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 order (m~10) dispersive spectrographs equipped with first-order cross-dispersers in an "echellette" configuration 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 the 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 $R \equiv \lambda/\Delta\lambda \geq 1000$ 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

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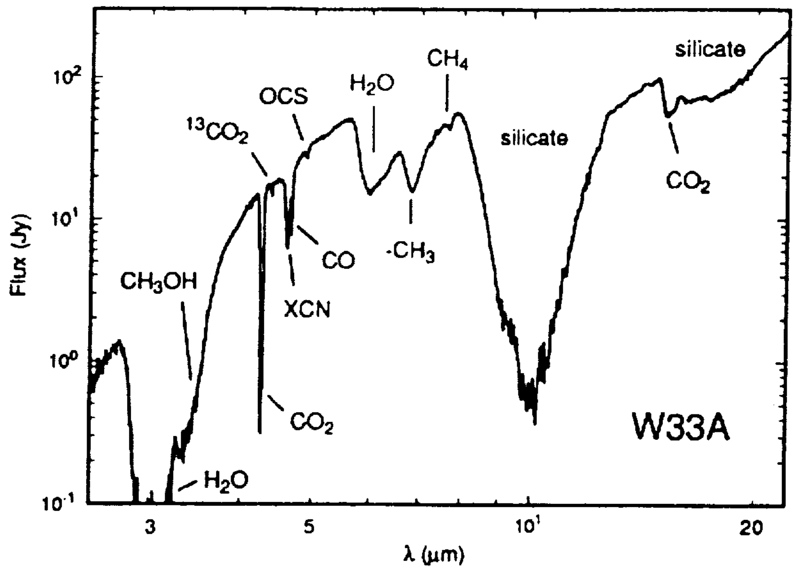

Figure 1. ISO SWS absorption spectrum of the massive protostar W33A.[10] A rich variety of molecular ice species are seen in absorption in its protostellar envelope. This object has a luminosity that is *at least 3 orders of magnitude* greater than that of the background stars, low-mass protostars, and 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 also require high sensitivities. Based on realistic expectations, we anticipate that obtaining the spectra of our target objects with the required 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 in an "echellette" configuration. 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 spacecraft is provided in Figure 2.

3.1 – The Telescope and Spectrographs

3.1.1 Optical design

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 goal 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. Near and mid-IR detector arrays up to 1024×1024 pixels in size are expected to be available for launch in 2005 or 2006.

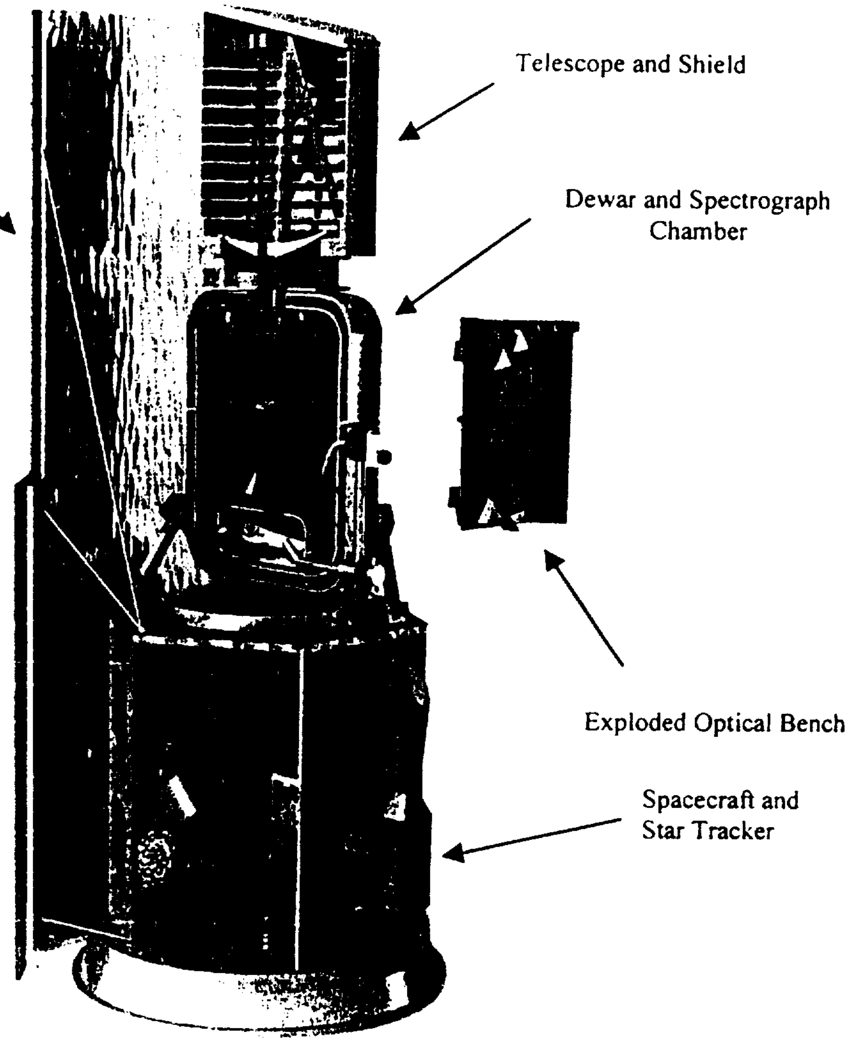

Figure 2. Conceptual Layout of the AstroBiology Explorer

Thus, 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. Moderately long slit (with ~ 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 ($\lambda/2D$ pixels). The entrance slit

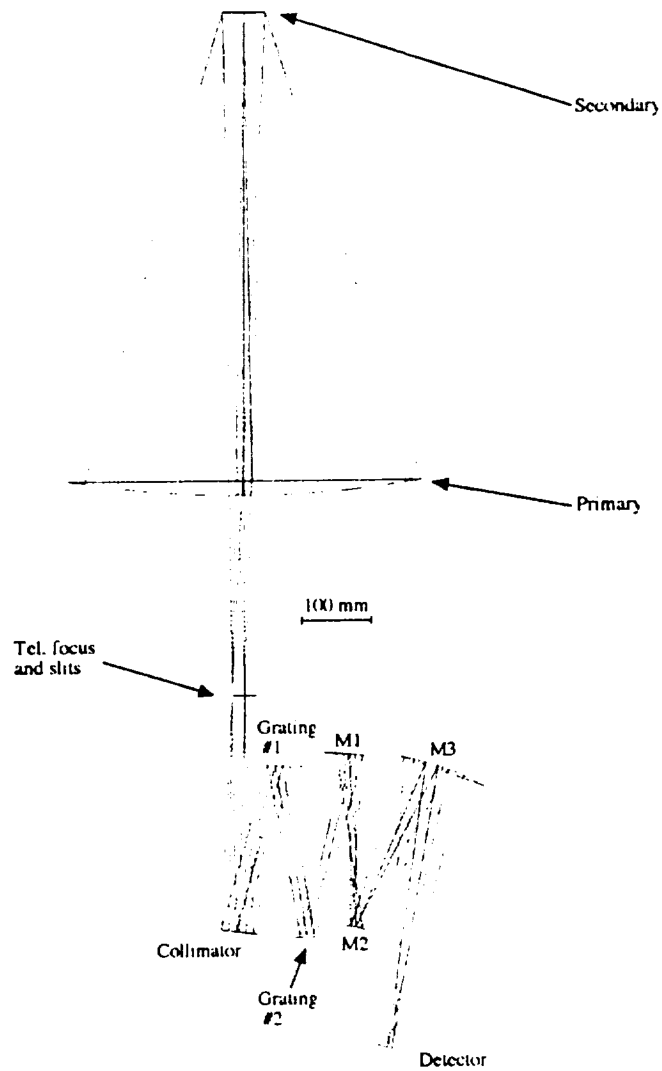

Figure 3. ABE Optics Schematic. Only a single spectrograph (MIR #1) is shown, and optics have been laid out in a single plane for clarity. The mirrors M1 – M3 form the spectrograph's three mirror anastigmatic camera.

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 Table 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.

3.1.2 Detectors

In addition to meeting the above format (≥ 1024×1024 pixels) and wavelength (2.5–20 μm) requirements, detectors should have high quantum efficiency (η > 50%) and low noise. Ideally, total detector noise [defined as $(\text{readnoise}^2 + \text{dark\_counts})^{0.5}$] should be less than the photon flux background on the detectors at all wavelengths. At a resolution of R=2000, 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 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
echellette lines/mm	12.17	11.10	8.18	lines/mm
echellette blaze	15.39	28.35	55.70	degrees
x-disperser lines/mm	26.06	27.90	25.53	lines/mm
x-disperser blaze	3.00	7.00	11.50	degrees

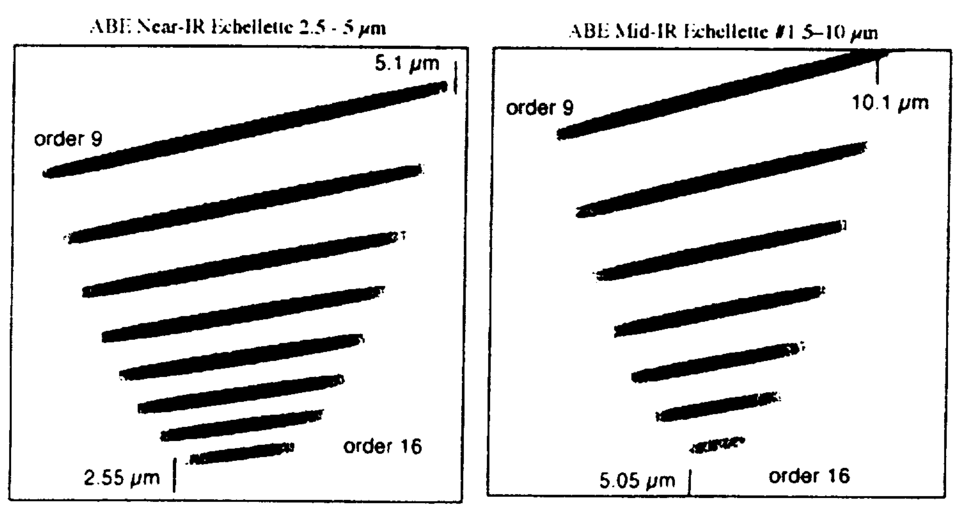

Figure 4. Example Layout of Two-Dimensional Spectra on the MIR Spec 1 and 2 Detector Arrays

Backgrounds at wavelengths $\lambda < 5$ 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 $T \leq 32$–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 is not critical. However, this detector should operate near the temperature of the primary mirror or perhaps slightly below. Therefore, a moderate-format (512×512 pixel or smaller) InSb or HgCdTe detector with small (less than or equal to 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).

3.1.3 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 1, 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 assuming that the spacecraft is 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, and associated effective emissivities (including scattering) of 0.05 and 6×10^{-5}, 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 $T \leq 18$ 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 $T \sim 8$ 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 candidate for the first stage. Solid Ne is also an option at these temperatures, but would require about 4.3 times as much mass as solid H_2. The first stage solid H_2 cooler could operate at about 12 K, 1.8 K below the H_2 triple point. Operating above the 13.8 K triple point would cause the H_2 to liquefy, and this liquid could be released from the vent line, thereby shortening the cooler lifetime.

Solid cryogen coolers are not without their problems but are probably the best option for an Explorer class mission that can afford very little development cost or schedule. Mechanical closed cycle coolers have the potential for longer lifetimes than stored cryogen coolers, but they induce vibration and there are no flight-qualified models which meet the ABE thermal requirements. Thus, they are currently not realistic candidates for an Explorer-class mission.

3.1.4 Array electronics and Data Rates

The ABE detectors will have at least 4 analog signal outputs per 1024×1024 pixel device. Therefore, ABE will require at least 4 signal chains, including preamps and ADCs that could be multiplexed to a single data bus which communicates with the spacecraft. The detector pixels will have to be read at a rate of $\sim10^5$ pixels sec^{-1}.

For a 65 K primary mirror, the detected backgrounds are expected to range from 0.15 to 5×10^4 electrons per second for the detectors in the 3 spectrographs (see Table 4). The values shown in Table 4 represent conservative estimates since, our current thermal designs (see Sect. 3.1.3) indicate that we should be able to attain primary mirror temperatures of $T < 50$ K. For example, at a temperature of 50 K, the rates shown for the long wavelength spectrometer (MidIR#3) would be over 10 times lower than shown in Table 4. The detectors are expected to have modest well depths, on the order of a few 10^5 electrons. Exposure times for the shortest wavelength spectrograph (MidIR#1) will be limited to ~1000 s by cosmic ray hits (assuming ~5 cm^{-2} sec^{-1}) while the background is expected to fill the wells of the MidIR#3 detector on a timescale of seconds.

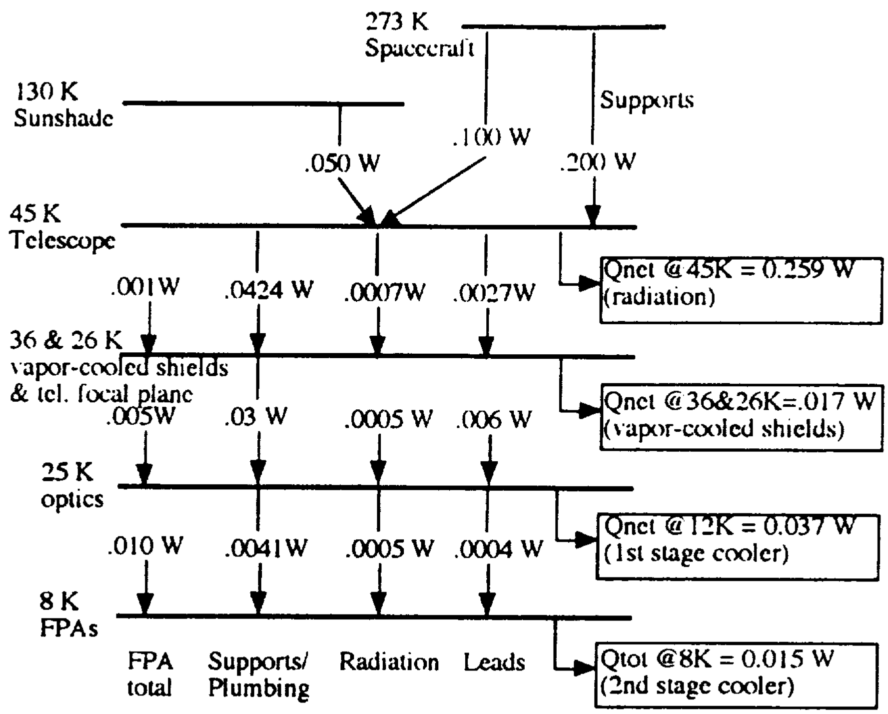

Figure 5. The ABE Heat Map

Figure 4 shows that only about 15–30% of the ABE detector area will be illuminated by a spectroscopic signal. Therefore, only these pixels need to be sent to the ground in normal operations. Modest compression algorithms can also reduce the data volume by another factor of 2–3. The resultant data rate is estimated to be on the order of 2–4 Mbps (per spectrograph) for 17 hours of data collection and 1 hr of data dumping per day as shown in Table 4. Further significant compression may be possible by calculating integration slopes and offsets on board for each complete exposure instead of sending down all data samples. However, this would require development of intelligent cosmic ray rejection algorithms.

Table 4. ABE Data Rates

	MidIR#1	MidIR#2	MidIR#3
wavelengths (μm)	2.5–5.0	5.0–10	10–20
pixels	1048576	1048576	1048576
bits/pixel	16	16	16
background (e-/s/pixel)	0.15	150	5.00E+04
well size	1.00E+05	1.00E+05	5.00E+05
exposure time (s)	1000	667	10
#reads/exposure	32	32	2
compression/extraction	5	5	15
bits/exposure	5.37E+08	5.37E+08	3.36E+07
bits/sec	1.07E+05	1.61E+05	2.24E+05
hrs/day	17	17	17
bits/day	6.57E+09	9.86E+09	1.37E+10
dump time (hr)	1	1	1
Comm bps	**1.83E+06**	**2.74E+06**	**3.80E+06**

4. THE ASTROBIOLOGY EXPLORER (ABE) SPACECRAFT

The basic conceptual design of the spacecraft system is shown in Figure 2. To attain the required temperatures by passive cooling, the telescope and spectrographs must always be screened from the sun by a sunshade. The sunshade is implemented by using the solar array, backed by insulation, to reduce radiation heat transfer to the telescope. This requires the spacecraft attitude during flight be roughly normal to the Sun-line with a SLA constraint of 80 to 120°. Thus, at any given time the spacecraft will only be able to observe objects within an annulus on the sky perpendicular to the sun-spacecraft line. During the course of the mission, this annulus will sweep across the entire sky.

Power is generated by a solar array using Gallium Arsenide cells. These cells have two advantages for this mission. First, they have higher efficiency than silicon cells. Second, Gallium Arsenide cells perform better than silicon cells at elevated temperatures. Since the solar array is backed by insulation to minimize heat transfer to the telescope and spectrographs, the solar cells in the solar array/sunshade will have to perform at elevated operating temperatures compared to a more typical application at 1 AU. A small Nickel Hydrogen (NiH) battery will be used for power during initial orbit insertion and for safe hold mode. Battery power will not be required during normal operations since the spacecraft will be in an Earth drift-away orbit and no solar eclipses will occur during the mission.

The spacecraft will be 3-axis stabilized using reaction wheels. The instrument pointing stability requirements of 1 arcsec can be met with an inertial reference unit, a bore-sighted star tracker, and a focal plane guider located in the instrument. Sun sensors are also used to keep the solar array pointed at the sun. Four reaction wheels would be used for redundancy. A cold gas system (gaseous nitrogen - GN_2) will be employed to offload any momentum build-up due to external torques, such as initial upperstage tip-off separation and solar pressure. The cryogenic H_2 boiloff from the optics dewars will be 'equal reaction' vented so that it imparts no net contribution to the spacecraft momentum.

The spacecraft is designed with a cryogen load for approximately one year of operation. Once the cryogens are exhausted there is the possibility of an extended observational mission using the short wavelength spectrograph, as the telescope and optics are expected to passively cool to sufficiently low temperatures that useful data can still be obtained from this instrument. Depletion of the cryogens will, however, result in the loss of the longer wavelength operations.

The spacecraft bus will contain all the uncooled spacecraft components for command and data handling/storage, power, pointing and control and communication. This portion of the spacecraft will be isolated from the passively cooled telescope and instrument deck by a standoff support structure and thermal insulation.

Communication with ABE would be carried out using a 10 W X-band high-gain antenna (HGA) mounted on the base of the spacecraft bus (at the base of the image in Figure 1, but not visible). The HGA would be rigidly mounted to the bus and data storage downlink and command uplink would be made at periodic intervals during which ABE would discontinue observations and slew to point the HGA at the Earth. Since the maximum distance to the Earth after 1.5 years is about 3×10^7 km (see Sect. 5), the DSN standard deep space transponder can be run at its maximum downlink capability of 4.4 Mbps for the entire flight when tracked from the 34M HEF antennae, well over the predicted ABE rates (Table 4). An omni-directional X-band antenna receiver would also be included to listen for unscheduled ground commands.

Table 5 summarizes the main requirements and constraints that would have to be met by the AstroBiology Explorer spacecraft to properly carry out the scientific programs outlines in Sect. 2.

Table 5. Spacecraft Core Requirements and Constraints

Parameter	Value
Launch vehicle envelope	Delta-II 7325
Attitude Control	3-axis stabilized
Instrument pointing stability	1 arcsec
Momentum offloading	cold gas
Telecommunication Standard	DSN
Frequency	X-band
Power	400W
Mission lifetime (minimum)	12 months

5. MISSION OPERATIONS

The current mission plan has the ABE spacecraft launched from the Eastern Test Range (Cape Canaveral) by a Delta-II 7325 three stage expendable launch vehicle. With the 2.9m fairing, the vehicle has a payload lift capability of ~600 kg with a 20% margin. Current estimates of the ABE mass lie below this limit. Volume is also not constrained by the 2.9 m fairing. An Earth-trailing trajectory has been selected to simplify flight operations while satisfying all mission design requirements. This trajectory minimizes pointing restrictions, avoids the Earth's thermal and radiation environments, and does not require orbital maintenance. An Earth-trailing trajectory meets all spacecraft pointing requirements for power, thermal, communication, and telescope orientation. The launch trajectory is characterized by a C3 of 0.4 km^2/sec^2, slightly over Earth escape, to account for the three-body gravitational affects. Within ~30 days after launch it enters a heliocentric orbit in the ecliptic plane with a period of ~372 days. In such an orbit, similar to that of SIRTF, the spacecraft only slowly drifts away from the Earth, never getting more than 0.12 AU from the Earth in its first year and never more than 0.22 AU over two years.

The AstroBiology Explorer can, in principle, be launched at anytime of the year. However, given that the mission has a nominal lifetime of about one year and that the list of target objects is significantly biased towards objects within our own galaxy, an optimal observation strategy would use a launch time when the annulus first viewable by the spacecraft is just beginning to sweep across the inner galaxy. This would allow the most target intensive portions of the sky to be observable at least twice, once early in the mission and once late in the mission. Within this broad requirement, the launch time can be selected to minimize the impact of launch dispersions as there will be no propulsion on the spacecraft for orbital corrections.

Mission operations for the ABE would consist of the standard flight operation facilities and activities necessary to maintain and control the spacecraft, support science and engineering data acquisition, and provide for data processing and distribution of data to the users. Spacecraft maintenance includes tasks for pointing and orientation control, communications for command and telemetry, orbit determination for tracking and the onboard spacecraft ephemeris, and momentum dumping. Data acquisition will consist of both telemetry to monitor the status of the spacecraft subsystems and science data acquisition. Typical ABE flight operations will include the preparation, transmission, and verification of command memory loads used by the spacecraft to control its subsystems and instrument observations. Science operational activities include analyzing, archiving, and distribution of science data together with ancillary data such as spacecraft orientation and flight path information. Mission operations for the ABE project would use the facilities and personnel of the DSN for the tracking and data acquisition (TDA) support. Both telemetry and command capability will be required. There will be a need for the orbit determination and trajectory prediction capabilities provided by the JPL's Multimission Navigation Facility (MMF).

Flight operations would be controlled from a dedicated spacecraft operations center which houses the computers, communications, and software needed to support real-time monitoring and control. Operation plans must specify operations procedures, command sequences, and payload performance requirements to evaluate real-time spacecraft and instrument status. The spacecraft operations center will also contain a science data unit responsible for the project science database and the ancillary trajectory and spacecraft pointing information. The science data unit would also be responsible for science data processing, science data archiving, and science data distribution.

The nominal ABE mission operations system would consist of a small organization reporting directly to the project manager and the mission director. Two primary teams, Mission Operations and Science, will be responsible for real-time spacecraft operations. A support organization, the ground data system, would coordinate the DSN tracking and the data flow requirements.

6. SUMMARY

We have described 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 order (m~10) dispersive spectrographs equipped with first-order cross-dispersers in an "echellette" configuration and large format (1024×1024 pixel) mid-IR detectors 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, the evolution of ices and organic matter in young planetary systems, and the deuterium enrichments in ices, PAHs, and diffuse medium organic refractory materials. 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.

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