrophysics but also on our understanding of the possibility of life emerging elsewhere in both time and place. Experimentally, the ability to carry out realistic simulations of the conditions holding in various astronomical environments and measure the spectral and other physical properties of various materials under these conditions has enabled this progress by showing how to interpret the data taken by ground−based (eg. IRTF, UKIRT, etc.), airborne (KAO), and spaceborne observatories (eg. ISO). Such highly interdisciplinary collaborations are essential to ensuring fundamental, in−depth coverage of the wide−ranging challenges posed by astrobiology. Central to continued progress in this area is the continued improvement in both the quality and quantity of astronomical observations of the organics in space. With this point in mind, we here describe an Explorer−class mission, the AstroBiology Explorer (ABE), capable of advancing our understanding of role of the ISM in astrobiology to the next level.

In Sect. 2 we briefly describe our core observational program to understand the molecular evolution of the biogenic elements in the universe and within our own galaxy and summarize the instrumental requirements levied by the science goals. Other areas of astrophysical, astrochemical, and astrobiological interest are also described briefly in Sect. 2. The overall AstroBiology Explorer mission concept is described in the next three sections which deal with the ABE Instrumentation (Sect. 3), ABE spacecraft (Sect. 4), and Mission Operations (Sect. 5). The paper is summarized in Sect. 6.

2. THE CORE ASTROCHEMISTRY SCIENCE MISSION

The scientific goals of the ABE Mission will be achieved by an observing strategy that uses a modest number of programs tightly focused on the creation and evolution of organic materials in space. Based on data from ground–based, airborne, and spaceborne observatories (eg. IRTF, KAO, ISO), there is substantial evidence for the existence of relatively complex organic compounds in a multitude of astrophysical environments. However, the identifications of these organics are based on limited spectral data taken from a relatively modest number of bright, and in most cases, 'local' objects. As a result, the objects studied to date reflect a serious selection effect. To make further significant progress in this area, a large, coordinated program of observations is needed. The science program of this mission should greatly extend our understanding of the composition, distribution, and history of organics in the universe through four inter–related observational programs.

2.1 – Major Tasks Within the Core Science Program

First, to address issues about the universality of chemical evolution, we propose to measure the infrared emission associated with widespread polycyclic aromatic hydrocarbons (PAHs)[1,2] in a variety of external galaxies by measuring their 2.5–20 μm spectra. The IR emission features attributed to aromatic materials were seen in the spectra of many of the distant galaxies examined by ISO.[3] If obtained with sufficient spectral resolution and S/N, such spectra would provide information regarding the size distribution of the emitting species, the fractions in neutral and ionized forms, and the dominant molecular structures and stabilities of the emitting species. Since PAHs are believed to be formed in circumstellar shells of evolved stars, their detection promises to be the best measure of the introduction of heavy elements into the interstellar media of other galaxies. Codifying the spectra with galactic type will yield insight into the conditions necessary for these species to form and the conditions that determine the molecular structures that are favored.

Second, we propose to study the composition and distribution of organics within the diffuse interstellar media (ISM) of our and other nearby galaxies by measuring their absorption bands in the light of background stars. Absorption spectra taken along a limited number of lines of sight within our galaxy,[4,5] as well as spectra taken of a small number of other galaxies,[6] have demonstrated that a significant fraction of the carbon in the diffuse ISM resides in complex aliphatic hydrocarbons (C_nH_{n+2}). However, we currently have a poor understanding of the distribution of this material,[7] and nothing is known about the variability (if any) of the composition of this material as a function of galactic location. Thus, to better understand the nature and abundance of the organics within the diffuse ISM in our galaxy, we propose to obtain high quality spectra at resolutions of $R \equiv \lambda/\Delta\lambda$? 1000 over the entire 2.5–20 μm range for a significant number of background stars distributed throughout our galaxy. We also intend to examine a number of nearby galaxies of different types to establish the frequency of this material in other galaxies, determine how its abundance and character vary with galactic classification or environment, and determine how this material is distributed within galaxies.

Third, we propose to study the evolutionary chemistry undergone by aromatic compounds as they transition through (1) the protoplanetary/planetary nebula (PPN/PN) stage that marks the original ejection of PAHs into the ISM, and (2) the H–II regions that typify stellar nurseries. The chemistry in these regions are far from equilibrium and the associated PAH populations (and consequently their spectra) should undergo drastic changes over relatively short periods of time. Thus, these regions hold great potential to reveal the details of interstellar PAH chemistry. Since we cannot follow the chemical changes in a PN as it evolves, we must instead rely on the spectra of many objects, each at different points along their evolutionary path, to provide a complete picture of their evolution. In order to study the functionalized PAH structures that are expected to arise in H–II regions where icy grain mantles have only recently volatilized, we must measure the emission spectra of very young (so–called "ultracompact") H–II regions or measure more mature H–II regions with sufficient spatial resolution to isolate the boundary where the ionization front is just beginning to erode local dense molecular cloud material. It will be necessary to study a number of objects to cover a range of environmental conditions and evolutionary histories.

Finally, we propose to study how organic molecules evolve as they pass from the quiescent dense ISM to protostellar envelopes to protoplanetary disks to planetary systems. Combined observational and laboratory studies show that complex organic compounds can be formed in interstellar ices,[8,9] even in ices made up of simple molecules like H_2O, CH_3OH, NH_3, etc. Many of these compounds are biologically important.[9] Therefore, making an inventory of the molecules frozen on grains in dense clouds is important to understanding the distribution and abundance of ices and organics in space (Figure 1). We propose to inventory the molecular ices characteristic of quiescent regions of ~6 dark clouds within 500 pc by observing weak (~1%) molecular absorptions seen against background stars over approximately 10 lines–of–sight within each cloud. To understand the potential importance of these materials for the origin of life, we need to follow them as they are incorporated

Figure 1. ISO SWS absorption spectrum of the massive protostar W33A.[10] A rich variety of molecular ice species are seen in absorption in its protostellar envelope. This object has a luminosity that is *at least 3 orders of magnitude* greater than that of the background stars, low–mass protostars, and circumstellar disks which must be observed to understand the pre–biotic chemical evolution of Earth–like planets around solar type stars.

into forming stellar systems. Thus, we also plan to conduct a systematic spectroscopic study of organic molecular ices in protostellar envelopes, pre–planetary disks, and post–planetary disks to trace the evolution and delivery of prebiotic materials in young planetary systems. That interstellar materials survive these transitions is clear; interstellar materials are found in primitive meteorites.[11] High S/N spectra are particularly critical if we are to obtain high quality spectra of low–mass protostars, stars seen through quiescent dark clouds, or circumstellar disks – objects which are most important for studying the chemical evolution of biogenic molecules that can end up on Earth–like planets.

2.2 – Other Enabled Science

The core science mission places constraints on the required capabilities of the instrumentation needed to carry out the observational program. The basics of such a system are described in the following sections. An instrument and spacecraft meeting these requirements is ideal for studying the molecular evolution of the biogenic elements in the universe. However, such an instrument would *also* be capable of making observations of great significance addressing a variety of astrophysical issues not falling directly into the observing programs described above. It would, therefore, clearly be advantageous to devote some portion of the instrument's scheduled time to making observations that address studies not outlined above. Examples of other observational programs which could benefit from use of this instrument include (but are clearly not limited to) the study of solar system objects (comets, asteroids, planets, KBOs), zodiacal dust in the solar system, supernovae remnants, stellar spectroscopy, interstellar mineralogy, novae, supernovae, and other targets of opportunity.

2.3 – Requirements Levied by the Science Program

The vast majority of the infrared bands produced by organic compounds fall in the infrared from 2.5 to 20 µm. This is a natural consequence of the masses and interatomic bond strengths of C, H, O, and N. While chemical functional groups, and some classes of molecules, can be identified on the basis of single infrared bands, it is usually necessary to detect multiple bands of a molecule to derive meaningful identifications. Thus, most of the scientific tasks outlined above require spectral coverage across most or all of this range. A spectral resolution ($R \equiv \lambda/\Delta\lambda$) of about 3000 is desirable for this work; it is high enough to resolve almost all the bands produced by organics in solids and provide sufficient detail of gas phase rotational lines and envelopes that they can be separated from the solid state features. At some wavelengths it is possible to require lower resolutions, but all the tasks outlined above require resolving powers of at least 1000.

Many of the absorption and emission features that will be studied will have strengths that are only a few percent of the continuum flux. Thus, signal–to–noise (S/N) values of 100 or greater will be required in almost all cases. The target list for

Table 1. Performance Requirements for the AstroBiology Explorer

Wavelength Coverage	2.5 – 20 μm GOAL 2.5–18.0 (minimum)
Spatial Resolution (slit width)	< 10" at all wavelengths
Spectral Resolution R ≡ λ/Δλ	3000 GOAL Minimum 2000 (2.5–5.0 μm) Minimum 1500 (5.0–10.0 μm) Minimum 1000 (10.0–20.0 μm)
Slit length	?15"
Sensitivity @λ=10 μm in 1hr (S/N=100)	25 mJy
Operational Lifetime	? 1 yr
Pointing Stability	1" for a 1000 sec exposure
Slit overlap on sky	coincident on sky to 0.5"

this mission will contain over 1000 objects, many of which are relatively faint, on the order of 0.01–0.10 Jy. Thus, proper execution of all the tasks discussed in Sect. 2.1 will require high sensitivities. Based on realistic expectations, we anticipate that obtaining the spectra of our target objects with the needed quality will require a mission duration of approximately 1.0 to 1.5 years, a timescale that will allow us to study objects in all parts of the sky.

The main requirements that the AstroBiology Explorer will have to meet if it is to properly carry out the science described in Sect. 2.1 are summarized in Table 1 above.

3. THE ASTROBIOLOGY EXPLORER (ABE) INSTRUMENTATION

Preliminary integration times needed to carry out the program outlined in Sect. 2 have been computed for optimized, background–limited spectrographs on a cool, Explorer–class, space–based 50 cm class aperture observatory as described below. The results show that such a comprehensive observational program is ambitious but within the scope of a moderate space mission. Despite being ambitious, this is probably the minimum comprehensive program that will significantly advance the state of the art in observational Astrobiology / Astrochemistry.

Our observational program could be accomplished in ~1 year with a relatively modest dedicated space observatory. For the purposes of estimating observing time, we modeled such a mission as consisting of a 50 cm aperture (primary mirror) which is passively cooled to T < 65 K and equipped with a suite of three moderate order (m ~ 10) dispersive spectrographs equipped with first–order cross–dispersers. We envision using very large format (1024×1024 pixel) near– and mid–IR detector arrays allowing collection of an entire spectral octave simultaneously. This simultaneity is tremendously important for our observing program which requires both moderately high spectral resolution and large spectral range. The instrument would require a modest amount of cryogen (perhaps solid H_2) in order to cool its detectors to operating temperature. An image of the current layout concept for the observatory is provided in Figure 2.

3.1 – Optical Design of the Telescope and Spectrographs

The resolution requirement is met by an effective aperture of approximately 0.5 m. A diffraction–limited Cassegrain telescope with a 0.5 m primary mirror at a temperature of 65 K would also meet the sensitivity requirement (also allowing for some incident stray light from a warm radiation shield). A Ritchey–Chretien design allows a field large enough to provide an acquisition camera without reimaging optics. In order to be Nyquist sampled the focal ratio of the telescope should be: f/# = (pixel size) * 2 / λ; f/# ? 18 if the acquisition camera operates at 2 μm and has a pixel size of 18 μm.

The 2.5–20 μm wavelength range spans 3 full octaves; at least 3 separate spectrographs (or 3 grating configurations of a single spectrograph) will be required if diffractive dispersion elements are used. Covering an entire octave in spectral range per exposure requires at least 2R pixels in the spectral direction in order to Nyquist sample the spectrum where R≡λ/Δλ. Near and mid–IR detector arrays up to 1024×1024 pixels in size are expected to be available for launch in 2005 or 2006. The spectrographs must be cross–dispersed if a single detector array is to be used in each one. This configuration is likely to be more compact and lower mass than one which has multiple detector arrays arranged linearly in the dispersion direction.

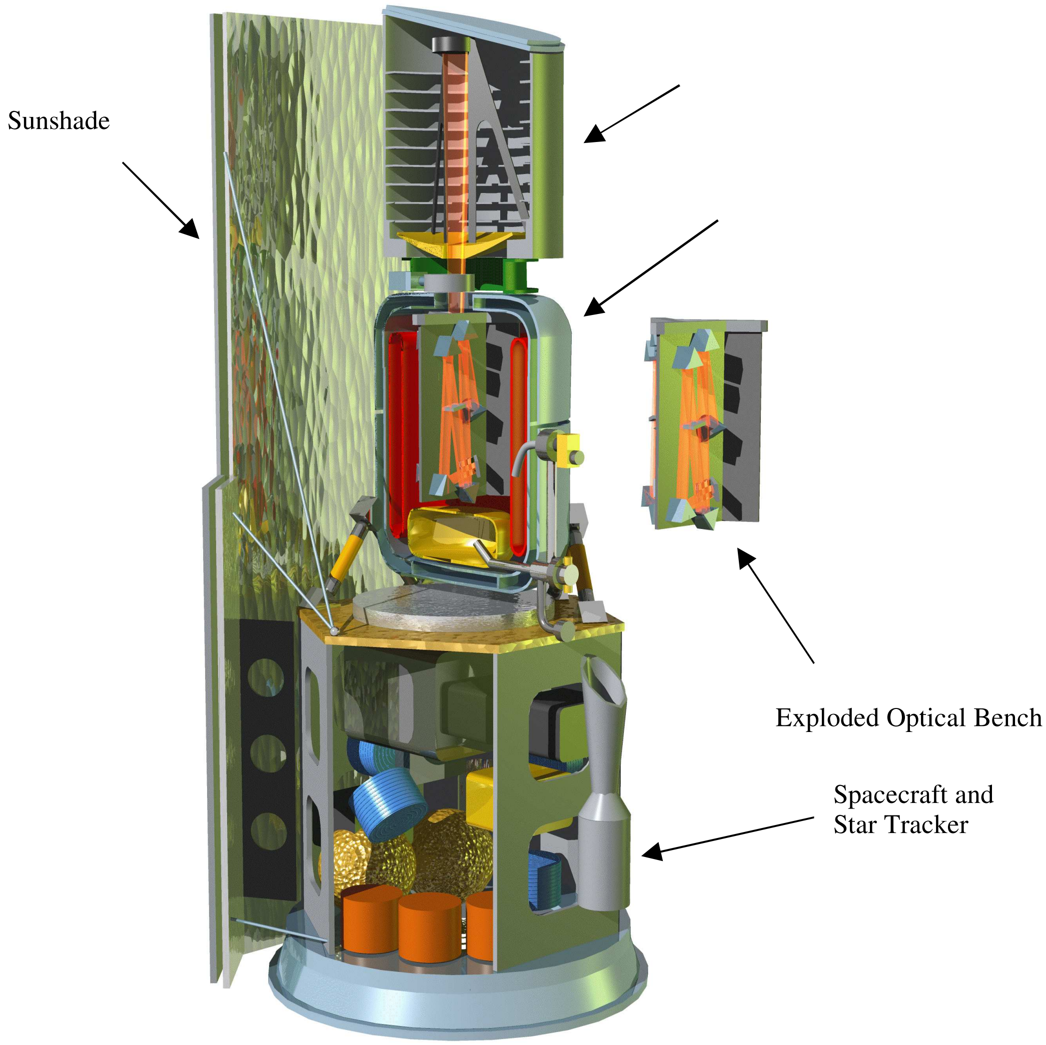

Figure 2. Conceptual Layout of the AstroBiology Explorer

Moderately long slit (~1.5×20 spatial resolution elements in size) cross–dispersed spectrographs would meet the resolution and spectral range requirements.

The spectrographs and the acquisition camera can share the telescope field of view in several ways. The simplest arrangement would have the acquisition camera and each spectrograph view a different area of the sky, each at different locations (spatial displacements or angular positions) within the focal plane (spatial sharing). An alternative technique would be to locate the acquisition camera detector as above but to share the same spatial field among all spectrographs. Dichroic beam splitters would direct light into each spectrograph by appropriate wavelength. This *spectral sharing* is more desirable than spatial sharing since each spectrograph could view the same object simultaneously, but the dichroic beamsplitters will reduce optical throughput and will likely have degraded performance (lower transmission and higher emissivity) at the wavelength limits of the spectrographs. The slit–size should also be a function of wavelength to maximize sensitivity.

All the spectrographs can share the same fundamental design. Each has an entrance slit located at the focal plane through which the beam expands at the telescope f/# until it reaches the collimator where it is the pupil diameter. The beam is then dispersed by an "echellette" and cross–disperser gratings and focused onto a detector by the camera optics. The collimator is likely to be a single element parabola, while the camera will probably be a multi–element anastigmatic design. The camera f/# is chosen so that the geometric mean wavelength of the spectrograph is Nyquist sampled (λ/2D pixels). The entrance slit

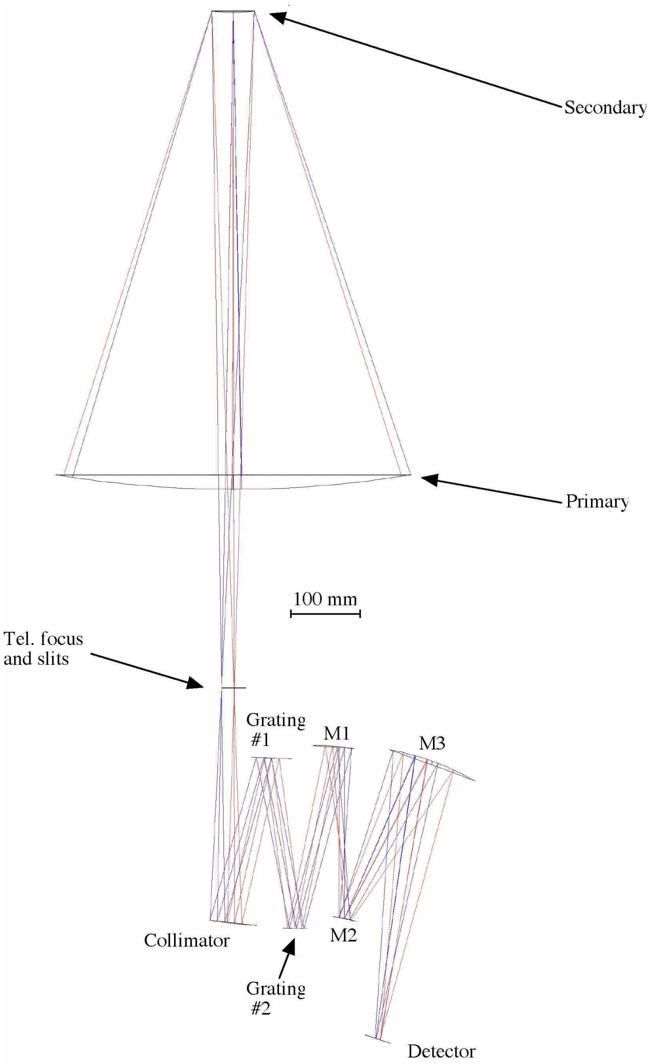

Figure 3. ABE Optics Schematic. Only a single spectrograph (MIR #1) is shown, and optics have been laid out in a single plane for clarity. The mirrors M1 – M3 form the spectrograph's three mirror anastigmatic camera.

is sized to be 3 detector pixels wide in order to maintain full spatial resolution and high optical throughput without a noise penalty when background limited. An example optical design of the telescope and MIR#1 spectrograph module is shown in Figure 3 above and the first order telescope and spectrograph parameters are summarized in Tables 2 and 3. The required gratings demand rulings that can be easily fabricated. These spectrograph designs produce two–dimensional spectra on the detector arrays like those shown in Figure 4.

3.2 – Detectors

In addition to meeting the above format (? 1024×1024 pixels) and wavelength (2.5–20 μm) requirements, detectors should have high quantum efficiency ($\eta > 50\%$) and low noise. Ideally, total detector noise [defined as (readnoise^2 + dark_counts)$^{0.5}$] should be less than the photon flux background on the detectors at all wavelengths. At a resolution of R=2500, the expected photon background (for the ecliptic pole, a T=50 K telescope, and minimal scattered light) per pixel is 0.03, 2, and 140 photons per second at wavelengths of 5, 10, and 20 μm, respectively, when spatially and spectrally Nyquist sampled. Thus, detector dark currents (electrons per second per pixel) should be equal to or lower than these values.

The Raytheon IR Center of Excellence (CoE) is developing 1024×1024 pixel format Si:As detector arrays for NGST and Origins observatories under the direction of NASA Ames Research Center. Complete devices are expected to be delivered in early 2000. These detectors require operation at T ~ 8 K in order to maintain low dark currents.

Table 2. First–order Telescope Parameters

Telescope Diameter	500 mm
Telescope f/#	16

Table 3. First–order Spectrograph Parameters

	NIR SPEC	MIR SPEC 1	MIR SPEC 2	Units
Array size	1024	1024	1024	pixels
pixel size	27	27	27	µm
Minimum λ	2.6	5.1	10.1	µm
Maximum λ	5.2	10.2	19.3	µm
Nyquist λ : λ/2D pixels	3.68	7.21	13.96	µm
Final Cam f/#	14.69	7.49	3.87	
pixel size	0.76	1.49	2.88	arcsec
Slit width	2.28	4.46	8.64	arcsec
Slit length	30.00	60.00	90.00	arcsec
Resolution (λ/Δλ)	2500	2500	3500	
Pupil Diameter	25	25	25	mm
Collimator Focal length	300	300	300	mm
camera focal length	367.15	187.18	96.69	mm

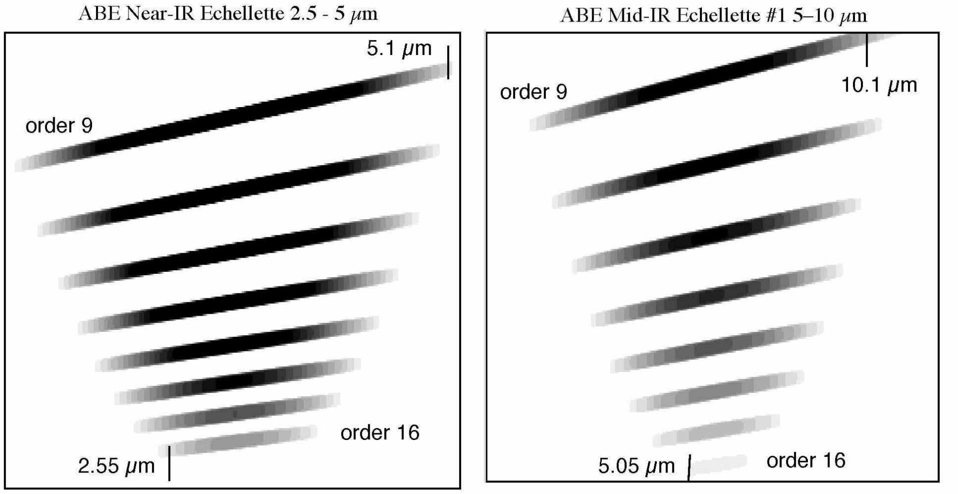

Figure 4. Example layout of two–dimensional spectra on the MIR Spec 1 and 2 detector arrays

Backgrounds at wavelengths λ < 5 µm are negligible, so observations will likely be detector–noise limited there. InSb arrays are currently available (Aladdin III from Raytheon IR CoE) in 1024×1024 pixel formats with good quantum efficiency in this region, read–noises ~30 electrons, and dark currents < 0.1 electrons/second. These devices operate at T ? 32–35 K to maintain this low dark current. Recently, the Univ. of Hawaii and the Rockwell Science Center have demonstrated HgCdTe arrays with high quantum efficiency in the 1–4.8 µm range with ~2× better read noise and dark currents. These prototype detectors are 1024×1024 pixels in size and have demonstrated this good performance at T = 64 K.[12] Furthermore, these detectors will also likely be developed in 2048×2048 pixel formats (sponsored by NGST).

Format, quantum efficiency, and noise performance of the detector array in the focal plane used for object acquisition/guiding is not critical. However, this detector should operate near the temperature of the primary mirror or slightly below. Therefore, a moderate−format (512×512 pixel or smaller) InSb or HgCdTe detector with small (? about 20 µm) pixels should work nicely. Sensitivity to 5 µm is preferred, but sensitivity to 2.5 µm may be adequate (2.5 µm HgCdTe detectors which operate at these temperatures are commercially available from the Rockwell Science Center).

3.3 – Thermal Design and Cryogenics

Calculations show that the sensitivity requirements can be met with a thermal design associated with the spacecraft configuration shown in Figure 2, where the telescope, spectrograph optics, and dewars are protected from solar radiation by a sunshade, and a shield around the telescope and spectrographs further isolates them from emission from the sunshade. The telescope and other optics are thermally isolated as much as possible from the spacecraft bus by minimizing connections and the careful placement of insulation. The equation for total background spectral flux density at the telescope focal plane is

$$F_\lambda = B_\lambda(T_{pri})\,\varepsilon_{pri} + B_\lambda(T_{shield})\,\varepsilon_{shield}$$

where F_λ is the observatory's total background flux, B_λ is the Planck function, and T_{pri} and ε_{pri} and T_{shield} and ε_{shield} are the temperatures and emissivities of the primary mirror and telescope shield, respectively. Figure 5 shows a summary of the system's heat map with the spacecraft at 273 K, the sunshade is at 130 K, and the primary mirror is the warmest optical element at 45 K. The heat map assumes primary mirror and sunshade emissivities of 0.05 and 0.03, respectively. It is possible to deviate from these parameters, but the resultant F_λ value must be low enough at all wavelengths to maintain the required sensitivities.

In addition to meeting the above primary, sunshade, and detector thermal requirements, high emissivity elements (order−blocking filters and gratings) in the spectrometers must be cooled to T ? 18 K to limit self−generated thermal backgrounds that hurt sensitivity. We wish to minimize cryogen mass and volume in order to conserve these resources for other instrument components. Therefore, we baseline a passively cooled telescope in a low background, deep space orbit far from Earth. Solid H_2 is the best candidate stored cryogen for the second stage, cooling the detectors to T ~ 8 K. The only other candidate cryogen at this temperature is liquid He, but it is ruled out because its latent heat is only 0.05 times that of solid H_2. Even with its higher density, 12 times more volume of liquid He would be required than for solid H_2. Solid H_2 is also a good