GSMT Science Use Case

Title: Linking Protostellar Core Initial Conditions to Final Stellar Mass

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Abstract: We propose a pilot program aimed at taking the first steps toward solving a problem central to understanding how stars form: what are the initial conditions in protostellar cores that determine the mass of a star? Our approach exploits the sensitivity provided by TMT to enable measurements of the kinematics and physical conditions in protostellar cores. By examining resolved CO fundamental profiles of these features at resolutions R ~ 100,000, we will be able to infer the temperature, density and velocity of infalling gas along the line of sight to forming star-disk systems and test directly the hypothesis that massive stars form from cores with higher infall speeds (a direct result of higher initial turbulent + thermal speeds, and thus sound speeds), while lower mass stars form in cores characterized by lower sound speeds. TMT will extend the range of potential target sources beyond the small sample of bright, nearby cores surrounding primarily low mass stars that are accessible with current generation telescopes, to a sample of ~30 cores selected to contain forming stars with masses ranging from the hydrogen burning limit to 50 M_{sun}.

Summary Table:

Summarize the observations in terms of telescope, instruments, number of nights, observing mode and instrument and AO requirements.

Telescope	Instrument	# Nights	Mode	λ range(μm)	λ/δλ	AO Mode	FOV
GMT	GMTNIRS	10	queue or service	4.6-5	100,000	none	1”
TMT	MIRES or NIRES-R	10 or 5	queue or service	4.6-5	100,000	MIR-AO	1”

Scientific Motivation:

Individual stars are believed to form in optically opaque (A_V > 1000 mag) rotating molecular cores of dimension ~ 0.1 pc. To date, these protostellar cores have been studied primarily at millimeter and sub-mm wavelengths, and largely in nearby (d < 500 pc) star-forming regions at spatial resolutions typically corresponding to 1000s of astronomical units. Such observations provide a measure of the core mass and large-scale morphology, and relatively coarse kinematic information sufficient to diagnose the onset of gravitational collapse.

At the earliest evolutionary phases, these cores are so opaque they preclude detection of the forming star and its associated circumstellar accretion disk even at mid-infrared wavelengths. The presence of the star-disk system can be inferred from (a) measurement of dust-reprocessed mid- and far-IR emission from which the total luminosity of the forming star and its accretion disk can be inferred; and (b) the kinematic signatures of collimated molecular outflows thought to arise from a magnetically-driven wind originating at or near the boundary between the stellar magnetosphere and a circumstellar accretion disk. At later stages in stellar assembly, the optical depth of the envelope decreases, and emission from the star-disk-outflow system can be observed, first at mid-IR wavelengths, and later at shorter wavelengths. It is at this point that we can begin to make the measurements needed to determine the relationship between the initial conditions in protostellar cores and the final mass of the forming star – a relationship key to understanding the basic physics of the star-formation process.

Current facilities lack the sensitivity to answer a question fundamental to understanding the star-formation process: what kinds (masses) of stars form in what kinds of cores?

By contrast, TMT (and GMT) will have the sensitivity to enable R ~ 100,000 spectroscopic analysis of star-forming cores, and the ability to diagnose the physical conditions and kinematics of infalling envelopes. This high spectral resolution is required in order to match the velocity widths characteristic of absorption features arising in infalling envelopes (widths ~ 1-3 km/sec).

Our approach will be to carry out a pilot program to estimate infall rates in protostellar cores surrounding a sample of ~30 cores surrounding embedded stars spanning a wide range of luminosities (10000) and presumably masses. Current theories suggest that stars of higher mass should form from cores having higher infall rates (a direct result of higher initial thermal + turbulent speeds, or sound speeds), while lower mass stars form from cores having lower sound speeds. The proposed TMT observations will enable direct confrontation of this hypothesis, and the empirical evidence needed to revise or reject this hypothesis.

Approach:

Our approach will be to measure the velocity-resolved profiles of a suite of CO fundamental transitions to infer temperature, density and velocity along the line of sight through the protostellar core to the spatially unresolved inner parts (r < 1 AU) of the star-disk system (which serves as the bright 'background' against which these features can be measured). In turn, these measurements can yield an initial estimate of the infall rates in cores surrounding forming stars spanning a wide range of masses.

An illustration of the potential of such measurements is provided by the pioneering study of Scoville, Kleinmann and Hall (1983) for the Becklin-Neugebauer source – a massive ($M > 10\ M_{sun}$) protostar located in the Orion star-forming complex. These authors used R

~ 50,000 spectra to obtain profiles for a large number of absorption features arising in the CO fundamental band and spanning a wide range in excitation conditions. In turn, these profiles mapped both the velocity field, temperature and density distribution along the line of sight to BN – leading to the only extant determination of mass inflow rate from a protostellar core to a star-disk system: a critical quantity for assessing the relationship between resulting stellar mass and protostellar conditions. Our choice of CO as our probe is motivated by the robustness of the molecule to photo- and collisional dissociation.

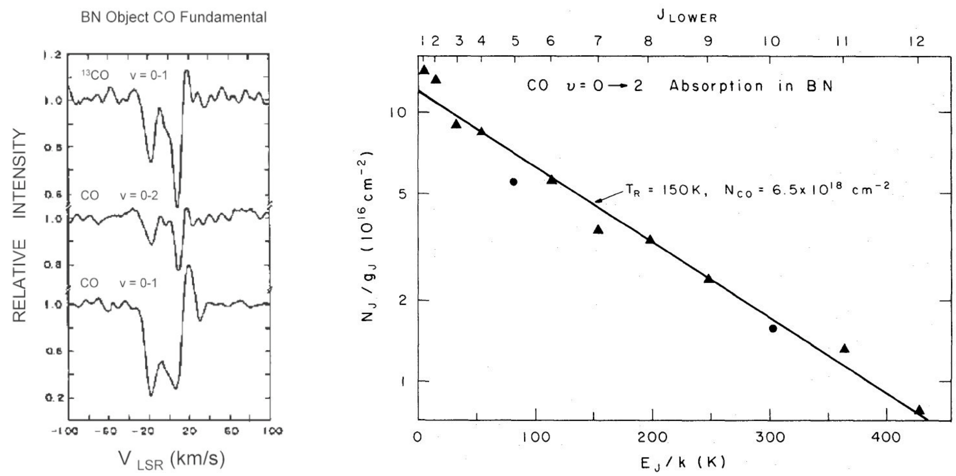

Figure 1: (a) Profiles of CO fundamental band absorption features obtained by Scoville et al. (1983) from high spectral resolution (R ~ 50,000) observations of the Becklin-Neugebauer Object – a high mass protostar deeply embedded within an optically opaque core. Observations of several tens of these profiles enabled Scoville et al. to derive temperature (see Fig 1b in which level population inferred from measured line strength is plotted against excitation potential, yielding an estimate of temperature for a particular CO transition) density and velocity structure in the protostellar core and to derive the first quantitative estimate of mass inflow rate from a protostellar core to a forming star-disk system

Limiting Factors and the Current State of the Art:

Current facilities lack the sensitivity needed to explore all but a few (10-20) of the brighter embedded sources in nearby (d ~ 150 pc) molecular clouds; this accessible sample is dominated by forming stars having masses of ~0.5 M_{sun}. In order to explore the relationship between core initial conditions and emerging stellar masses among a full range of stellar masses, we need to extend our observations to the Orion Molecular Cloud (d ~ 500 pc) which contains objects of masses up to 10-20 solar masses, and beyond (d ~ 1-2 kpc) to capture forming objects between 20-100 solar masses. The sample size required is at minimum 30 sources, in order that we span the mass range between 0.1 and 100 M_{sun} with at least 10 sources within each order of magnitude range in mass. Typical integration time per source will be ~3 hours/source.

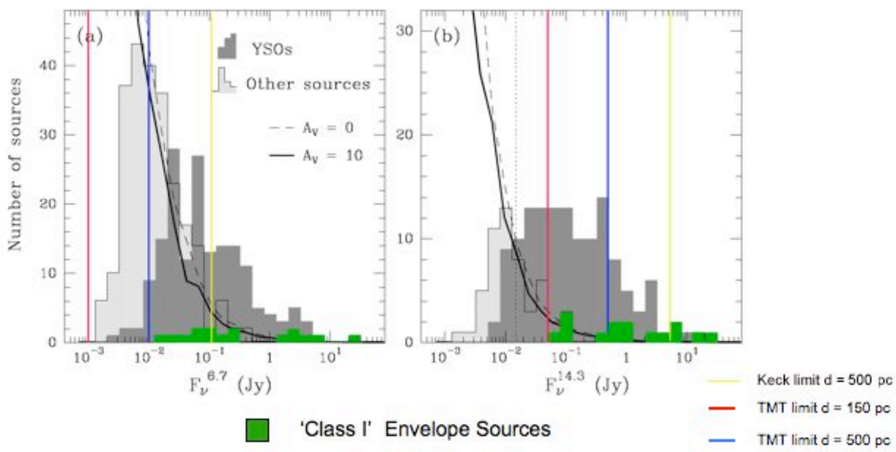

Figure 2: A histogram depicting the frequency distribution of known young stellar objects in the nearby Ophiuchus molecular cloud complex (d ~ 150 pc) observed from an ISO survey at 6.7 microns and 14.5 microns. The dark grey region depicts optically-revealed T Tauri stars (young stars still surrounded by accretion disks). The light grey region depicts weak-lined T Tauri stars (young stars lacking disks) or foreground stars. The bright green region depicts stars still surrounded by optically-opaque protostellar cores. These latter objects are representative of the targets for which we wish to carry out high spectral resolution measurements aimed at deriving mass infall rates. We estimate that these targets span a range of bolometric luminosities from 0.1 to 30 L_{sun}, and that the corresponding masses of the embedded forming stars range from 0.1 to 2 M_{sun}. The limiting fluxes to reach a S/N ~ 100 in the continuum (required to resolve individual spectral features and derive line profiles; see Figure 1) accessible in a 3 hour integration for TMT are noted (a) for objects located at 150 pc; and (b) objects located at the distance of Orion. The limit for Keck (were it equipped with a mid-IR spectrograph) for objects located at 500 pc is also noted (yellow line). The left-hand panel shows the sensitivity for measurements of the CO fundamental using NIRES-r, while the right-hand panel shows the sensitivity for measurements of the H_2 S(2) using MIRES. CO measurements using GMT+GMTNIRS or TMT+MIRES will be less sensitive, but still feasible.

Technical Details:

Surveys with the Spitzer Space Telescope will provide complete target lists of actively star-forming cores during early collapse phases both in Orion (d ~ 450 pc), as well as in more distant complexes (d ~ 2kpc) expected to harbor large samples of forming high and intermediate mass stars (which with few exceptions are absent in more proximate star-forming regions). Targets will be selected to span a range of approximate bolometric luminosity from 0.1 to 100,000 L_{sun}. Ground-based observations at 2 microns with Keck and/or Gemini will refine the target list by providing information regarding core morphologies. This will allow us to select sources amenable to low resolution spectroscopy capable of providing approximate spectral types (and thus masses) for the central stars from observation of light scattered earthward from the inner regions of cavities swept clear of intervening dust by powerful stellar winds (see Figure 3). TMT will be used to carry out a survey of 30 sources spanning a wide range of luminosities – sufficient to establish the relationship between core infall rate and the mass of the emerging star.

Either TMT or GMT could be used for this program. The most sensitive instrument+telescope combination is TMT with NIRES-R (see Figure 2). The program could be done with TMT+MIRES, which will have a detector that is less efficient at the wavelength of the CO band. GMT+GMTNIRS will provide roughly comparable performance to that of MIRES; that is because the instrument is more efficient for CO measurements than MIRES, but the telescope has less collecting area and a larger diffraction spot.

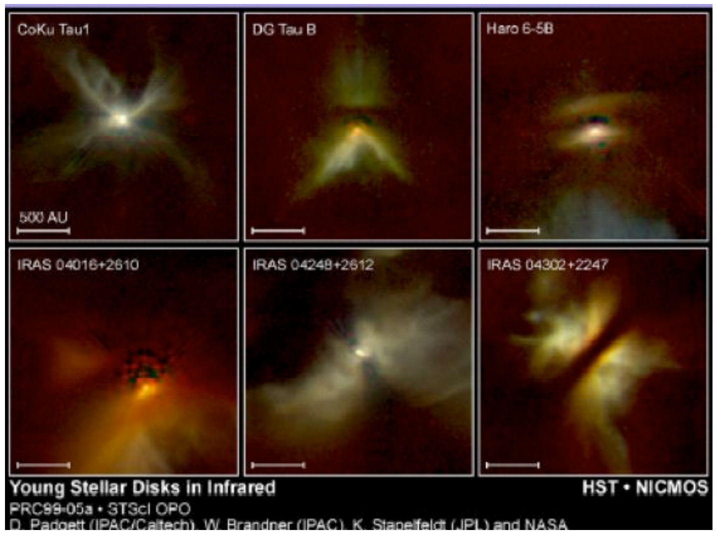

Figure 3: HST NICMOS images of star-disk systems just emerging from their protostellar cores. The protostellar core material is made visible via near-IR (2 micron) light scattered earthward by dust embedded in the inner regions of the infalling core. The disk is manifest in 'silhouette' against the bright scattered light arising from core material. In all cases, the central forming star is obscured from view by the optically opaque circumstellar disk material. The optical path from star to envelope is believed to be produced by a powerful collimated outflow emanating from the inner disk regions. Observations of the bright, scattered light envelope with Gemini or Keck will enable spectral classification of the forming star, and in combination with near- and mid- IR photometry, an estimate of its mass. From this mass estimate, combined with the infall rates derived from the proposed TMT measurements, we will be able to deduce the relationship between the mass of the forming star and the initial conditions (specifically mass infall rate) characterizing the protostellar core.

Preparatory, Supporting, and Followup Observations:

Spitzer from the cores-to-disk team will be required in order to select a sample of embedded protostars spanning a range in luminosity from 0.1 to 100,000 L_{sun}. Gemini or Keck observations will be required in order to (a) image the Spitzer target list; (b) select objects with scattered light envelopes of brightness sufficient to (c) measure the spectral type of the embedded star. Based on the observations of White and Hillenbrand (2004), approximately 20-30 hours of Keck time with NIRSPEC will be required.

Complementary observations with Herschel (observations of shock-excited far IR features – e.g. O I, CI, CII) will provide a (model-dependent) check on the infall rates derived from the mid-IR absorption spectra.

Followup observations with TMT and/or GMT will include (a) measurement of additional probes (e.g. H_2O; H_2) to confirm the initial results inferred from CO; and (b) extension of the pilot survey to a larger sample of cores surrounding stars formed in different environments (e.g. rich, dense clusters analogous to those thought to dominate the stellar population in the Milky Way and other galaxies; and lower density unbound associations).

Anticipated Results:

We expect to derive a relationship between the infall rates and mass derived for 30 protostellar sources spanning a wide range in mass. From these measurements, it should be possible to estimate the initial core conditions that give rise to emerging stars spanning a range of mass from 0.1 to 100 M_{sun}, thus answering a fundamental question: what kinds of protostellar core conditions are required to form stars of different masses.

Requirements and Goals Beyond the GMT and TMT Baseline Instrument Designs:

The required TMT capability (R=100,000 spectroscopy at 4.7 microns) is not included in the first-light instrument complement, but is planned for the first generation instruments. The required GMT capability is currently included in the first generation instruments.

In order to observe CO features spanning a range of excitation conditions, queue or service scheduling is required in order to enable observations at times when key features are widely separated from contaminating terrestrial absorption features. Furthermore, a higher altitude site is preferable (but not essential)in order to reduce the effects of pressure broadening on terrestrial features.

Summary:

Sensitive high resolution mid-IR observations with TMT will enable measurement of spectral features diagnostic of infall rates in protostellar cores surrounding forming stars spanning a wide range of masses. They will provide the basis for deriving the relationship between protostellar core initial conditions and the mass of the emerging star – fundamental to understanding how stars of differing mass are formed.

References

Scoville, N., Kleinmann, S.G., Hall, D.N.B., and Ridgway, S. 1983 ApJ 275, 201
White, R. A. and Hillenbrand, L.A. 2004 ApJ 616, 998