

# The Physics of Star Formation: Understanding the Youngest Protostars

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Scientific category: STAR FORMATION  
Instruments: MIR/CAM, MIR/SPEC  
Days of observation: 53

## Abstract

We propose to bring the power of NGST to bear on one of the most important problems in star formation – understanding protostellar formation from parent molecular cores and subsequent evolution towards becoming young stars. A few extremely young ( $10^4 < \tau < 10^5$  yr) protostars have finally been discovered with sub-millimeter telescopes in recent years, but the high extinctions ( $A_v \gtrsim 400$  mag) towards their central regions have prevented detailed study of their inner structures and mass accretion properties. Thus many key questions of the star formation process remain unanswered, such as: What determines the final mass of a forming star; do initial conditions of the ambient gas play the dominant role, or does feedback from the process itself fix stellar mass? How do protostellar envelopes evolve from pre-stellar cores to star+disk systems, and is the actual process consistent with our current theoretical models? When and under what conditions do binary systems form? What are the accretion histories of protostellar objects? When do protostellar disks form and when are jets first launched from the system?

We propose to answer these questions by undertaking a program of mid-IR imaging and spectroscopic observations of protostellar sources with NGST. We will probe the infalling envelopes, central objects, accretion disks, and accretion-powered jets from protostars which are still accreting the bulk of their masses. These observations will be used to infer the morphologies and density structures of infalling circumstellar envelopes, measure the binary frequency of protostars, determine envelope infall rates from shocked line emissions, and evaluate mass outflow rates and accretion histories from observations of jets. This information will be crucial in determining the process by which stars and disks are assembled from molecular cloud cores and for understanding what mechanisms regulate stellar masses and determine the initial mass function.

ASWG DRM Proposal

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**Observing Summary:**

Target	RA	Dec	$m_{AB}$	Configuration/mode	Days
120 CLASS 0/I YSOS	~ galactic plane		$Q_{AB} = 19 - 22$	MIR/CAM R ~ 5	10
120 CLASS 0/I YSOS	~ galactic plane		$N_{AB} \sim 17$	MIR/SPEC R3000	18
120 CLASS 0/I YSOS	~ galactic plane		$Q_{AB} = 19 - 22$	MIR/CAM R100-300	25
				Grand total days	53

## ■ Scientific Objectives

Over the past 20 years, a theoretical paradigm of low-mass star formation has emerged (e.g., Shu 1977; Terebey et al. 1984; Shu et al. 1987). This standard model has successfully interpreted the IR spectral energy distributions (SEDs) of young stellar objects (YSOs) as an evolutionary sequence from highly embedded protostars still accreting mass (Class I SED) to young stars surrounded by substantial accretion disks (Class II SED) to revealed young stars which have dissipated their disks and may have completed their planet formation (Class III SED). Although we have made considerable progress in observing and understanding pre-main sequence evolution (Class II and III phases), the earliest phases of *star formation* – the events which lead to Class I YSOs – remain highly enigmatic.

In recent years, several protostars in the earliest stage of assembly have been discovered. Known as “Class 0” objects (André et al. 1993), many were initially identified from their powerful and highly collimated jets which were found to be emerging from dense molecular cloud cores. Most have only been detected at far-IR (e.g.,  $\lambda \geq 25 - 60\mu\text{m}$  IRAS data) and sub-mm wavelengths. They appear to be protostars that have yet to accrete the bulk of their masses and are characterized by very cold ( $T \sim 30$  K), extended ( $r \sim 1000$  AU) envelopes and powerful bipolar outflows. Their ages, inferred from their SEDs and number frequency, are less than  $10^5$  yr, and the dynamical ages of their outflows (length / velocity  $\sim 10^4$  yr) are often much younger than those of the more evolved Class I YSOs.

The Class 0 YSOs represent the most crucial phase in the star formation process, when the physics that determines the mass of the final star is imprinted on the system. Key questions regarding Class 0 sources are: Is the mass infall rate onto the protostar+disk system determined solely by the isothermal sound speed as predicted in the “inside-out” collapse models? What is the initial ratio of protostellar to disk mass and how does it evolve with time? Does fragmentation of massive accretion disks lead to the formation of binary systems? What determines the onset of disk accretion and how are the powerful outflows triggered? Does outflow disrupt the envelope, terminating infall and thereby influencing the final mass of the forming star? Is the mass of the star built up through steady accretion of material from its disk, or is most of its mass accumulated in short bursts with very high rates of mass accretion?

In order to study the energetic processes that occur deep in the potential well of these collapsing systems, mid-IR observations that trace the emission of the inner regions directly are required. We propose here a suite of imaging and spectroscopic NGST investigations of Class 0/I YSOs and their outflows that we anticipate will provide the first detailed understanding of these enigmatic objects and the star assembly process.

### 1 Protostellar Sources and Envelopes: Physical Structures

Sub-mm observations have been able to constrain the luminosities and overall sizes of Class 0 YSO systems but have yielded few details of the central protostars or their inner circumstellar regions. The luminosity of Class 0 YSOs emerges predominantly in the sub-mm wavelength

region as a result of re-processing of shorter wavelength radiation by grains in their extended protostellar envelopes. The sub-mm spectra of these objects are feature-less and similar to blackbodies  $T \simeq 20 - 30$  K (see Figure 1) and thus convey little information on their warmer driving central protostars or inner circumstellar regions. Mass accretion rates and luminosities are highly dependent on local volume densities through the sound speed of the gas. As a protostar evolves, the density and temperature profiles of its inner envelope may change (e.g., see André et al. 1996), thereby changing the accretion rate onto the central source. We propose to characterize this evolution by conducting a multi-color imaging survey of a large sample of 120 Class 0/I objects found in nearby star-forming regions selected for intrinsic luminosity (i.e. mass and accretion rate), SED shape (i.e. evolutionary state), and star-forming environment (i.e. initial conditions).

Class 0 YSOs are expected to have fluxes 100 or more times higher than cool ( $T = 20 - 30$  K) blackbodies in the mid-IR (Figure 1). This is because radiation from warm central sources and scattering off dust grains in inner circumstellar envelopes are strongest at “short” wavelengths,  $10 \lesssim \lambda \lesssim 50 \mu\text{m}$ . The exact amount of scattering is a strong function of the density and geometry of inner YSO envelopes, so departures from blackbody emission are highly diagnostic of envelope structures (density profiles etc.) and warm central sources. Radiative transfer models (e.g., Wolfire & Cassinelli 1986) also predict strong grain and gas features in mid-IR spectra which further constrain protostellar envelope radiation environments and geometries. Knowledge of envelope structures (i.e.,  $\rho(r)$  and  $T(r)$ ) leads to direct predictions of mass accretion rates onto the central protostars. We will compare these predicted rates to those measured from emission line observations described below and rates inferred from protostellar luminosities. This comparison will clearly reveal whether actual protostars accrete mass at rates predicted by the standard model or whether refinements of the model are needed.

Spatially resolved ( $\sim 50$  AU at  $\lambda = 10 \mu\text{m}$  is possible for many nearby protostars) images will also provide needed constraints to the source, envelope, and disk geometries for a given mid-IR energy distribution (Yorke et al. 1995). Furthermore, these mid-IR images will be the best and most universal probes of protostellar multiplicity on scales of 100 AU and smaller. This is very significant for testing whether fragmentation of a massive accretion disk leads to the formation of binaries with separations 50–100 AU, typical of multiple systems observed in the field.

## 2 Protostellar Disks and Mass Accretion

After a central protostellar core develops, theory predicts that higher angular momentum material continues to infall from the circumstellar envelope along stream-lines which eventually “miss” the central object. A circumstellar disk is formed with mass comparable to the central protostar. Such a massive disk quickly becomes unstable and can rapidly transport mass onto the central object while redistributing angular momentum outward. This process repeats until infall onto the protostar+disk system terminates ( $M_*/\dot{M} \sim 10^5$  years), signaling the end of the Class I phase. It is only during these early stages, when  $A_V > 100$  mag,

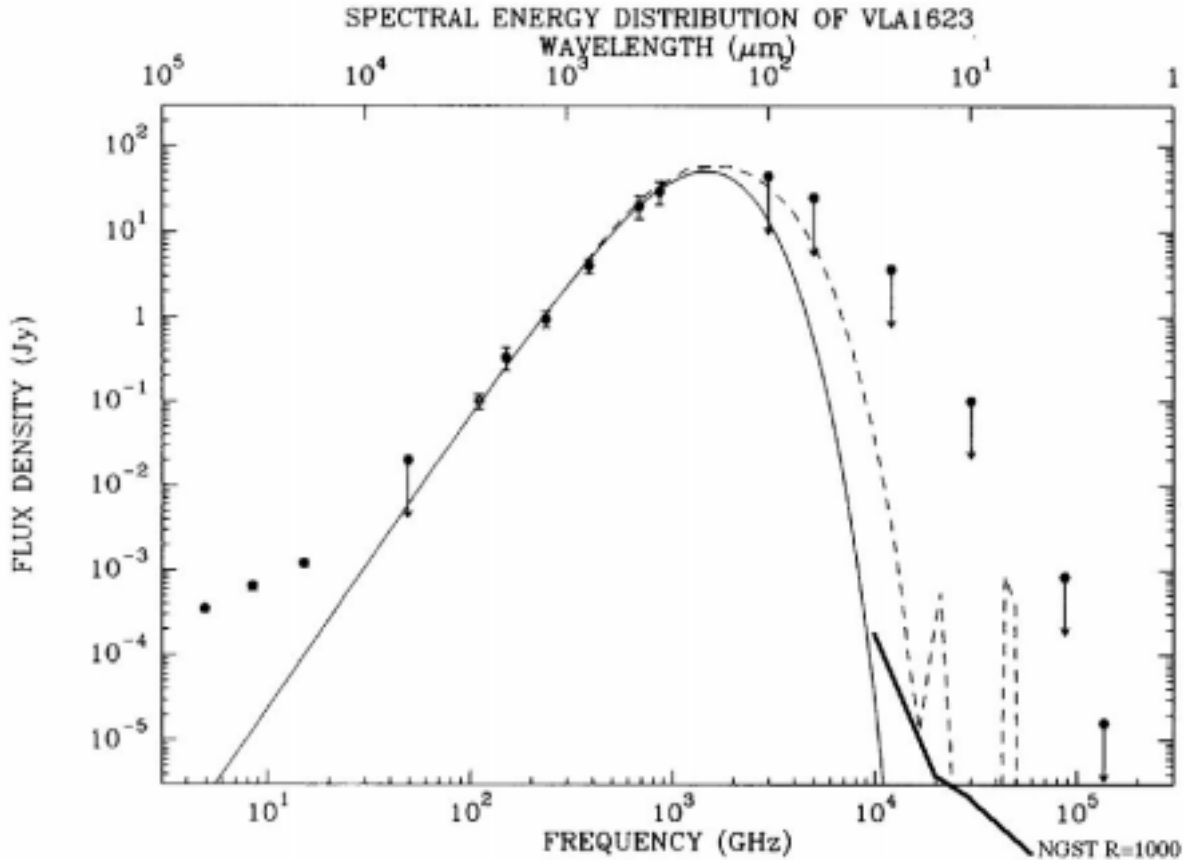


Figure 1: Spectral Energy Distribution of Class 0 protostar VLA 1623 from André et al. (1993). Points are existing observations, solid line is a  $T=20$  K blackbody, and dashed line is the prediction of the Wolfire & Cassinelli (1986) radiative transfer code with  $\rho \propto r^{-0.5}$ . Observations in the  $10 - 50 \mu\text{m}$  region are required to reveal details of the inner infalling envelope. The sensitivity of NGST ( $T=50$  K primary) at  $R=1000$  for  $S/N=10$  and  $10^4$  s exposure time is shown over  $5 \mu\text{m} < \lambda < 30 \mu\text{m}$  as a thick curve. Most known Class 0 YSOs are equally or somewhat less luminous and approximately a factor of 3 more distant. Thus they are about a factor of 10 fainter but should still be observable (continua at  $R \gtrsim 5$  and lines at  $R \gtrsim 1000$ ).

that the the physics of the collapse process can be investigated.

We propose to quantify *mass infall rates* from collapsing envelopes by observing mid-IR emission line diagnostics of envelope material crashing onto protostar+disk systems in accretion shocks. We will observe a large sample of objects (as outlined above and described later in the Observing Strategy section) in nearby star-forming regions. Our goals are: i) to test whether infall rates and disk radii evolve with time during the protostellar (Class 0/I) phase; ii) to determine whether infall rates are consistent with those predicted by the observed envelope structures and cloud conditions; and iii) to explore whether higher mass protostars are assembled in a way fundamentally different from low mass ones.

As illustrated in Figure 2, shocks propagating into a dense molecular medium can produce a wide variety of emission line diagnostics. The relative strengths of various emission lines (ro-vibrational modes of  $\text{H}_2$ , and vibrational bands of  $\text{H}_2\text{O}$  and  $\text{CO}$ ) indicate the shock velocities of the impacting material (Neufeld & Hollenbach, 1994). For a fixed velocity, the line luminosities are directly proportional to the infall rate. Further, the shock velocity provides an indication of at what radius the infalling material is impacting the circumstellar disk. Thus measuring the line ratios and fluxes of these diagnostic features will enable us to infer the mass accretion rates and infall radii for our sample of protostars as a function of mass, evolutionary state, and initial conditions. In order to determine infall rates within 10%, line fluxes must be measured with  $S/N \sim 10$  against the continuum of the underlying protostar. Spatially resolved spectra of nearby protostars will separate infall and outflow regions and also yield the physical extent of active accretion onto disks. These data would allow us to test in detail models of infall radius and calibrate our shock diagnostics for application to more distant regions. Analysis of solid state ice features in protostellar envelopes (acquired simultaneously with the emission lines) will provide information on present and past envelope temperatures, further constraining accretion properties.

### 3 Formation and Histories of Protostellar Jets

Stellar outflows and jets provide fossil records of the mass loss history of young stars, so they are also very useful in chronicling the very earliest phases of star formation. Attention was first drawn to many Class 0 protostars by the detection of outflows from unidentified sources which were not visible in the IRAS data (see Bachiller 1996 for a recent review). Once attention was drawn to the points of symmetry of these ‘sourceless’ outflows, deep sub-mm or radio continuum observations were used to directly detect these protostars.

Outflow observations can probe several fundamental questions of star formation: exactly when do protostellar outflows first turn on – does the formation of a massive accretion disk instantly ignite a powerful outflow? What determines the energetics of a protostellar outflow - stellar mass, accretion history, or cloud conditions? Where exactly does the outflow jet form? How much momentum do outflows deposit in clouds? Is the outflow responsible for terminating infall, thus determining the final mass of the forming star? Mid-IR images and spectra of outflowing protostellar jets can address these questions.

It appears that nearly all protostars show outflow activity as soon as a central source

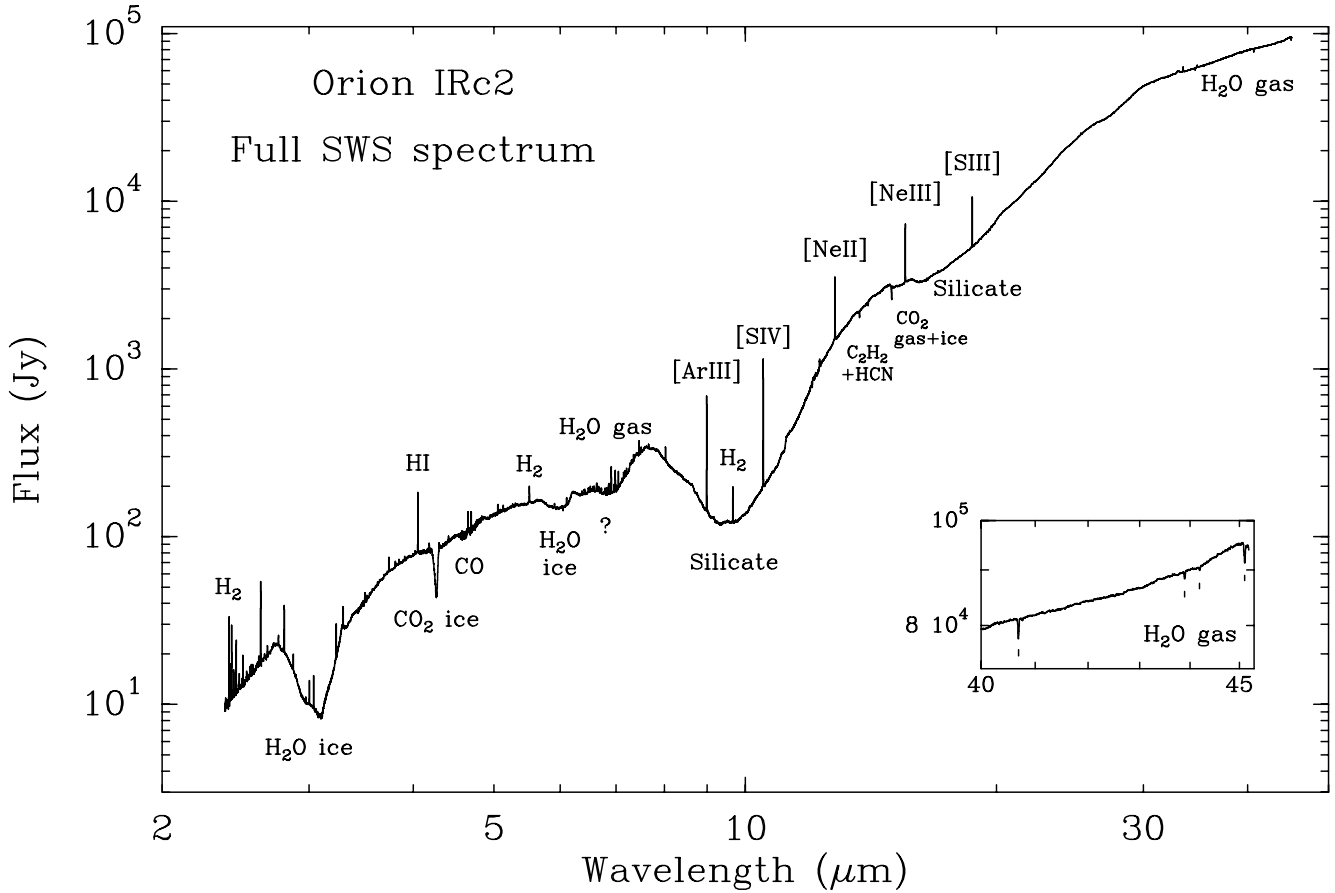


Figure 2: Shock-excited emission lines due to ro-vibrational modes of  $H_2$  (17.0, 12.3  $\mu\text{m}$ , etc.), and vibrational bands of  $H_2O$  (6–7  $\mu\text{m}$ ) and CO (fundamental band at 4.6  $\mu\text{m}$ ). This ISO-SWS spectrum from van Dishoeck et al. (1998) was obtained toward a dense embedded cluster associated with the very luminous protostellar object IRc 2 ( $L_{bol} \sim 10^4 L_{\odot}$ ). These line fluxes observed with a 20'' input aperture diagnose the impact of a large-scale outflow with ambient dense gas in the molecular cloud core ( $n \sim 10^6 \text{ cm}^{-3}$ ). Calculations by Neufeld & Hollenbach (1994) predict that infall onto a disk surrounding a solar-mass protostar will produce emission line strengths orders of magnitude lower, impossible to observe without NGST. However, this figure does illustrate the richness of mid-IR spectral diagnostics of energetic processes in star-forming environments.

has formed; i.e. accretion and outflow appear to go hand-in-hand. If outflow and infall are indeed causally linked, can the knot structure in outflows reveal details of a protostar's accretion history? Indeed, many jets show bipolar symmetry in their ejecta structures, so jet morphologies do appear to be related to events which occurred at the central protostars.

The size of outflows, their symmetries, and velocity fields provide constraints on their ages, momenta, and formation locations / mechanisms. ISO has shown that the rotational transitions in the  $\nu = 0 - 0$  vibrational lines of  $H_2$  between 28 and  $6\mu\text{m}$  provide the most sensitive tracer of outflows powered by the youngest stars, those that are heavily obscured, or those that power only relatively weak ( $v \sim 5 \text{ km s}^{-1}$ ) shocks.

In order to address the above questions of jet ages, formation, and energies, we propose NGST imaging and spectroscopic observations of  $H_2$  emission from the jets of our Class 0 and I YSO sample. Via these jet observations, NGST will probe protostars and their environmental interactions in conditions that range from dense cluster forming regions to relatively sparse isolated groups.

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## ■ NGST Uniqueness/Relationship to Other Facilities

NGST is the only existing or planned facility which can make these observations. Its large aperture and low background produce high sensitivities in the mid-IR where it has superb spatial resolution ( $\sim 0.''3$  or  $\sim 50 \text{ AU}$  for nearby clouds) for the continuum and line-emission imaging studies. NGST will be sensitive enough to image hundreds of low-mass Class 0 protostars within 1 kpc at  $S/N > 10$  in  $t \sim 10^{3-4} \text{ s}$  at wavelengths  $5 \mu\text{m} < \lambda < 40\mu\text{m}$ .

SIRTF and IRIS will identify new Class 0 YSOs but will lack the spatial / spectral resolution and sensitivity to study them in the mid-IR regime. SOFIA will lack the sensitivity and spatial resolution required for these observations. Although ISO performed a pioneering observation of the  $63 \mu\text{m}$  [OI] feature in an accretion shock for the most luminous Class 0 source IRAS 16293-2422 (Ceccarelli et al. 1998), it did not have the sensitivity to detect line emission from the hotter shock diagnostics described above and was unable to perform this observation on any of fainter Class 0 sources. We anticipate that a few pioneering observations of this type will be conducted with SOFIA, but NGST will be required to



perform the systematic program capable of addressing the fundamental questions asked above.

NGST will achieve  $S/N = 10$  detections of emission-line diagnostics at  $R=3000$  against the continuum of Class 0 and 1 YSOs in approximately  $10^4$  seconds in nearby ( $d \sim 500$  pc) regions. Ground-based observations with the Keck or GEMINI telescopes are impossible as they would require over 1000 times as much time even when NGST is source-noise limited! Also, only NGST can observe the key  $H_2O$  bands at  $6 \mu m$  and the  $\lambda = 6 - 28 \mu m$   $H_2$  lines which are crucial to the success of this program.

## ■ Observing Strategy

Our approach is to conduct an aggressive observing campaign of a representative sample of 120 objects using the best practical techniques for the goals of the investigation. This sample will contain several ( $\sim 10$ ) protostars in each of 12 categories as a function of intrinsic source luminosity (greater / less than  $3 L_\odot$  to probe underlying mass and accretion rates), SED shape (Class 0/I to track evolutionary state), and star-forming environment (3 regions within 1 kpc distance with different global cloud properties).

Broad-band ( $R = 3 - 5$ ) photometric observations of Class 0 and I protostars are needed in at least 4 filters in the  $10 - 28 \mu m$  range. Extension to  $40 \mu m$  would provide considerably more scientific return. These spatially resolved multi-color data will provide constraints on extinction and envelope properties (i.e.,  $\rho[r]$  and  $T[r]$ ) and will also be combined with far-IR (SIRTF), sub-mm, and mm energy distributions to best determine source luminosities and large-scale envelope properties. This will require 10 days of observing time for our sample of 120 objects. These same YSO fields will also be imaged in narrow ( $R \geq 100$ )  $H_2$  to observe their jets over linear fields of  $1' - 4'$  each. The best transitions for such observations are the 28 and  $17 \mu m$  S(0) and S(1) lines in the  $\nu = 0 - 0$  vibrational states since these lines are easily excited by shocks that heat the medium to only a few hundred degrees or less. Thus these observations will be sensitive to cold ( $40 < T < 100$  K) gas, which constitutes the bulk of the material in molecular outflows. 1 hour of integration in each of these lines will detect  $10^{-3} - 10^{-5} M_\odot$  per square arcsecond, several orders of magnitude better than ISO and by far the most sensitive observations of this material. Observing the object sample in both line filters will require an additional 25 days of observation. These observations will be performed in advance of the spectroscopic survey outlined below so that slit orientations can be set appropriately to include spatial information on the extended jet emission.

We shall also acquire mid-IR spectroscopic observations of protostellar envelopes and disks to measure mass infall rates and constrain envelope temperatures. We will observe the same sample of 120 protostars divided into 12 categories as described above. In order to obtain  $S/N \sim 10$  in a line, we require  $S/N \sim 80$  on the continuum of a typical Class 0 / I YSO at  $R = 3000$ . This results in an integration time of  $1.5 \times 10^4$  s when we model the central object as a very active T Tauri star extinguished by an envelope with  $A_v = 400$  mag. We wish to observe several lines and bands over the  $6 - 12 \mu m$  range which we expect to cover in a single exposure. We estimate that spectroscopic observations of 120 objects

will require 18 days with 2 wavelength settings per object. Lower spectral resolution results in much longer integration times needed to detect these unresolved features (i.e. over  $\times 10$  increase at  $R = 1000$  for the emission line program outlined here).

## ■ Special Requirements

Minimum Spatial Resolution: 300 mas at 10  $\mu\text{m}$   
 Minimum Spectral Resolution: 3000 at 10  $\mu\text{m}$   
 Minimum FOV: 4 arcmin<sup>2</sup> at 17  $\mu\text{m}$

## ■ Precursor/Supporting Observations

Millimeter Array and NGST observations of protostellar envelopes and jets are complimentary. For example, André et al. (1993) noted that the dust envelope structure and accretion properties of protostars are best constrained by fitting the spectral energy distributions and radial profiles simultaneously over mid-IR through mm wavelengths. The spatial resolution of the MMA (at 350  $\mu\text{m}$ ) and NGST (in the near-IR) will be comparable. However, the MMA will probe cooler envelope material (at  $r \gtrsim 20$  AU from the protostar) compared to the observations of warm inner regions (which are actually accreting onto the protostar) described here. Accretion rates derived from infalling gas (spectrally and spatially resolved MMA observations) can be compared with shock diagnostics (NGST) as can mass loss rates from the jet components. Thus both mid-IR ( $10 \lesssim \lambda \lesssim 50\mu\text{m}$ ) NGST and existing / future sub-mm observations are required to understand fully protostars and their circumstellar environments.

Source lists of Class 0/I objects will be provided by surveys that will be conducted with SIRTFF and IRIS. SOFIA and ground-based 8–10 m class telescopes will conduct initial spectroscopic studies of several interesting objects which will serve as precursors to the kind of systematic program enabled by NGST as outlined here.