

Dynamics and Evolution of the Interstellar Medium: Cosmic Recycling

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Instruments: NIR/CAM, NIR/SPEC, NIR/MSPEC, MIR/CAM,
MIR/SPEC
Days of observation: 80

Abstract

Matter within galaxies cycles between the interstellar medium (ISM) and stars. *High mass stars* synthesize most of the chemical elements during their relatively short lives. They irradiate the ISM, inject kinetic energy and freshly synthesized elements into the ISM. Therefore high mass stars regulate the physical and chemical state of the interstellar gas, and recycle most of their mass in less than 30 million years. Though *low mass stars* lock away matter for > 30 million to billions of years, their formation is violent and their outflows stir the ISM. As such stars die, they also recycle a substantial fraction of their material, often enriched by thermonuclear fusion products dredged to the stellar surface during their post-main sequence stellar evolution. In dense clouds, which can only be investigated at infrared wavelengths, a rich chemistry produces a complex variety of molecules. Refractory species and ices condense onto grains, leading to their growth; processing by radiation and shocks alters their composition and structure.

We propose to use NGST to characterize the most important elemental enrichment processes and stellar energy injection mechanisms. *We will probe the composition, chemical, and physical state of the ISM.* Specific observations include: • Investigate the interaction of stars with the ISM. We propose to use imaging and spectroscopy of obscured H II regions, stellar wind bubbles, SNR, and supershells to probe the morphology, excitation, and kinematics of the gas in various phases of the ISM where interactions are occurring. Atomic and ionic lines (cf. Brackett α , the lines of noble ions, and forbidden transitions such as [Fe II]), molecular transitions, and solid state features will be observed. • Identify the stellar populations associated with obscured molecular clouds, H II regions, and superbubbles. • Determine the CO/H₂ ratio, the abundances of molecules, atoms, and ions, and various solid state features. • Probe the relationship between grain growth and interstellar gas phase depletions. • Constrain MODELS of interstellar cloud chemistry. • Determine the composition of stellar ejecta and search for local and Galactic composition variations.

Observing Summary:

Target	RA	Dec	K_{AB}	Configuration/mode
ABSORPTION			18 – 14	NIR/SPEC R100000
AGAINST STARS				
YOUNG SNR				NIR/CAM, MIR/CAM, NIR/SPEC, MIR/SPEC R100000
GALACTIC OB				NIR/CAM, MIR/CAM, NIR/SPEC, MIR/SPEC R10,000
ASSOCIATIONS				
GALACTIC GMCS				NIR/CAM, MIR/CAM, NIR/SPEC, MIR/SPEC R100000
REFLECTION				NIR/CAM, MIR/CAM, NIR/SPEC, MIR/SPEC R100000
NEBULAE, PDRS				
H II REGIONS				NIR/CAM, MIR/CAM, NIR/SPEC, MIR/SPEC R10,000
CLOUD CORES				NIR/CAM, MIR/CAM, NIR/SPEC, MIR/SPEC R100000
				Grand total days

■ Scientific Objectives

1 INTRODUCTION

The evolution of the interstellar medium (ISM) and the system of stars is fundamentally coupled through star formation, stellar evolution, and stellar death. A comprehensive examination of various phases of the ISM, their mutual interactions and couplings, and the mechanisms by which stars inject matter and energy back into the ISM is required to understand the chemical enrichment of the Universe, the evolution of galaxies, the formation of stars and planets, and the fate of all baryonic matter.

Due to their proximity, objects within our own Galaxy provide the best opportunity to probe cosmic recycling. However, since most of the Galaxy is highly obscured by interstellar dust at UV, visual, and even near infrared wavelengths, comprehensive investigation requires access to the thermal infrared portion of the spectrum (2 to 30 μm). Furthermore, fundamentally new types of transitions become accessible to observation in this wavelength range including the vibrational transitions of a large selection of molecules (including lines and bands of the most abundant species such as H_2 and CO), the fine structure transitions of various elements and ions (especially of the noble gases which are not depleted onto grains), solid state features of various ices and refractory compounds, and the thermal (broad band) emission of grains. The species accessible for study with NGST can be used to probe the range of physical conditions in the interstellar medium.

NGST will provide orders of magnitude increases in sensitivity, angular resolution, and spectral coverage over any other mission that has flown or is being planned. It will therefore be capable of making fundamental contributions to our understanding of the physical and chemical state of the ISM, its history and evolution, and the processes by which matter is cycled between stars and gas. Though some measurements could be performed with imaging or low dispersion spectroscopy, most require high dispersion. Though $R = 100,000$ is ideal, most experiments would still be possible at $R=30,000$, but would suffer significantly at $R < 10,000$. Though many experiments require only a small slit or hole (e.g. absorption line experiments) to admit the light of a point source into the spectrograph, many will explore the kinematic and spatial distribution of emission lines and would therefore greatly benefit from 3D imaging spectroscopy (e.g. image slicing or a dense pack integral field unit [IFU] at the input of a spectrograph). However, a long-slit capability (with some loss of efficiency over an IFU) would suffice for many of these sub-projects.

2 SCIENCE GOALS

2.1 *The Self-Regulation of Star Formation*

2.1.1 The Origin, Evolution, and Destruction of Molecular Clouds

Though we have made great progress in our understanding of star formation in the Solar vicinity, we do not have a coherent model for the formation, evolution, or destruction of

the clouds from which most stars form, the giant molecular clouds (GMCs). It is becoming clear that most stars form in GMCs that eventually spawn OB associations. Furthermore, progress in our understanding of massive star formation has been slow. In part this is due to the circumstance that most massive stars in our Galaxy form in the Molecular Ring or near the Galactic center where distance and obscuration limit our view. NGST will greatly improve our understanding of both cloud and high mass star formation.

The high angular and spectral resolution at infrared wavelengths to be provided only by NGST will be essential for the spectroscopy of the obscured star forming regions where the majority of stars in our Galaxy are born. These regions are very crowded so sub-arcsecond angular resolution at IR wavelengths is essential to resolve individual stars. The NGST aperture is needed to obtain spectra and to characterize the faint stars at the low mass end of the mass spectrum in the presence of heavy obscuration typical of most lines of sight to massive star forming GMCs.

We propose NGST studies that will target H II regions, stellar wind bubbles, SNR, and supershells throughout the Galaxy. The goals of these ISM programs are to measure the composition and chemical abundances of these regions and to characterize systematic variations with location within the Galaxy; to map the excitation conditions and kinematics of the various phases of the ISM both by emission and absorption line spectroscopy; and to characterize the stellar contents of these star forming regions by both photometry and spectroscopy, which can be used to determine the ages, masses, luminosities, and compositions of member stars. Specific tracers include the Bracket α line, lines of noble gasses (cf. Ne II), and molecular lines seen in emission and absorption, as well as tracers of interface regions at the edges of clouds and H II regions, shocks, and ionized media, including a variety of noble gases and their ions, molecules such as H₂O, CO, and H₂, and solid state features (PAH features at cloud edges, CO and water ices).

The pure rotational lines of H₂ provide the best available diagnostics of low velocity (2 to 30 km/s) shocks propagating in dense molecular clouds ($n > 10^3 \text{ cm}^{-3}$) in the ISM. Observations of the 28, 17, and 12 μm lines are especially important since they can be used to trace post-shock gas with temperatures as low as 100 K. ISOMCAM on ISO has provided a dramatic demonstration of the power of imaging of H₂ in the S(2) - S(5) (12-6.9 μm) lines in some outflows from young stars. Temperature variations of 500-1500 K are seen across the shock on small scales, as well as ortho/para variations. The 18 μm S(0) and 17 μm S(1) lines would allow such variations to be traced down to 100 K. The luminosity in these H₂ shocks seems to be comparable to that necessary to set the whole CO outflow in motion.

Imaging these lines at high spatial resolution ($<1''$) in various regions such as shocks, PDRs and even "normal" interstellar clouds will provide a unique diagnostic of the propagation of shocks, the injection of radiative and mechanical energy into clouds, and the origin and development of cloud turbulence. These lines will provide direct constraints on the amount and temperature of warm gas, and stringent tests to models of cloud heating and cooling. Ground-based telescopes or SOFIA will lack the spatial resolution and/or sensitivity. With NGST, the entire Galaxy is accessible for investigation.

The pure rotational lines of HD (deuterated molecular hydrogen) in shocks (R(4), R(5),

... at 29, 19 ... μm) may provide important information on the $[\text{D}]/[\text{H}]$ ratio, complementary to the proposed FIRST observations of the R(0) 112 μm line. The R(5) line has just been detected in the Orion shock with ISO.

2.2 *Abundances in the Gaseous and Solid State*

2.2.1 Abundances and Abundance Gradients in the ISM

Abundances of Trace Constituents:

There is virtually nothing known about depletions in dark clouds. However, it is precisely in these environments that grains must grow and we need to find out whether this happens due to coagulation of grains (which would not alter depletions), or to accretion from the gas (which would alter depletions, perhaps on an element-specific basis, depending on the relative sticking coefficients). NGST observations can help address these issues by measuring gas-phase abundances (along with grain mantle solid-state features), of simple molecules which are expected to comprise the majority of many elements when cloud densities get high enough for molecular species to dominate (e.g. when all the carbon is in CO and only negligible amounts in C I).

ISO has shown that the infrared features of polycyclic aromatic hydrocarbons (PAHs) are a dominant constituent of the ISM that produce prominent features in the 3 to 20 μ portion of the spectrum. Recent ISO results indicate that PAHs can be used as redshift indicators in high- z galaxies. Undoubtedly, they will play an important role in extragalactic proposals, so it is of crucial importance to NGST to understand the relative strength and variations of the various PAH features better in the local Universe. Some of this information will be provided by ISO, SOFIA, and ground-based telescopes. However, NGST is the only proposed facility that can provide continuous wavelength coverage and subarcsec resolution that is needed to understand the precise location and origin of the PAH features in PDR fronts, H II region interfaces, reflection nebulae, post-main sequence stellar envelopes, and other environments.

Testing Interstellar Cloud Chemistry:

The NGST will provide abundance and excitation data on classes of molecules previously unobserved through gas-phase vibrational transitions (which are an order of magnitude stronger than the rotational transitions observed in the radio portion of the spectrum) thus providing data which can be used to constrain and guide models of chemistry in dark clouds and star-formation regions.

The CO molecule is the most widely used tracer of the molecular phase of the ISM. Yet, its abundance with respect to H_2 is only characterized near the outer edges clouds in the Solar vicinity. The calibration of the CO/ H_2 ratio towards lines of sight that penetrate the full range of conditions encountered in interstellar clouds is of fundamental importance to our understanding of the molecular phase of the ISM. Direct measurements of the CO/ H_2 column density is possible in the $2\mu\text{m}$ window by the observation of the absorption lines of the $v=1-0$ band of H_2 and the $v=2-0$ overtone bands of CO seen against background stars. From the ground, attempts at such measurements have only produced one results

towards one line of sight (NGC2024 IRS2). Though the next generation of 8 meter class telescopes are likely to produce more results, such measurements are limited by the high thermal background, even at high dispersion. A cryogenic NGST is expected to provide factors of hundreds improvement in sensitivity over ground based instruments of comparable aperture. This should make it possible to measure the CO/H₂ ratios towards hundreds of lines of sight towards bright stars and to probe the full range of column density and physical conditions in molecular clouds. At R=100000, these measurements will also provide unique and sensitive determinations of cloud radial velocity fields in both CO and H₂ along the pencil beam lines-of-sight towards individual stars. Such measurements are not possible by any means except NGST.

One key absorption band that is very important from the viewpoint of chemistry and that absolutely requires space instrumentation is the ν_2 band of water near 6.2 microns. ISO obtained some nice results for the very brightest sources (Van Dishoeck et al. 1996, 1998; Gonzalez-Alfonso, E. et al. 1998; Helmich, F.P 1996). The ν_2 water EMISSION will be a powerful kinematic probe of protostellar disks, and other warm environments because it is excited in somewhat cooler gas than the CO bands that have been used previously.

Observations of Solid-State Grain Features:

NGST will be the most powerful tool yet for observing directly the composition of interstellar grain mantles, by providing measurements of solid-state absorption features in new regimes and regions. Among the most important and interesting questions are: (a) comparisons of infrared absorption profiles from the NGST with laboratory measurements of possible IS grains embedded within interplanetary particles, to gain information on such things as the extent of crystallization in the IS grains; (b) studies of the transition of the elements from the gas phase to the dust, by investigating the conditions under which depletions increase while solid-state features grow stronger (e.g. conducting observations to see when CO is transformed from primarily a gas-phase constituent, as observed through the vibrational bands at 2.3 and 4.6 microns, to being primarily in the solid state, as observed through the CO ice band at 4.6 microns); and (c) to gain information on the formation of molecular species on grain surfaces, and the roles of ion bombardment and sputtering processes in controlling grain surface chemistry. NGST will provide unique access to the study of various ice and solid-state features that may illuminate the physical and chemical properties of interstellar grains and ices.

Galactic Scale Variations in Stellar and Interstellar Composition:

The NGST studies will be used to characterize Galactic and local metallicity gradients as determined from the abundances of various species in stars, H II regions, planetary nebulae, and supernova ejecta. The use of noble species accessible in the infrared is crucial since these species do NOT suffer depletions due to gain or gas phase processes.

2.2.2 The Origin of the Elements

Studying supernovae (SNe) in the distant Universe is already an important part of the NGST Design Reference Mission. The distant SNe program will help to determine the rates of star

formation and metal production in young galaxies, as well as establish the cosmological distance scale. By studying nearby supernova remnants (SNRs) we investigate the role that supernovae play in the structural and chemical evolution of galaxies. Galaxies become chemically enriched when supernovae inject the by-products of nucleosynthesis occurring in the cores of massive stars into the interstellar medium (ISM). In addition, shock waves produced by supernovae can heat the ISM, determine the velocity dispersion of interstellar clouds, and govern the scale height of the ISM in galaxies (McKee 1990).

Core-collapse supernovae play a major role in enriching the ISM in young galaxies and surrounding intergalactic medium with heavy elements. Understanding nearby core-collapse supernovae, their abundance yields and energy output, leads to a better understanding of these important processes in the early Universe, at epochs when the first galaxies were formed and the first heavy elements were synthesized. For example, the metal-rich SNRs in the Magellanic Clouds and other nearby metal-poor galaxies reflect nucleosynthesis in a low-metallicity regime of initial abundances, applicable to high- z galaxies.

The fundamental processes of nucleosynthesis that take place deep inside the cores of massive stars are hidden from our scrutiny until the stars explode as supernovae. Young SNRs therefore allow us to investigate material from the cores of massive stars directly, leading to observational tests of theories for stellar evolution and nucleosynthesis. Our glimpse of the uncontaminated supernova debris lasts for at most a few thousand years before this material mixes into the ISM. Young SNRs that contain fast-moving filaments of uncontaminated debris are relatively rare, so it is important to gain as much information as possible about these SNRs, to compare their differences and similarities, and hopefully to develop a consistent picture of SNR evolution. Cas A in our Galaxy is the prototype of this class (Chevalier & Kirshner 1979). However, studies of Cas A and other young Galactic SNRs have been difficult owing to the high extinction toward these remnants, while studies of young SNRs in nearby galaxies have been hampered by a lack of spatial resolution. We will make significant progress in the study of young SNRs by virtue of NGST's ability to make high spatial resolution imaging and spectroscopic observations in key diagnostic features at IR wavelengths through high extinction sight-lines.

It is important that the young metal-rich SNRs be studied as a class. For example, as interesting and important as an object like Cas A is, it needs to be viewed in the context of other similar objects. Each object contains distinctive features which allow us to investigate different aspects of SNR dynamics and evolution. When studied collectively, we can attack some very fundamental questions concerning the origin of the elements. This study seeks to assemble basic information about this important and intriguing class of objects, and to relate the results to the community of theoreticians who model SNe explosions and the chemical enrichment of galaxies. Some of the questions to be addressed include: (1) Which objects are the result of Type II, Ib, or Ic supernova explosions? (2) Do the observational data from the various wavelengths lead to a consistent picture of SNR evolution? (3) Do current emission and hydrodynamic models successfully account for the luminosities, morphologies, and kinematics of these objects? (4) Can theories of nucleosynthesis in massive stars and mixing in SN explosions explain the distribution of elemental abundances in the metal-rich

ejecta? (5) What are the probable progenitor stars of these SNRs and are Wolf-Rayet stars viable candidates? (6) Do the oxygen-rich SNRs foreshadow the evolution of SN1987A? (7) What will be the long-term evolution of these objects and how do they affect the chemical evolution of galaxies? Several key NGST observations are outlined below:

Core Wavelengths. There are two principal goals of the observations to be made in the primary $1 - 5\mu\text{m}$ band:

1. Detect low and high excitation emission from key ejecta species such as Fe ($1.3, 1.6\mu\text{m}$), S ($1.04\mu\text{m}$), CO ($2.35, 4.66\mu\text{m}$), Si ($3.9\mu\text{m}$), Mg ($4.5\mu\text{m}$), and Ar ($4.9\mu\text{m}$). Both imaging and spectroscopic observations are needed. Imaging reveals the spatial distribution of fast-moving knots and allows us to estimate the degree to which mixing between successive burning layers in massive stars occurs during SNe explosions. The spectral data show the kinematics of the constituent species and allows us to measure diagnostic line ratios for estimating physical conditions and relative abundances.

2. Measure the nonthermal continuum in the interaction zone with the circumstellar medium. Abundances in SN ejecta are often estimated from X-ray spectral data. However, emission-line strengths can be under estimated in the soft X-rays if corrections for nonthermal continuum emission are not made. Corrections are currently made by extrapolating the nonthermal radio spectral slope all the way to the X-rays. The accuracy of this method would be greatly enhanced if continuum measurements could be made in the near-IR, giving a crucial data point at energies midway between the radio and X-rays. NGST is needed because the synchrotron emission from shocks is faint and it is necessary to observe over a limited bandpass to avoid contamination by line emission.

Stretch Wavelengths. Numerous key emission line diagnostics of O, C, Ar, Ne, and Si bearing knots are available in the $0.6 - 1.0\mu\text{m}$ and in the $5 - 34\mu\text{m}$ ranges. The optical tracers include [O II], [Ca II], [Fe II], [S III], and [C I]. There are too many long wavelength tracers to list here, but a few of the most important are [Ar II], [Ar III], [S IV], [Ne II], [Ne III], [O IV], and [Si II]. Observations in these diagnostic lines can be combined with those made at other wavelengths to map the ionization state of the gas, crucial for estimating elemental abundances and nucleosynthesis yields. It is also possible to study the ejecta dust composition using spectroscopic observations of the prominent features in the $\sim 20\mu\text{m}$ region. It is believed that most of the SN ejecta mass in young SNRs is in the form of dust. Dust formed very early in the ejecta of SN1987A and is clearly revealed in ISO observations of Cas A (Lagage et al. 1996). This dust is heated when it passes through the reverse shock and radiates at IR wavelengths (e.g., Dwek & Arendt 1992). *The luminosity from a young SNR peaks in the mid-IR due to the thermal dust emission.* Identifying the dust composition through the mid-IR features traces the supernova abundance yields and the degree of mixing in the ejecta.

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■ NGST Uniqueness/Relationship to Other Facilities

■ Observing Strategy

NGST will provide the first opportunity to observe the infrared sky with both high spatial *and* high spectral resolution. Abundance determinations require that the spectral resolution be closely matched to the thermal line width of the observed species. For the production of emission lines near $5\mu\text{m}$, the excitation temperature must be close to 1,000 K, so the hydrogen thermal line width is about 3 km/s. Thus, the science return on most measurements of atomic, ionic, and molecular species is degraded when the resolution is less than 3 km/s, or $R = 100,000$. For the warmer (10^4 K) phases near H II regions, the sound speed and line widths are about 10 km/s. Thus, these region can be studied well with $R = 30,000$. For most classes of ISM science, $R = 10,000$ is a minimum requirement. Already at this resolution, the uniqueness and ISM science return of NGST is eroded.

In summary, the optimum goal is to provide $R=100,000$ from 1 to 30 microns. The compromise goal is $R=30,000$ from 1 to 30 microns. The minimum goal is $R=10,000$ from 1 to 30 microns.

For the imaging portions of this program (supernovae, stellar wind bubbles, H II regions, molecular clouds, and superbubble morphology), a wide usable field of view is essential. A field 10 arcminutes in diameter (100 arcmin^2) is ideal and would permit rapid mapping of large segments of the Galactic plane, providing the first super sub-arcsecond infrared view of the majority of the Milky Way. The NGST cameras must be equipped with narrow band filters centered on the key emission line features such as those listed in the Appendix (cf. Brackett and Paschen α , [Fe II] at $1.64 \mu\text{m}$, H_2 , [Ne II] at $12.8 \mu\text{m}$, etc.).

However, the rapid readout and large area coverage implied by a Galactic plane survey impose requirements on the NGST communications system. It must be placed either in a near-Earth orbit, or be equipped with ultra-high frequency (cf. millimeter wavelength or optical) and high bandwidth communications hardware for operations in heliocentric orbit.

■ Special Requirements

- Maximum FWHM: 50 mas at $2 \mu\text{m}$
Minimum Spectral Resolution: 10,000 at 1 to $30 \mu\text{m}$
Minimum FOV: $100'$ at $2 \mu\text{m}$
RMS absolute pointing accuracy: $0.01''$
RMS repointing accuracy: 10 mas

■ Precursor/Supporting Observations

MSX, ISO, SIRTf, SOFIA, and narrow band surveys, imaging, and high dispersion spectral surveys with ground based 2 to 8 meter class telescopes will be needed to select an optimum source list for NGST targeting. These observations will be essential to fully exploit NGST sensitivity and wavelength coverage.

MMA (millimeter-wave array) observations of the cloud cores and lines of sight to be targeted for abundance determinations are needed to characterize the emission line excitation conditions, densities, temperatures, and column densities using ground state rotational emission lines. MMA and NGST are highly complementary, in that the MMA will determine conditions in cold environments from emission lines and cold dust continuum emission while NGST will access these parameters from more reliable absorption line measurements towards pencil beam lines-of-sight towards background stars.