Identifying Organic Molecules in Space – The AstroBiology Explorer (ABE) Mission Concept

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ABSTRACT

The AstroBiology Explorer (ABE) mission concept consists of a dedicated space observatory having a 60 cm class primary mirror cooled to $T < 50$ K equipped with medium resolution cross-dispersed spectrometers having cooled large format near- and mid-infrared detector arrays. 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 mission's observational program would make fundamental scientific progress in establishing the nature, distribution, formation and evolution of organic and other molecular materials in the following extra-terrestrial environments: 1) The Outflow of Dying Stars, 2) The Diffuse Interstellar Medium, 3) Dense Molecular Clouds, Star Formation Regions, and Young Stellar/Planetary Systems, 4) Planets, Satellites, and Small Bodies within the Solar System, and 5) The Interstellar Media of Other Galaxies. ABE could make fundamental progress in all of these areas by conducting a 1 to 2 year mission to obtain a coordinated set of infrared spectroscopic observations over the 2.5-20 micron spectral range at a spectral resolution of $R > 2000$ of about 1500 objects including galaxies, stars, planetary nebulae, young stellar objects, and solar system objects.

Keywords: Astrobiology, infrared, Explorers, interstellar organics, telescope, spectrometer, space, infrared detectors

1. INTRODUCTION

The AstroBiology Explorer (ABE) mission concept supports the first space mission dedicated to astrobiology, to systematically study the nature, evolution, and distribution of organic molecules in the local universe and assess the role of extraterrestrial organics in the development of life. Previous ground, airborne-, and space-based infrared (IR) instruments have provided glimpses of the rich insights to be gathered from interstellar materials.[1] However, our current understanding of the composition and evolution of gas-phase and solid organics in space has been limited by observations of materials along only a few lines of sight, and often with limited IR spectral resolution, coverage and sensitivity. As a result, we currently have a very incomplete understanding of the organic inventory and interrelationships between the various molecular components of the interstellar medium (ISM). This field would be greatly enhanced by the collection of a comprehensive spectral database from a set of targets that sample different evolutionary states of a variety of classes of objects. The ABE mission is designed to provide that sample. Additionally, laboratory studies have created a large and growing database of IR spectra of astrophysically-relevant organic materials that, in combination with sophisticated astrochemical theoretical modeling, can be used to interpret ABE data.[2,3,4,5]

ABE was first proposed as a Medium Class Explorer (MIDEX) Program Proposal to NASA in October 2001, when it was highly rated for its science and approach and chosen as one of four "semi-finalists" to complete a Phase A study in April 2002. At the end of this concept study, although the ABE proposal was not selected for immediate implementation, the mission was still highly rated and the ABE team will submit the ABE Mission Concept at the next MIDEX opportunity in 2005, leading to a launch around 2011.

This paper describes the scientific motivation [Section 2] and technical implementation [Section 3] of the AstroBiology Explorer (ABE) Mission Concept, a modest sized (60 cm diameter), dedicated IR (2.5-20 μm) spectroscopic ($R = 2000$-3000) observatory to study the evolution of organic material in the local universe.

2. SCIENCE INVESTIGATION

The scientific goal of ABE is to explore the identity, abundance, and distribution of molecules of astrobiological importance throughout the universe. The rapidly growing field of astrobiology has two principal goals: 1) learn how life began on Earth, and 2) establish whether life exists elsewhere in the universe. Vital to this quest is understanding the evolution of molecules that carry the cosmically abundant elements C, H, O, and N. The origin of life is closely tied to

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3. TECHNICAL APPROACH

3.1 Scientific Requirements

IR spectroscopy is unique suited to remote detection and identification of the molecules and dust in space because the vast majority of vibrational transitions of molecules fall in the mid-infrared, 2.5 to 20 µm (400-500 cm^{-1}) [Figure 2]. While many chemical functional groups and some classes of molecule display distinctive characteristic infrared bands, it is necessary to detect multiple bands of a molecule to derive meaningful information. Thus, the ABE instrumentation must be capable of providing spectral coverage across all of this range. A spectral resolution ($R \equiv \lambda/\Delta\lambda$) of about 2000-3000 is also 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.

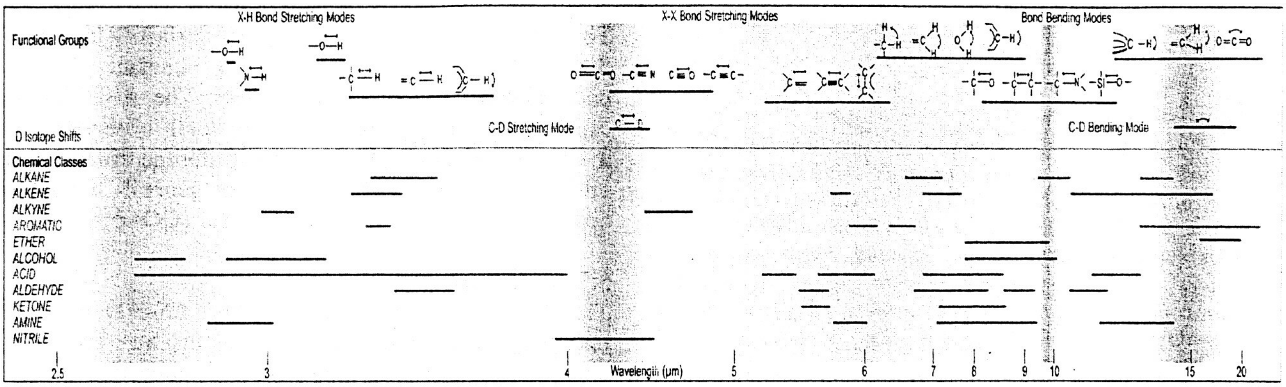

Figure 2. Fundamental vibration frequencies associated with the most common chemical bonds between the most abundant elements C, H, O and N, populate the 2.5-20 µm region. The shaded bands correspond to the wavelength regions that inaccessible from ground-based and/or airborne observatories due to atmospheric H_2O and CO_2 and O_3.

Additionally, many of the absorption and emission features that will be studied have strengths that are only a few percent of the continuum flux. Moreover, the target list for this mission will contain ~2000 objects, many of which are relatively faint, on the order of 0.01–0.10 Jy. Thus, achieving the goals in the ABE science mission will require high sensitivities, with signal-to-noise (S/N) values on the order of 100 in many cases. 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 1.2 years, a timescale that will allow us to study objects in all parts of the sky. The main scientific requirements that ABE will have to meet if it is to properly carry out its science mission are summarized in Table 2.

3.2 Mission Overview

The ABE Observatory, total mass 615 kg, will be launched by a Delta 2425 into an Earth-trailing, heliocentric orbit, similar to that of Spitzer and Kepler.[9,10] The flight profile is straightforward with no orbit maintenance required after separation from the Delta II launch vehicle, and no significant launch window constraints. ABE is launched cold with an aperture cover that is ejected on orbit. The full science mission, a spectral survey of ~2000 targets (including calibration targets) is complete in 15 months [30-day checkout period followed by 14 months of normal science observations], providing for a simple mission design with launch windows any day of the year. ABE will drift away from Earth at the rate of ~ 0.1 Astronomical Unit (AU)/year, to a max Earth range of 0.13 AU at the end of its main Science mission.

***Table 2.** ABE Nominal Scientific Requirements*

Wavelength Coverage	2.5 - 20 µm; gaps permitted within regions 3.85-4.1µm, 4.8-5.05µm, 9.85-10.1µm
Spectral Resolution $R \equiv \lambda/\Delta\lambda$	2500-3500 (2.5-4.8 µm) 2000-3000 (4.8-20 µm)
Spatial Resolution (slit width)	Compatible with sensitivity and spectral resolution requirements. Nominal 8.3"
Slit length	Long enough to allow two sequential measurements (>33" for nominal 8.3" slit)
Sensitivity 1σ, 1000s [mJy]	0.08 (2.5 µm), 0.16 (5 µm) 1.3 (10 µm), 1.6 (16 µm)
Calibration	Absolute flux accuracy 25%; Wavelength dependent relative accuracy 10%
Pointing Stability	< 3" for a 1000 sec exposure
Spatial coverage of slits on sky	Co-spatial on sky
Tracking Objects	> 0.1 arc-sec per second

A consequential benefit of the solar orbit is that ABE will have a large instantaneous view of the celestial sky [Figure

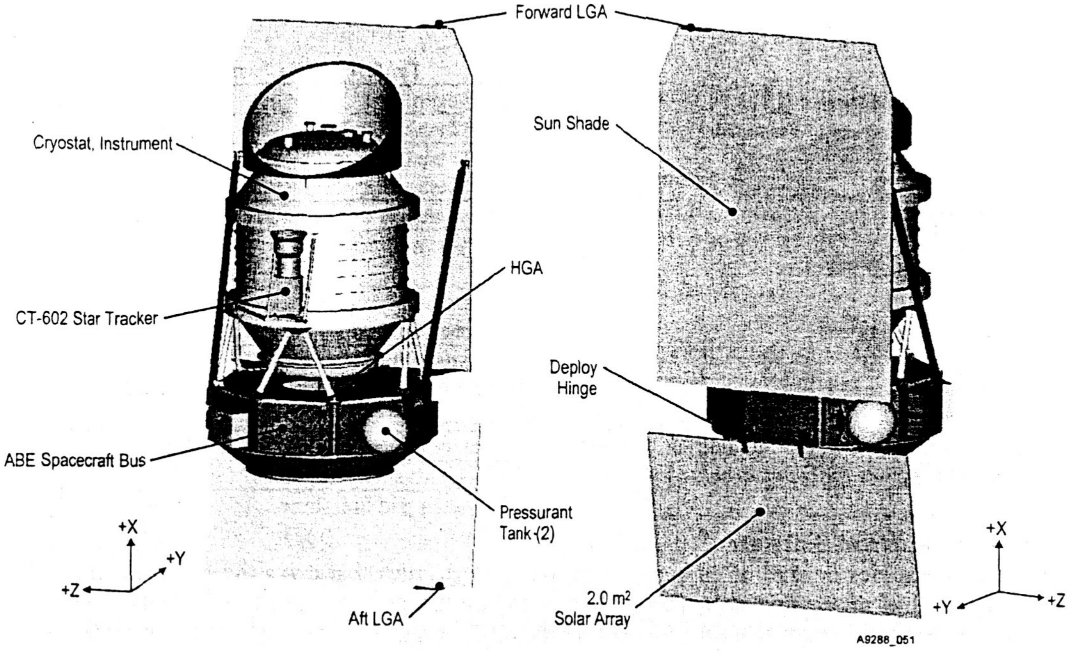

Figure 4. The ABE spacecraft concept.

beamsplitters after the slit separating the light into three bands [Figure 5]. Spectral coverage breaks are reduced by using beamsplitters having sharp transitions.

Each spectrometer arm covers a full spectral octave using a similar compact optical design based on a reflective off-axis parabolic collimating optic, echelle grating, cross-disperser grating, and a two-element on-axis camera lens which images the spectra onto a single 1024 x 1024 pixel IR FPA [Figure 6]. Each arm's camera system is f/2.2 with an effective focal length of 152 mm. Both the spectrometer structure and the reflective elements of the optical train will be fabricated from the same 6061-T6 Al alloy as the telescope and its metering structure, to provide an athermal design.

3.4.2 Cryostat

The ABE cryostat uses solid hydrogen (SH_2) for cooling the optics and the infrared focal plane arrays (FPAs). The heliocentric orbit chosen for ABE enables a low vacuum shell temperature that greatly reduces the cryostat heat load. This permits the use of a single-stage to cool the Si:As FPA to < 7.7K without vapor-cooled shields. This significantly simplifies the cryostat design, and reduces both cost and development risk.

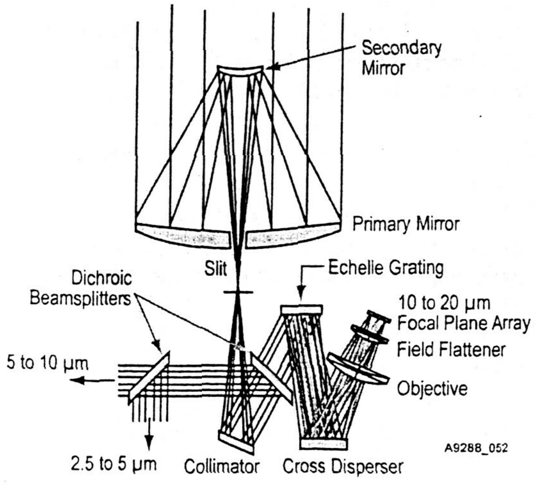

Figure 5. Optical ray trace conceptual diameter for the ABE telescope and spectrometer (not to scale). Only one spectrometer arms is shown explicitly.

ABE uses an annular tank design similar to that used on IRAS and COBE. The spectrometer and telescope are thermally attached to the 7.2 K solid H_2 tank. The tank is filled with aluminum foam to improve thermal conductance between the solid H_2 and the tank and provides cooling with adequate conductance margin for the two Si:As detectors, which operate at 7.3 K. The InSb detector will be actively thermally controlled to T ~ 30 K.

Both the vacuum shell and the cryogen tank are aluminum. The ABE payload (telescope, spectrometer, cryostat) is mounted to the spacecraft via four bipod struts, which provide thermal isolation and mechanical stiffness. The telescope and spectrometer are launched cold. A deployable, vacuum-tight aperture cover seals the cryostat until its ejection two weeks after launch. The top-level details of the ABE cryostat are described in Table 4.

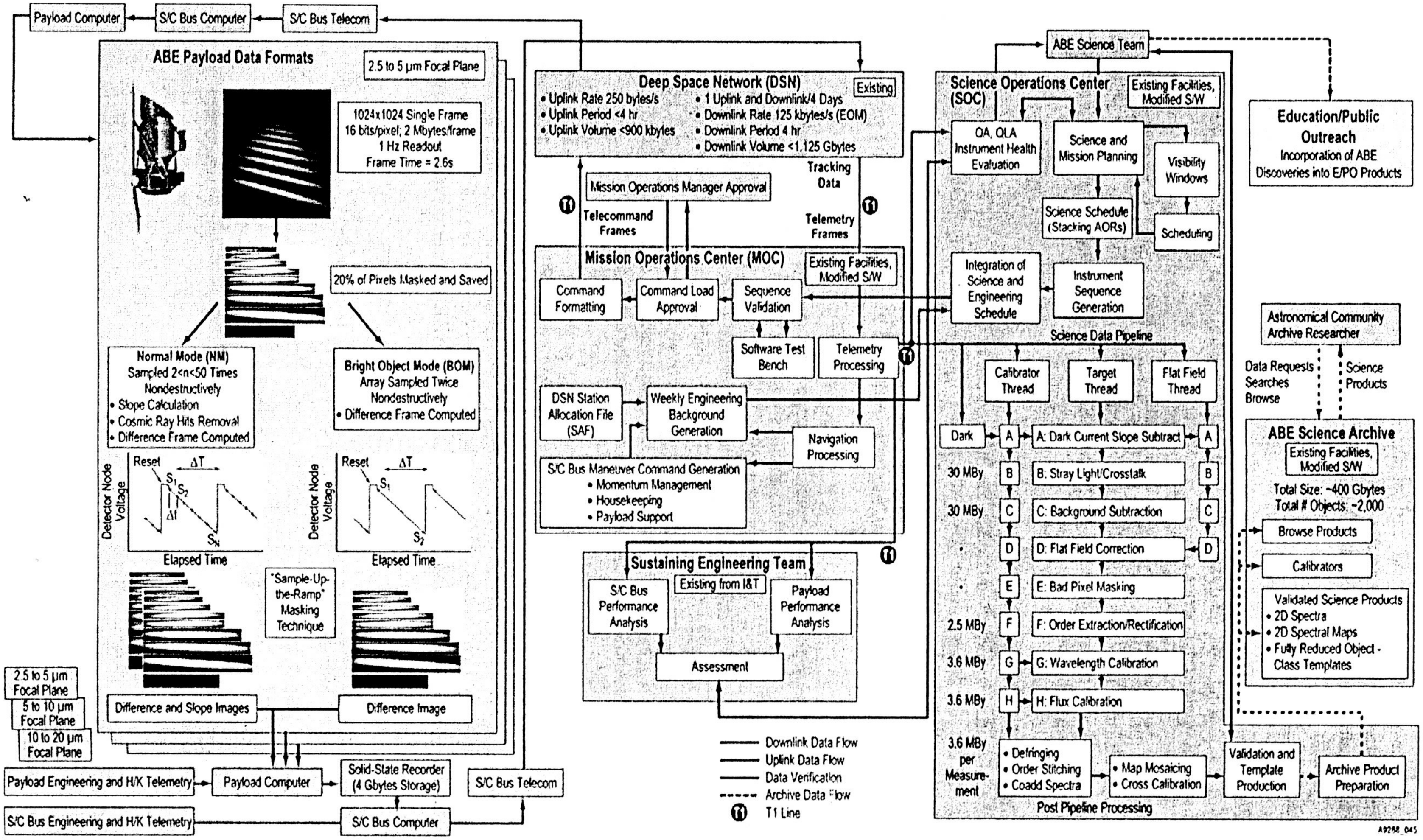

Figure 7. *The ABE data flow and ground system. Data uplink flow includes the science schedule generation of the ABE targets by the SOC, which combined with MOC-generated engineering commands, are sent to the MOC for sequence validation and translation to the DSN. Data downlink flow begins within the ABE payload where 2-D array data, consisting of cross-dispersed IR spectra from three separate FPAs, is masked in the payload electronics to preserve only the illuminated and dark reference pixels. On-board processing is performed before transfer of the ABE data to the spacecraft bus telecom for downlink. ABE has four data-taking modes: two science modes (Normal and Bright Object) are shown in this figure; two diagnostic modes (Raw and Diagnostic), used during integration and test and on-orbit checkout, are not shown. ABE telemetry is sent to the MOC for processing. Science data is sent to the SOC for quick-look verification and more detailed pipeline analysis. Data processed through the pipeline are at most 15-minute integrations that are co-added in the post-processing pipeline. The Sustaining Engineering team checks spacecraft bus and payload health. After science data processing, the SOC prepares final fully-calibrated science products to be placed in the ABE Science Archive at IPAC where there are made available to the astronomical community.*

The JWST, to be launched circa 2011, is being planned to provide R~3000 from 0.6-27 μm and lower resolution capability from ~1-10 μm. With a >10x larger collecting area, JWST could carry out any single ABE observation. However, ABE's main advantage over JWST for the science described above is that ABE would be dedicated to astrobiology and devote its mission efforts to this area. Only a dedicated mission with a focus on one science theme - which is not feasible with JWST – can provide the comprehensive view of the life cycles of astrobiological material that are critical to answering the scientific questions addressed by ABE.

4. MANAGEMENT AND TEAM MEMBERS

The AstroBiology Explorer (ABE) mission is a partnership between NASA-Ames Research Center, the Jet Propulsion Laboratory, and Ball Aerospace & Technologies Corp. Ball Aerospace is the prime-contracting partner for the ABE mission, and will lead all design, development, building, testing and delivery of the ABE payload. JPL is providing oversight management of the ABE mission. NASA Ames Research Center, under the direction of the PI Scott Sandford, will lead the science planning and Science Operations Center (SOC), provide for testing and analysis of the focal planes for flight selection, coordinate Education and Public Outreach (E/PO) activities, and provide management of the instrument payload.

The ABE Science Team [Table 5], headed by the ABE PI, consists of a number of members having world-class experience in the scientific and technical areas relevant to ABE and share responsibilities associated with target selection and scheduling, data analysis and publication within one or more of ABE's primary tasks [see Section 2].

***Table 5**. The ABE Science Team Task Participation and Responsibilities*

Team Member and Institution	Task Participation						Other Responsibilities
	1	2	3	4	5	6	
Scott Sandford (PI) ARC	√	√	√	√	√	√	All aspects of the mission through all phases of its activity
Louis Allamandola (Co-I) ARC	√	√	√			√	Participate in lab work needed to interpret observations
Jesse Bregman (Co-I) ARC	√			√	√		Assist with models of PAH emission, SOC Manager
Martin Cohen (Co-I) UC Berkeley		√	√				Develop ABE's stellar calibration spectra database and procedures
Dale Cruikshank (Co-I) ARC				√			Monitor for possible targets of opportunity, particularly comets
Christina Chen (Co-I) JPL				√			Serve as JPL Mission Scientist
Kimberly Ennico (Co-I) ARC		√	√				Assist with detector test & instrument design, I&T, and calibration algorithms
Thomas Greene (Co-I) ARC			√				Scientific oversight to instrument development
Douglas Hudgins (Co-I) ARC	√						Science lead for E/PO, carry out lab work to interpret observations
Sun Kwok (Co-I) ASIAA, Taiwan	√						Test, develop, and refine models of PNe evolution models
Steven Lord (Co-I) IPAC/Caltech					√		Lead software development for data analysis and data archiving
Suzanne Madden (Co-I) CEA					√		Test, develop, and refine galactic models
Craig McCreight (Co-I) ARC				√			Assist detector procurement, lead detector testing and selection effort
Thomas Roellig (Co-I) ARC		√				√	Serve as ARC Mission Scientist
Donald Strecker (Collaborator) Ball	√	√		√			Lead Payload Systems Engineer at Ball
A.Tielens (Co-I) SRON /Kapteyn			√				Lead efforts to develop and test relevant astrochemical models
Michael Werner (Co-I) JPL					√		Assist PI w/ SIRTF experience on design, Science, & Ops issues
Karen Willacy (Co-I) JPL					√		Develop and test relevant theoretical astrochemical models
Krisstina Wilmoth (Co-I) ARC	√	√	√	√	√	√	E/PO Manager

5. SUMMARY

It is now known that a significant portion of the cosmic inventory of the elements C, O, N, and H in space are incorporated into a variety of volatiles and organics that are of astrobiological interest. However, much remains to be learned about the inter-relationships of these materials and about how they are formed and evolve in space. In this paper have briefly described a potential new MIDEX-class space mission, the AstroBiology Explorer (ABE), consisting