Dust Enshrouded Star and Planet Formation

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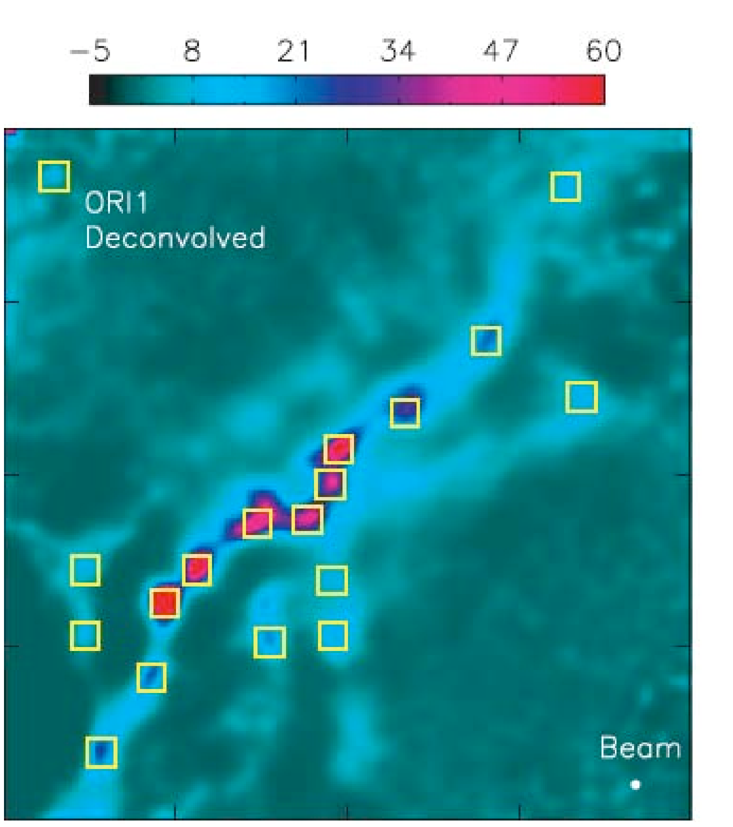
Lee G. Mundy

University of Maryland, 301 405-1529, lgm@astro.umd.edu

Paul Goldsmith (Caltech/JPL), David Leisawitz (NASA GSFC), Alwyn Wootten (NRAO)



Dense cores in the Ori 1 Region from 350 μm observations at 9” resolution and maximum entropy deconvolution to 3” beam size. The color scale is flux density in Jy per 9” beam. The size of the image is 169” on a side. The yellow square indicate identified clumps within this cloud core. From Li et al. 2007, ApJ, 655, 351.

Abstract: *How does the star formation process result in the diversity of star systems, stars, and planetary systems found in our Galaxy?* The answer to this question will enhance our understanding in fundamental aspects of the star formation process with broad impact. What are the modes and extents of star formation and what insights do they give to why and where stars form? What physical processes control the various stages of the star/planet formation process? How do they determine the outcome? How and where do planets form? Expansion in instrumental capability over the past 10 years and in the next decade can provide the spatial resolution, spectral resolution, wavelength coverage, mapping coverage, and sensitivity required to probe the star formation process in our Galaxy on scales from parsecs to AU and begin to study systems on the scale of planet formation.

Introduction: Stars form in isolation, in binary and multiple star systems, and in clusters within molecular clouds. Studies over the past 50 years have established the broad-brush character of the star formation process, but these studies have left fundamental mysteries about how and why the stellar births occurs where they do, and what processes control the outcomes. With the discovery of the variety of extrasolar planets, the mysteries have increased as we try to understand this added dimension of outcomes.

This white paper examines the top level question: *how does the star formation process result in the diversity of star systems, stars, and planetary system found in our Galaxy?* This question is fundamental to our understanding of how our Sun and Earth formed and how unique our world is in the cosmos. As stars are the building blocks of galaxies and the creation sites for the heavy elements, the star formation process is also key to the creation and evolution of galaxies.

Why is this a question for the next decade? Simply put, the instrumentation that is currently being developed and can be developed over the next decade will provide, for the first time, access to the broad range of spatial scales and the broad range of wavelengths that is required to construct a full observational picture of star and planet formation.

This is essential because star and planet formation are driven by a complex interaction of phenomena. The formation process involves a range of physics: gravity, radiative transfer, and magnetohydrodynamics. It encompasses a range of gas phase chemical and solid state processes that interact with the physical processes. For example, dust grains and molecular chemistry play a role in controlling the ionization fraction in circumstellar disks and dense molecular clouds, and the ionization in turn impacts the coupling of magnetic fields to dynamics. The growth of ISM dust grains into pebbles and onward to planetesimals in disks depends on the interplay of dust/ice bulk and surface properties and gas dynamics.

Observations provide the fundamental data which guide our theory and modeling, and drive our understanding. To bring into focus the full picture of star formation requires observations spanning from parsec scale molecular cloud structure down to the scale of the stellar radius. It spans from centimeter radio wavelengths to probe the highest surface density regions of circumstellar disks and the ionized gas, to far infrared tracing of the dust emission, to optical and X-ray emission associated with the star and the energetic processes near the star. Each factor of two to four in wavelength provides different insights and highlights different processes. In addition, molecular and atomic lines provide a wealth of information about physical conditions, dynamics, and chemical state of the gas and dust.

The scope of this white paper is limited to star formation in "typical'' conditions nearby in our Galaxy. It looks at the embedded phase from molecular cloud core to stellar formation to the T Tauri phase. The focus is on the scale from parsecs to AU, not on the young star itself or the region within 1-10 stellar radii. Hence we will touch lightly on the important science accessible to near infrared, optical, and X-ray wavelengths. This paper also neglects the chemistry of star formation and the spectral features of dust and ices. Each of these provides valuable complementary information.

This paper is organized around three sub-questions which follow from our initial question.

A. *What are the modes and extents of star formation*, *and what insights* do *they give* as to *why and where stars form?*
B. *What physical processes control the various stages of the star/planet formation process and how do they determine the outcome?*
C. *How and where do planets form? What determines the extent and number of planets?*

A. The modes and extents of star formation

In order to examine the broad scope of star formation, it is necessary to study a wide range of molecular clouds through broad surveys (c.f. Evans et al 2008). Sensitive wide-field mapping of the stellar content and dust and molecular emission provides basic information about the distribution of the stellar and cloud components. The key advances for the next generation of studies will be attaining the level of precision, sensitivity, and spatial resolution to: find the lowest luminosity young stars, probe multiplicity and interaction during star formation, and establish the relationship between the stellar and gas/dust components on the 1,000 AU scale or better. Observations need to be done at multiple wavelengths for the stellar and dust components and in a number of different molecular tracer lines to overcome the difficulties in distinguishing young stars from background galaxies (Harvey et al 2006) and to have resilience against changing dust properties, molecular depletions, and molecular abundance variations.

These types of surveys will delineate the connection between cloud structure and current star formation. The detailed correlation of parent cores and young stars at different stages of evolution will permit measurement of the core mass function and follow the evolution of cores into the initial mass function of stars (Simpson et al 2008; Goodwin et al 2008). Comparisons of different places in clouds and different types of cloud environments (isolated small cores, extended large molecular cloud, or cluster forming cores) will address the modes of star formation: isolated, cluster, and induced. Given the range of cloud conditions, individual evolutionary state, nearby star formation history and perhaps even chemical age of the material, these surveys require large format array detector instrumentation. To achieve the high resolution to probe the individual star-core connection, these projects would be enhanced by the development of array detectors on interferometers.

Such large datasets will also lay bare the statistical structure of clouds for comparison with, and refinement of, dynamical models for cloud structure formation and evolution (Vázquez-Semadeni et al 2007; Heitsch, Stone, and Hartmann 2008). As the capability of far-infrared through millimeter wavelength instrumentation pushes to higher sensitivity, we may be able to uncover the web-like structure of turbulent shocks in clouds though the spatial and velocity distribution of species like C^+, HD, water, methanol, or other highly volatile species. Such species could be the tools to directly track turbulence and its action in creating gravitational bound structures. These species might also yield insight into the porosity of clouds or the global impact of stellar outflows on the cloud.

One of the important facets of any extensive survey work is the new discovery opportunities. In this case, the imaging of a large number of clouds and dark cores, as needed to cover the range of star forming environments, will capture the rare events: events that rarely occur and events that happen quickly and are therefore very shortly lived. The first hydrostatic core that forms in a core's initial collapse will be faint and cool; and, the time that it is bright enough to distinguish from the surrounding parent core may be very brief. The very low end of the "stellar" mass function, going from down in mass from L and T dwarfs may cut off sharply, have a low probability tail that allows the formation of free-floating giant planets in rare instances.

Data Requirements:

- Multi-wavelength and wide-field imaging at the best resolution obtainable from near infrared to radio.
- Wide-field imaging of the molecular and atomic spectral line emission at the resolutions from 10” to better than 1”.
- High sensitivity imaging in the mid through far infrared continuum and selected atomic and molecular lines.

Science Goals:

- To understand the relationship between gas and stars in various stages of evolution.
- To trace the dynamics of molecular clouds and their interaction with structure formation and evolution.

- To define the outcomes of the star formation process in the birth environment.
- To explore discovery space and search for rare objects -- short evolutionary states or intrinsically rare objects - that may give unique insights.

B. The Interplay of physical processes shaping star formation

Turning now to the scale of the formation of individual stellar systems, there is a standard evolutionary sequence starting with a starless core with a central concentration evolving to an internally collapsing core with a central forming star. The star grows in mass and forms an outflow, perhaps as early as around the time of the collapse of the first hydrostatic core and the formation of a disk. The core feeds mass onto the circumstellar disk and the disk onto the star. The outflow sculpts the core. As the system evolves, the stellar mass increases; the envelope mass decreases and the combination of outflow and stellar luminosity drive away the envelope.

The above simple picture, while very useful, does not fully appreciate the significant roles that are likely played by magnetic fields, turbulence, the local competing star formation activity, and the specific angular moment content of accreting material. The fact that many mature stars are in binary systems, and a significant number of stars have giant planets, underlines the role of one or more of these processes in influencing the outcome of core collapse. When we look at embedded systems, we see multiplicity in the current limited datasets (Looney et al 2000, Connelley et al 2008). Systems with stellar separations below 1000 AU appear to form inside a common core; systems with separations greater than 6,000 AU, which are unlikely to be binaries in maturity, form in separate cores. But, very limited data are available with the resolution of 1" or better which is needed to see embedded analogs of typical mature binaries.

It is essential to start probing the morphology, dynamics, and magnetic field of embedded systems on scales from 1000's to 10's of AU to gain insights into what is happening. What is the shape of the core on these scales? Is there a circumstellar and/or circumbinary disk? How does the system make the transition from a core to a disk? Can measurements of the polarized emission trace the strength and role of the magnetic field? How do these properties change during the evolution of the system and how much variation is there from system to system?

High resolution observations from mid-infrared through centimeter wavelength will be needed to answer these questions. The infrared from 5-30 microns will have the best chance of isolating the stellar components – telling us the outcomes to date in the systems. The mid to far infrared with the best resolution possible will trace the luminosity and distribution of the bulk energy and warm material. The continuum from sub-millimeter through millimeter wavelengths will trace the material distribution. The combination of these wavelengths yields information about the dust temperature distribution.

Molecular line tracers provide complementary dynamical information. Common molecules and their isotopes trace the bulk material and bulk dynamics. Specialized molecules like water and other volatiles may trace locally warmed or shocked gas. Other molecules can be used to trace the gas temperature, the ionization state, and the physical density. The Zeeman effect and the polarization of dust emission may allow measurement of the magnetic field structure in the core. Another interesting possibility is that a tracer atomic or molecular species may allow detection of the disk accretion shock and allow measurement of the disk accretion rate for comparison with the stellar accretion rate (Bitner et al 2008).

Data Requirements:

- Imaging of the emission at mid-infrared, far-infrared, and sub-mm/mm wavelengths.
- Resolution to image the circumstellar disk, the transition from inner core to circumstellar disk and the inner core: 1,000's to 10's of AU.
- Imaging of key atomic and molecular lines on scales from 1,000's to 10's of AU.

Science Goals:

- To elucidate the primary physical structures within the a star forming core on 10's to 1,000's of AU scales at different stages of evolution.
- To identify the processes that drive the morphology.
- To understand how physical conditions and processes link up to the stellar outcome as a core collapses to form one or multiple stars.

C. Exploring the planet formation process

With the discovery of > 300 planets around nearby stars (http://planetquest.jpl.nasa.gov), the richness of variety in planetary systems is now apparent. Notions of our Solar System being typical have fallen into question. It is time to consider anew when and where giant planets form. It is time to push our observational capabilities to characterize other planetary systems and to understand how they form.

Current instrumentation is already starting to characterize the structure of circumstellar disks in embedded and visible T Tauri stars. With of order 3 dozen systems studied with adequate resolution, the characteristic size of disks is 100-200 AU and the surface density typically, roughly falls off as 1/R (Andrews and Williams 2007). This work is starting to outline the initial conditions for planet formation.

In order to understand the planet forming capability of these disks, we need to push the observations to higher resolution and signal-to-noise, and cover the age range of the embedded phase. When do disks begin to have enough mass and surface density to be capable of planet formation? Can we see clumping within the disk that might trace instabilities? Is the disk in the embedded phase more susceptible to giant planet formation by direct collapse (Boss

2008)? We expect about ½ of solar type stars will have companions; do we see structures in the disk driven by the binary? How do other properties differ between circumstellar and circumbinary disks? Do those differences impact the planet forming capability?

As in the previous sections, the answers are found by bringing together data from different wavelengths which probe different aspects of the systems. The key capability in here is high resolution. The observations need to be pushed down to few AU linear resolution, appropriate resolution to start seeing few AU size structures in the disk. As discussed in more depth in the white paper by Wootten et al, one exciting possibilities is to image gaps and density structures created in disks by embedded Jupiter mass planets. Another exciting possibility is to trace the build-up of dust particle size from micron sizes characteristic of the molecular cloud to millimeter or centimeter size in the disk. This requires high sensitivity, high resolution imaging at sub-millimeter through centimeter wavelengths.

The detailed imaging of disks in continuum and line emission will also give insights into the vertical and radial disk structure and detailed dynamics. For example, two recent works (Andrews and Williams 2007; Hugh et al 2008) find disk radial structure consistent with simple viscous accretion models. But, at higher resolution, the disk surface density may be more complicated if different viscous processes are active at different radii. The emission lines of molecules and their isotopes, and different continuum wavelengths, can probe the vertical temperature structure of the disk due to their differing opacity. Molecular and atomic lines in face-on disks provide information about the vertical turbulence. Comparisons of the thicknesses of edge-on disks from centimeter through sub-millimeter wavelength can provide information about dust settling to the mid-plane as a function of radius. There is wealth of information about the initial conditions for planet formation and the early planet formation process available in the atomic, molecular, and dust emission.

Data Requirements:

- Highest obtainable resolution imaging of disks from cm to near-infrared wavelengths: ideally 10 to 100 milli-arcseconds .
- Spectrally and spatially resolved imaging of atomic and spectral line emission from disks. At wavelengths were that is too demanding R>3000 imaging at the arcsecond level.
- Imaging over years and decades to track the evolution and motion on orbital timescale.

Science Goals:

- To understand the planet forming capacity of circumstellar disks
- To trace the evolution of circumstellar disk masses and structures through time
- To follow the evolution of dust in disks to see how and when planetesimals form.
- To find for very young and forming planets in disks.

D. Summary of Instrument Needs

The question, *How does the star formation process result in the diversity of star systems, stars, and planetary systems found in our Galaxy*?, can be addressed well with instrumentation that will be available, or could be developed, in the decade. Three instruments with major impact that will be operational in the decade are the James Webb Space Telescope, the Atacama Large Millimeter Array, and the Expanded VL A. These instruments will provide high resolution, high sensitivity imaging in their wavelength ranges. ALMA and the EVLA will provide both the spatial and spectral resolution to study dynamics and structure on sub-arcsecond scales. A second set of instruments with complementary impact will be the wide-field survey instruments: large format infrared cameras, bolometer arrays, and heterodyne arrays on large telescopes.

The Herschel Space Observatory will open up the full submillimeter wavelength range, allowing observation of key cooling lines from species such as H_2O and CO, and fine structure lines. The high spectral resolution of the HIFI instrument will allow detailed studies of the kinematics of star and planet formation on an angular scale as fine as a few arc seconds. It will also enable large-scale surveys to detect and characterize prestellar and protostellar cores. SPICA will offer much better sensitivity than Herschel and the same angular resolution.

One area for future improvements is the spatial resolution at mid to far infrared wavelengths. The Single Aperture Far-IR Telescope (SAFIR) would improve angular resolution by a factor ~2 over SPICA, and offer even greater sensitivity. The Space Infrared Interferometric Telescope (SPIRIT) will offer 25x better resolution than Herschel and SPICA, with integral field spectroscopy and spectral resolution ~3000 from 25 – 400 microns. On the ground, cm/mm/sub-mm interferometers need to develop array detectors to improve their wide-field mapping speed.

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