Understanding the Youngest Protostars

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Understanding the processes by which star-disk systems form from collapsing protostellar cores is a fundamental unsolved problem in star-formation. Both JWST and GSMT will make critical contributions to this problem: JWST via its extraordinary mid-IR sensitivity and complete wavelength coverage throughout this spectral region, and GSMT through its combination of sensitivity and angular resolution. Both are needed in order to probe the physical, chemical and kinematic structure of protostellar cores in which extinction at visible wavelengths can reach Av ~ 1000. Together, they can provide measurement of mass infall and outflow rates during the stellar assembly phase for stars of differing mass, and insight into the basic processes that occur as stars and their circumstellar accretion disks begin to take form.

Background

Individual stars are believed to form in optically opaque ($A_v > 1000$ mag) rotating protostellar molecular cores of dimension ~ 0.1pc. To date, these cores have been studied primarily at mm- and sub-mm wavelengths with spatial resolutions typically corresponding to 1000s of astronomical units. These observations provide a measure of the core mass and large-scale morphology, and kinematic information sufficient to diagnose the onset of gravitational collapse. At the earliest evolutionary phases, these cores are sufficiently opaque as to 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 acccretion 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 emission from the star-disk system can be observed directly, often at the center of a highly collimated ionized bipolar 'jet' which traces the outflow, and provides evidence of variations in mass accretion rate during the stellar assembly phase.

Current facilities lack the combination of angular resolution, sensitivity and wavelength coverage critical to enabling more quantitative study of the assembly process. Key questions that must be addressed but cannot be using available facilities include:

(1) How do star-disk systems evolve from protostellar cores?
(2) What determines the final mass of a star? Initial conditions in the protostellar core? Feedback from a forming star-disk-wind system?
(3) When and how are collimated outflows launched? How are their properties related to those of the forming star-disk system? What role do they play in determining the final mass of the star?
(4) When and how do binary/multiple stars form?

The Spitzer Space Telescope promises to make significant contributions to answering these questions via its ability to detect protostellar cores early during the assembly phase, and providing spectroscopic probes of bipolar outflows as well as diagnostics of mass inflow rates. JWST will have the sensitivity, angular resolution and spectral resolution to build on the reconnaisance of protostellar cores begun with Spitzer and provide initial estimates of basic physical properties (mass accretion rates; wind outflow rates; wind and core morphologies in nearby star-forming regions). GSMT will have the sensitivity needed to probe the kinematic and physical structure of star-disk-envelope systems via ultra-high resolution spectroscopy critical to probing cold gas located at distances of 100s to 1000s of astronomical unitis from the forming star.

The Role of JWST

The mid-IR sensitivity of JWST will enable deep imaging at spatial resolutions (300 mas at 10 microns or 50 AU at the distances of the nearest star-forming molecular clouds, d ~ 150 pc) sufficient to determine:

(1) the detailed morphology of protostellar cores (at spatial scales of 100 AU), and via comparison of thermal emission and scattered light with models, the temperature and density in the cores. The low thermal background of JWST make it exquisitely sensitive to low surface brightness features unobservable from the ground.
(2) the location and number of pre-stellar condensations, thus informing the origin of stellar multiplicity: formation via instabilities in circumstellar disks or via fragmentation within star-forming cores;
(3) the morphology of winds (narrowly collimated? broad enough to expel a significant amount of core material?) and, via reprocessed radation arising at the shock-heated interface between winds and surrounding molecular material, the mass outflow rate and wind energy input
(4) the structure of ionized jets, and from this structure, quantitative estimates of the number and cadence of high accretion rate episodes that take place during the stellar assembly phase.

The uninterrupted access to spectroscopic features in the mid-infrared will enable measurement (at resolutions, R ~ 3000) of spectral features (e.g. molecular hydrogen; water; and atomic line emission) arising from shocks (a) at the interface between infalling material from the core and the circumstellar accretion disk; and (b) between the outflow/jet and the surrounding molecular material. Observed fluxes from diagnostic lines arising in these shock regions will provide estimates of mass accretion and mass outflow rates via comparison with models. Critical questions that can be addressed include:

(1) how is the mass accretion rate in the protostellar core related to the mass of the star as inferred from its luminosity? Can we develop an understanding of the conditions that give rise to stars of different mass?
(2) What is the relationship between stellar mass and wind outflow rate?

The Role of GSMT

A 30-m class GSMT will have the sensitivity to enable ultra-high (resolutions R ~ 100,000) spectroscopy of star-forming cores. This provides a major advantage given that the velocity widths of many diagnostic emission and absorption features are typically several to 10 km/s, and that characteristic velocities in protostellar envelopes and in the outer parts of circumstellar disks are ~ 1 km/sec.

High resolution spectra using diagnostics such as molecular hydrogen, water, CO and both permitted and forbidden atomic transitions can be used to map 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). An example of the potential of such measurements is provided by the pioneering study of Scoville, Kleinmann and Hall for the Becklin-Neugebauer source – a massive (M > 10 Msun) protostar located in the Orion star-forming complex. These authors used R ~ 50,000 spectra to obtain profiles for a large number of absorption lines arising in the CO fundamental band. In turn, these profiles mapped both the velocity field and density distribution along the line of sight to BN – leading to the only extent 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.

A telescope with the power of GSMT is required in order to provide quantitative study of a large number of star-forming cores surrounding objects of different mass. Such measurements can directly test the currently popular hypothesis that massive stars form from highly turbulent cores (whose velocity structure can be probed at mm wavelengths) characterized by high mass inflow rates. Spitzer and JWST will provide target lists of actively star-forming cores during early collapse phases, and a reconnaisance of core morphologies and approximate physical properties. GSMT will have to power to derive essential physical quantities directly.

GSMT will also have the spatial resolution (5 times that of JWST) to probe core and jet morphologies in more distant (d ~ 2 kpc) star-forming regions – those that are likely to harbor examples of forming high and intermediate mass stars (which, with few exceptions, are absent in more proximate (d < 500 pc) molecular clouds. Hence, GSMT will be essential to understanding the differences between cores that form low and high mass stars, and to probing multiplicity in high mass star-forming regions (at 1500 pc, it will have angular resolution corresponding to ~ 150 AU).

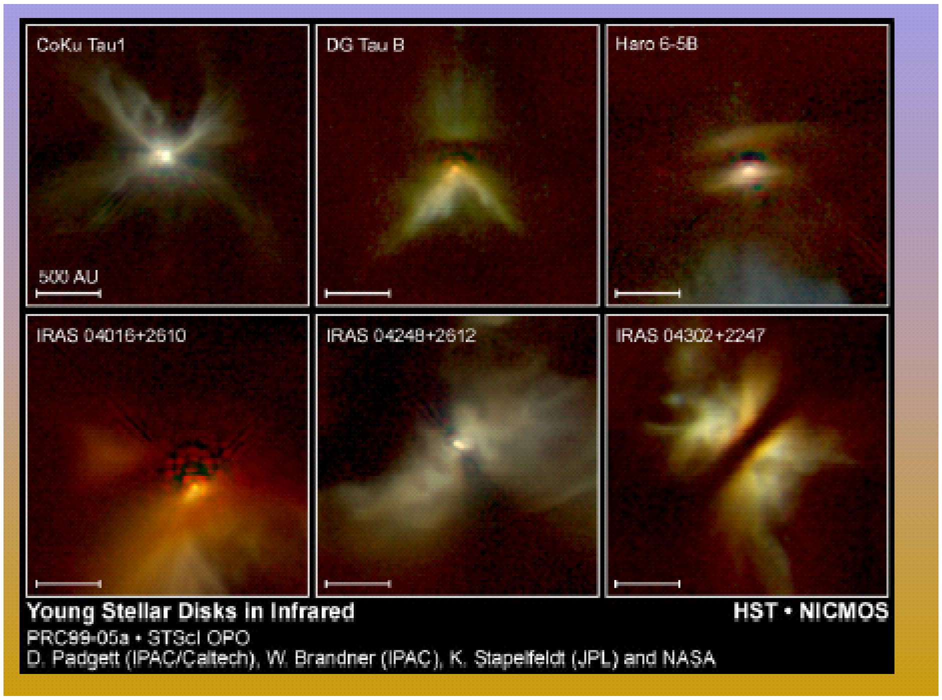

Figure 1: HST NICMOS images of star-disk systems just emerging from their protostellar cores. The protostellar core material is made visible via near-IR (2 micron) light scattered earthward by dust embedded in the inner regions of the infalling core. The disk is manifest in 'silhouette' against the bright 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 thought to be created initially by a powerful collimated outflow emanating from the inner disk regions. The solid white lines indicate a scale of 500 AU.

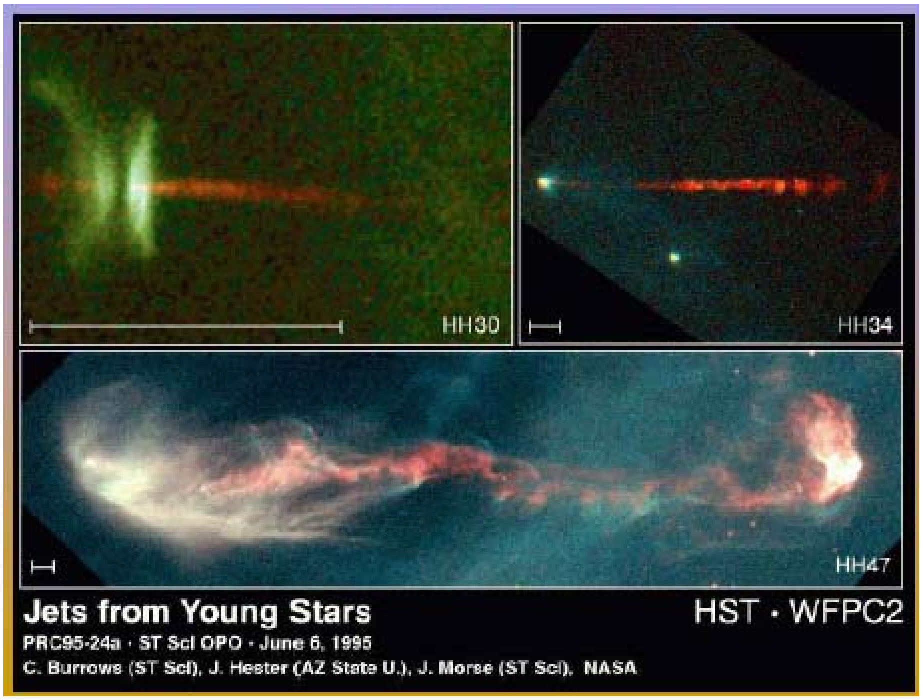

Figure 2: HST images of stellar jets surrounding forming star-disk systems. In the case of HH30 (above) the disk is clearly visible in silhouette against the background scattered light of the inner regions of the remnant protostellar core. Also visible in these monochromatic images of various shock emission tracers are multiple "blobs" thought to be diagnostic of episodes of rapid mass outflow linked to episodes of rapid accretion through circumstellar disks. JWST and GSMT will be able to provide maps of exquisite spatial resolution of similar features located within the optically opaque protostellar cores inaccessible to observation at wavelengths shorter than 10 microns.

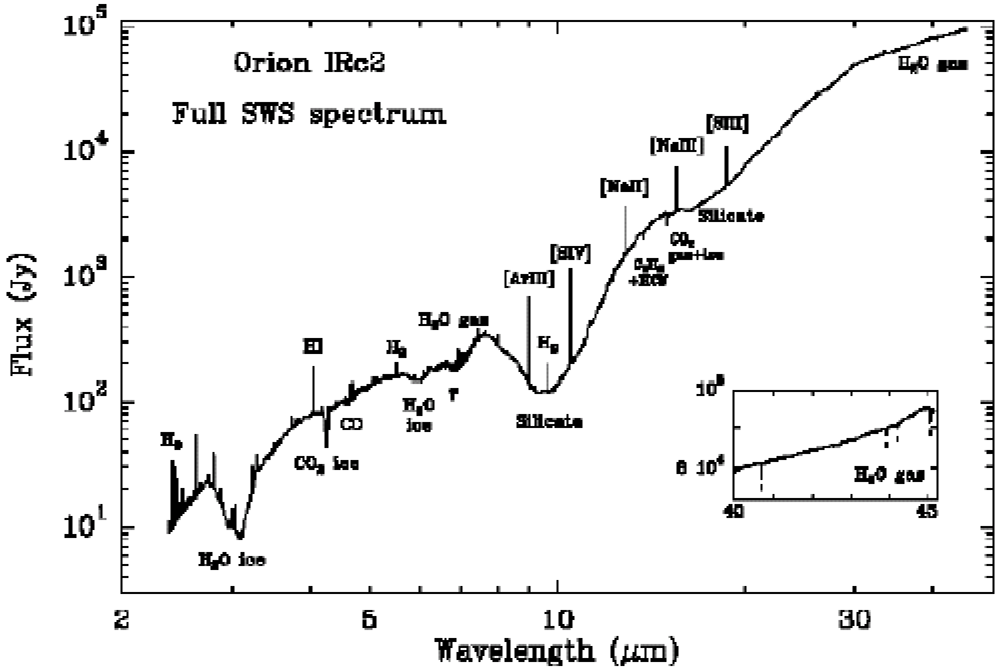

Figure 3: The plethora of spectral features diagnostic of physical and chemical conditions within protostellar cores that will be available to JWST. JWST will carry out essential reconnaisance of star-forming cores out to several kpc. GSMT will have the sensitivity to enable detailed analysis of the temperature, density and velocity structure of these cores, and the derivation of quantities such as mass accretion rate through the core – essential to linking initial core conditions to outcome stellar properties.

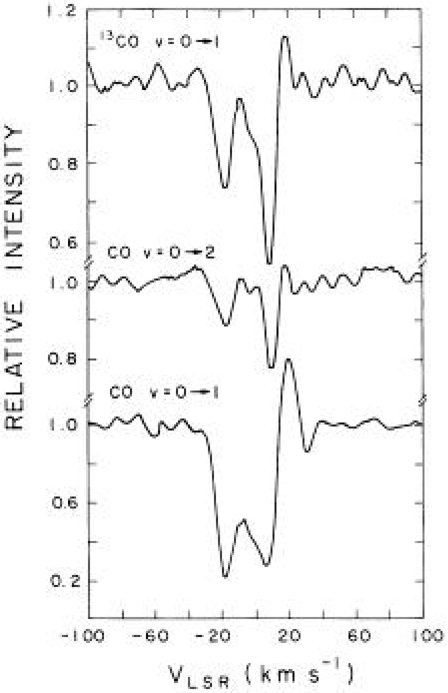

Figure 4: Profiles of CO fundamental band absorption features obtained by Scoville et al. (1983) from high spectral resolution (R ~ 50,000) observations of the Becklin-Neugebauer Object – a high mass protostar deeply embedded within an optically opaque core. Observations of several tens of these profiles enabled Scoville et al. to derive temperature, 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.