Explorations in Astrobiology: Evolution of Organic Matter from the ISM to Planetary Systems

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Scientific category: OTHER: Astrobiology
Instruments: MIR/SPEC, OTHER: CORONAGRAPH FOR DISKS
Days of observation: 72

Abstract

We propose to observe the mid-IR spectroscopic signatures of biologically important organic molecules in molecular clouds, protostellar envelopes, planet forming systems, and planetary debris disks. In addition to yielding a more complete census of organic materials in the ISM, these observations will provide insight into how these molecules are physically and chemically processed into the chemical precursors of life in the circumstellar environments and planetary systems around young stars. Understanding the nature, sources, and evolution of this matter in solar systems is a major objective of the NASA Astrobiology program.

NGST is uniquely suited to this observational task. It is the only planned observatory sensitive enough to sample multiple lines of sight in nearly any galactic molecular cloud or resolve the spatial distribution of pre-biotic organic matter in protostellar envelopes and planetary disks.

Observing Summary:

Target	RA	Dec	m_{AB}	Configuration/mode	Days
100 DARK CLOUD LOS ABSORPTIONS	gal plane	gal plane	$N_{AB} \sim 15-20$	MIR/SPEC R3000	12
50 PROTOSTELLAR ENVELOPES	gal plane	gal plane	$N_{AB} \sim 15-20$	MIR/SPEC R3000	12
25 T TAURI DISKS	gal plane	gal plane	$N_{AB} \sim 15$	MIR/SPEC R3000	6
25 β PIC DISKS	gal plane	gal plane	$N_{AB} \sim 15$	MIR/SPEC R1000	42
				Grand total days	72

Scientific Objectives

The biogenic elements needed for the formation of life, including C, N, and O, are created via nucleosynthesis in stars. Within the circumstellar shells of carbon-rich giants, some of these elements combine with each other and H to form simple molecules. Once incorporated in dense clouds and ultimately into circumstellar disks of young stellar/planetary systems, these molecules are processed into more complex ones, including some of pre-biotic interest. This processing is caused by ambient UV radiation in the cloud and also radiation from the young central stars of pre-planetary systems. This hypothesis is supported by IR spectroscopic evidence for energetic processing as well as the detection of a wide variety of complex organic molecules in dense clouds and in comets. Thus it is likely that complex organic molecules were delivered to the young Earth and may well be common in extra-solar planetary systems.

This picture for the origin and evolution of the chemical precursors to life has emerged and come into focus over the past several decades. Combined laboratory and observational astronomical studies have recently shown that: i) the major components of ices in dense molecular clouds are usually H_2O, CH_3OH, CO, CO_2, and H_2 (e.g., Allamandola et al. 1988; Tielens et al. 1991; Sandford et al. 1993; d'Hendecourt et al. 1999); ii) Polycyclic Aromatic Hydrocarbons (PAHs) are the largest source of accessible carbon in the Universe (Allamandola, Hudgins, & Sandford 1999) and upon modification in the ISM are biochemically active (Bernstein et al. 1999; Dwek et al. 1997); iii) the organic molecules frozen on dust grains can be changed into new compounds by protostellar radiation fields (Bernstein et al. 1995, 1999); and iv) a large variety of organic molecular ices have been detected in recent comets and on the surfaces of the outer planets and on Kuiper belt objects (Brown et al.1999; Crovosier et al. 1999) .

Although this is a very intriguing scenario for the chemical evolution of biological precursors, there is a large dose of speculation involved. This is because tremendous gaps exist in understanding how prebiotically important molecules evolve from the quiescent ISM to protostellar envelopes to planetary disks to planetary systems. For example, NH_3 (ammonia) and H_2CO (formaldehyde) are very interesting prebiotic molecules since they can be chemically combined to produce amino acids. Both NH_3 and H_2CO are known to be abundant in the interstellar gas, and there is evidence for both frozen in ices (Schutte et al. 1995, Lacy et al. 1998). Ices on grains in the circumstellar disks around young stars are the most likely place for NH_3 and H_2CO to combine to form amino acids, especially since there is evidence for gas-phase abundance enhancements attributed to grain mantle vaporization in protostellar environments. However, we cannot predict the amount of amino acids or understand the conditions that produce them until we carefully measure the abundance of frozen NH_3 and H_2CO along the same lines-of-sight in molecular clouds. Conducting a basic inventory of prebiotic and organic molecular ices in quiescent clouds is one part of the work to be done in this area. To truly understand the evolution of interstellar carbon into solar system ices, we must also measure the abundances of organic molecular species as a function of location in quiescent dark clouds, protostellar envelopes (Figure 1), pre-planetary disks, and debris disks. These are the most important objects for studying the evolution of biogenic

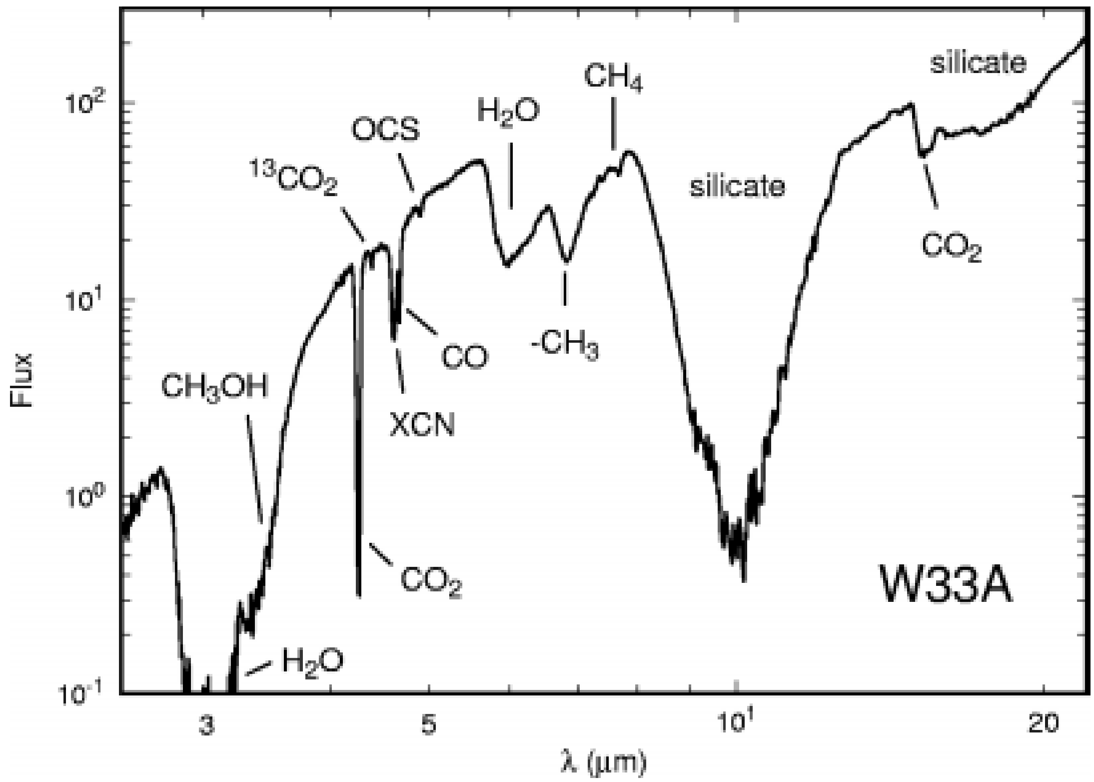

Figure 1: ISO SWS absorption spectrum of the massive protostar W33A from Gibb et al. (1999). A rich variety of organic ices are seen in absorption in its protostellar envelope. This object has a luminosity $L \simeq 3 \times 10^4$ $L_\odot$, and its flux is *at least 4 orders of magnitude* greater than that of the background stars, low-mass protostars, and circumstellar disks which are the targets of this proposed study. NGST will also be able to spatially resolve the envelopes and disks of nearby protostars.

molecules during the formation of solar systems like ours. When combined with laboratory data and knowledge of local radiation environments, these measurements will reveal the detailed physical and chemical processes by which organic compounds are formed and modified in these systems. Recent laboratory studies (as cited above) have shown that biologically important chemical evolution of organic compounds is likely to occur on dust grains around young stars. However, to date we have very little observational astronomical data which show which of the possible reactions actually do occur. We must acquire such data to determine what organic compounds may have been present on the young Earth, which ones were likely delivered by comets, and where life is most likely to form in extra-solar planetary systems. These are major goals of the new NASA Astrobiology initiative, and the required astronomical observations are a major objective on the NASA Astrobiology Roadmap.

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NGST Uniqueness/Relationship to Other Facilities

NGST is uniquely suited to make these observations. The spectral signatures of organic molecules and amino acids are primarily in the 3 – 20 μm wavelength region, with the 5 – 8 μm range being particularly important for identifications. Most of this region is obscured from ground-based observation by atmospheric H_2O, CO_2, and other *terrestrial* organic and inorganic molecules. Therefore observation from airborne or spaceborne observatories is required. ISO was only sensitive enough to observe the most luminous protostars in the galaxy (Figure 1) and did not measure absorptions in the 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 on earth-like planets. Furthermore, even the best signal-to-noise ratios (S/N $\sim$ 100) currently obtained by ISO in the important 5 – 8 μm region preclude detection of 1% features, the level at which some very important absorptions are expected.

SOFIA will not have the sensitivity or spatial resolution required for these observations. The high temperature of the SOFIA telescope limits its sensitivity to the point where it is not capable of observing a single known line-of-sight absorption through a quiescent dark cloud, and it will be capable of measuring organic ice absorption spectra for only the brightest protostars (F > 1 Jy). The spatial resolution of SOFIA will also be approximately $1\farcs5$, about the size of protostellar disks and inner protostellar envelopes in nearby dark clouds, so it will be incapable of studying the evolution of material as a function of position in these systems. Thus, while SOFIA will make important inroads in this area, it will be incapable of achieving the goals of surveying the entire evolution of organic material as it is processed from quiescent dark clouds through protostars through planetary systems.

A large-aperture, cold space observatory is necessary to make these required observations. NGST is the only planned US or international mission which will be sensitive enough to probe the organic absorption spectra of galactic molecular clouds along many lines of sight and to detect weak organic ice absorptions in the debris disks around young stars. The diffraction-limit of NGST (about $0\farcs2$ in the mid-IR) will provide spatial resolution of approximately 10 AU in nearby debris disk systems (e.g. β Pic and TW Hya stars) and approximately 30 AU in the envelopes of nearby protostars. This sensitivity and resolution are required for meeting the goals of this survey so that key astrobiological questions are probed and answered.

Observing Strategy

We wish to conduct a systematic spectroscopic study of organic molecular ices in quiescent dark clouds, protostellar envelopes, pre-planetary disks, and post-planetary disks. R=3000 observations over 5 – 12 μm are required to identify molecular species and to determine in what matrices they are embedded. High sensitivity and dynamic range are required to detect weak absorptions against both extinguished background stars and weak disks with bright protostars in or near the slit. A multi-order, echelle-type long-slit ($\sim 5 - 10''$) spectrograph would be ideal for these moderate-resolution, wide-bandwidth, spatially-resolved observations.

We shall inventory the molecular ices characteristic of quiescent regions of approximately 10 dark clouds within 1 kpc by observing weak ($\sim 1\%$) molecular absorptions seen against background stars over approximately 10 lines of sight within each cloud. A reasonably bright background star would be $N_{AB} = 15$ mag through a dark cloud, and its 1% organic ice absorption should be measured at S/N=100 for adequate compound identifications. This is equivalent to S/N = 10^4 on the continuum, requiring an exposure time of 10^4 s at R=3000. Therefore a total of 12 days observing time is required to complete this phase of the project.

The next observational phase requires spatially-resolved spectra of Class 0 and I protostars. These observations shall show the differences in compounds present in the dense, radiation-rich protostellar regions versus those in the quiescent portions of dense clouds and will characterize the photo-chemical evolution of organic molecular species in protostellar envelopes. We expect to see the onset of such processing at distances of approximately 500 AU (5" in nearby regions) from the protostars, where we expect to encounter continuum flux surface densities of approximately $N_{AB} = 15$ mag per spatial resolution element, also leading to exposure times of 10^4 s per object. An inventory of ices in 5 bright protostars in 10 nearby clouds would also require 12 days of observation if 2 slit orientations (10" long slit) were observed per object.

The final set of observations will study the types and *distribution* of organic compounds in the pre-planetary (T Tauri) and post-planetary (debris) disks around young stars. These environments are most interesting and relevant for the formation of biologically important molecules, so we seek to study 25 objects of each type. We estimate that the T Tauri disks will also have an average flux $N_{AB} = 15$ mag per spatial resolution element at a distance of 100 AU from their central stars. Observing 25 of these objects shall require 3 – 6 days, depending on whether disk orientations are known and whether random slit orientations are possible. Observations of debris disks will be most difficult due to their unknown and very low surface densities, but we estimate that the required sensitivity will be a factor of 5 lower than for T Tauri disks. Therefore 1.7 days exposure time will be required to observe each object at a reduced resolution of R=1000 (adequate for identifications), requiring a total of 42 days for this sample.

Special Requirements

Minimum Spatial Resolution:	190 mas at 6 μm
Minimum Spectral Resolution:	1000 at 6 μm
Minimum obs time with same orientation:	1 days

Precursor/Supporting Observations

Ground-based ($\lambda = 1 - 4\mu$m) and SOFIA ($\lambda = 2 - 25\mu$m) spectra will greatly leverage the scientific value of this program by extending the sample to brighter objects. TPF will also provide important complementary information on the disks of extra-solar systems; it will provide much higher spatial resolution in disks at the expense of spectral resolution. All of these facilities will provide a very powerful arsenal, but NGST is clearly the key observatory for conducting this unified scientific program.