Astro2020 Science White Paper

Dense Cores, Stellar Feedback and the Origins of Clustered Star Formation

Thematic Areas: ☐ Planetary Systems ☒ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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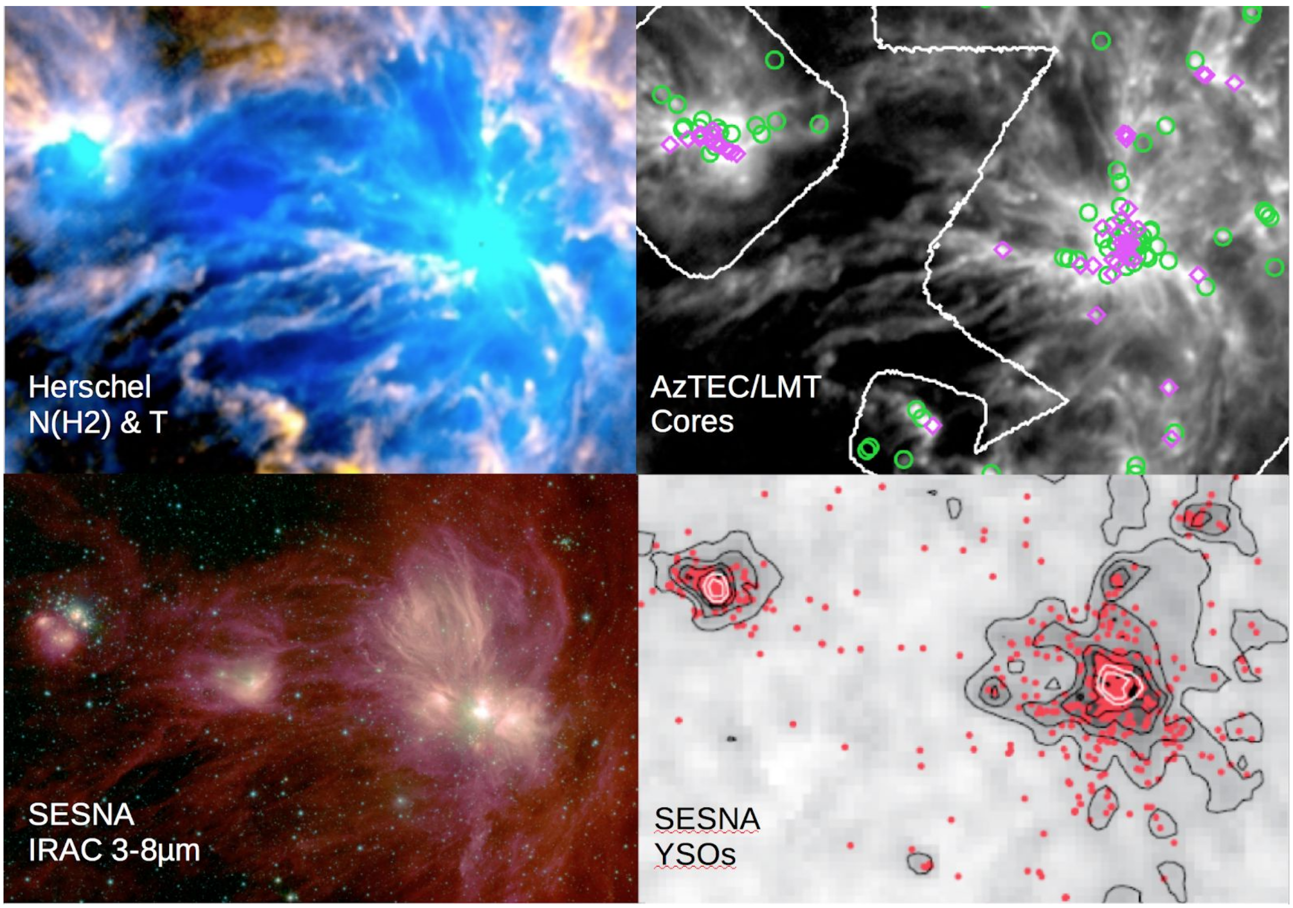
Abstract - Background: Stars form in the densest regions of molecular clouds, where close proximity dictates that feedback from one star impacts the formation of nearby neighbors. Over the last decade, large surveys by Herschel and Spitzer have provided important insights into the hierarchical nature of star formation, the properties of dense cores, and the evolution of protostars. However, fundamental questions remain unanswered: What is the dominant physics that sets the clustering and masses of stars? As new stars form and launch feedback within a given cloud, how do the outcomes change? How does mass flow from cloud to star?
Goals: Progress requires connecting gas flows from large to small scales and increasing statistics of cores across different stellar masses and environments in order to address the origin and evolution of dense cores, relationship between dense gas and the stellar initial mass function, role of environment and impact of stellar feedback.
Requirements: Sensitive, high spatial dynamic range mid-IR to mm continuum, polarization, and multiple spectral line surveys at physical resolutions < 0.05pc; improved astrochemistry in simulations, and development of automated, statistical approaches to identify and characterize star-forming gas uniformly and quantify the impact of feedback are necessary to advance the field.

Introduction

The process of star formation plays a profound role in a wide range of astrophysical phenomena, from the formation, structure, and evolution of galaxies to the formation of potentially life-bearing planetary systems. Open questions abound regarding the degree that various physical properties of molecular gas over a range of size scales impact the incidence and efficiency of that gas turning into stars (e.g., Fig. 1). Namely, what is the dominant physics that sets the clustering and masses of stars? As new stars form and launch feedback within a cloud (~10 pc scale) or cluster-forming clump (~1 pc scale), what impact is there on the formation of subsequent generations of stars? How does gas flow from the largest scales to the smallest?



<u>Figure 1</u>: A demonstration of the complex ecosystem of an active molecular cloud (MonR2, here as an example), with pre-stellar and protostellar cores and other YSOs forming co-spatially. Upper left: Herschel greybody fits reveal the wide range of gas column densities (intensity) and spatial variance in dust temperature (color, with red for T<10K and blue for T>20K) caused by stellar feedback (Pokhrel et al. 2016). Upper right: Herschel column density in greyscale, overlaid with starless (green) and protostellar (magenta) core positions (Sokol et al. 2019). Lower left: Spitzer Extended Solar Neighborhood Archive (SESNA) 3-8 micron image of the same field of view, revealing UV-excited PAH-emission-traced bubble features (Gutermuth et al. 2011; Gutermuth et al. in prep.). Lower right: 2MASS-derived near-IR extinction map overlaid with Av contours (black/white lines) and IR-excess-bearing YSO positions in red (Gutermuth et al. 2011).

Pre-stellar dense gas "cores" are the most direct known link between molecular cloud structure and the formation of individual stars. Cores are typically 0.05 pc and a few solar masses each, with mean densities of a few 10^4 cm^{-3} (e.g. Benson & Myers 1989; Enoch et al. 2006, 2007, 2008; Rumble et al. 2015; Mairs et al. 2016; Kirk et al. 2017; Eden et al. 2019). Cores are often observed to be marginally bound by gravity and external turbulent pressure and thus are vulnerable to the effects of feedback (Arce et al. 2013, Offner & Chaban 2017). Yet observed core mass functions (CMFs) are similar to the stellar initial mass function (IMF) shifted to higher masses (Fig. 2, e.g., Alves et al. 2007). Whether this implies a direct link between core mass and star mass or the similarity is coincidental, hiding greater complexity, remains debated (Offner et al. 2014).

Mapping the star-forming history of clouds, and producing predictions for where star formation will proceed and how it will end within a cloud, demands a complete census of forming stars, starless and pre-stellar cores, and a detailed characterization of the gas distribution from low density (~10^3 cm^{-3}) to high density (>10^5 cm^{-3}), including gas kinematics, multiple-line surveys to constrain chemical evolution, magnetic field morphology, all down to <0.1 pc scales. Such efforts require: sensitive mid-IR to far-IR imaging to both identify the forming YSOs and place limits on non-detections of YSOs; detailed far-IR and mm-wave mapping of molecular gas and dust distributions to identify and characterize cores as well as their natal gas and dust structures (e.g., filaments and clumps); polarization mapping to constrain the strength and morphology of the magnetic field at a wide range of size scales. Considerable high resolution follow-up is also needed to observe the many locations where large-scale, moderate resolution surveys are limited, namely in confused, dense, and more distant regions. Both at mm-cm wavelengths and in the mid-IR, better resolution and sensitivity are necessary to differentiate cores and embedded protostars from contamination, e.g., associated structured emission or coincident background galaxies.

Several capability improvements on the horizon for the next decade will enable transformative new data on cores and their evolution. To maximize the insight we can derive from the nearest star-forming clouds, sensitive, high spatial dynamic range (e.g., large area and small beam size), far-IR to mm continuum, polarization, and multiple spectral line surveys are required, with physical resolutions at least as small as the typical core size (~0.05 pc). Large aperture telescopes (i.e. 30-50m diameter single dishes like IRAM and LMT for the tens of clouds within 1-2 kpc and large interferometers like ALMA and ngVLA for more distant clouds or particularly crowded parts of nearby clouds) with fully sampled focal planes can provide this capability at millimeter wavelengths. Large aperture space-based facilities can do the same in the mid-to-far-IR (e.g., JWST and OST, respectively) where forming YSOs are best detected and characterized. In the mm regime, extremely sensitive continuum detectors can now be densely packed in large arrays, yielding superb flux sensitivity and mapping speed. The addition of polarization capability to these detectors (e.g., LEKID detector arrays; Doyle et al. 2008) can yield magnetic field morphology and strengths from the high signal to noise observations that these instruments can deliver over a wide range of surface brightness. Similarly, spectrometers that fully sample the focal plane (e.g., phased array receivers; Erickson et al. 2015) with both wide spectral bandpasses and fine spectral resolution (<0.1 km/s) will enable the fast mapping throughput at sufficiently small beam size and sensitivity to enable a substantial leap in the number of cores for which detailed kinematic and astrochemical analyses can be undertaken.

Greater observing capabilities also create a clear need for parallel investments in improved theoretical understanding, particularly in simulations where synthetic observations can yield direct connections between observations and self-consistent physical modeling. For interpreting future surveys of cores, YSOs, star-forming gas kinematics, B-field morphology, and astrochemical signatures, we require detailed astrochemical modeling and large parameter space explorations to build predictions for how observable signatures such as core mass distributions, core clustering, and core-to-YSO conversion efficiency are affected by different types of feedback, diverse initial conditions, and astrochemical evolution. Above all, funding to support the development and use of new methods and subsequent analysis and growth of physical insight is essential to maximize the scientific progress enabled by new observational capabilities.

Improve empirical core property distributions

Confronting the relationship between core and stellar masses requires high-sensitivity mapping and large statistical observations (see Fig. 2). Reference distributions of core masses must be measured to high precision (requiring hundreds of cores per mass bin to drive down Poisson noise below 0.1 dex) down to low masses (M < 0.1 Msun) to establish the true functional form for the CMF. Such distributions are only achievable with mm-wave continuum surveys that are simultaneously deep and large in physical area (hundreds to thousands of square parsecs of star-forming molecular clouds). Excellent physical resolution (<0.05 pc) is also required to distinguish cores from surrounding diffuse gas structure and contaminating background galaxies.

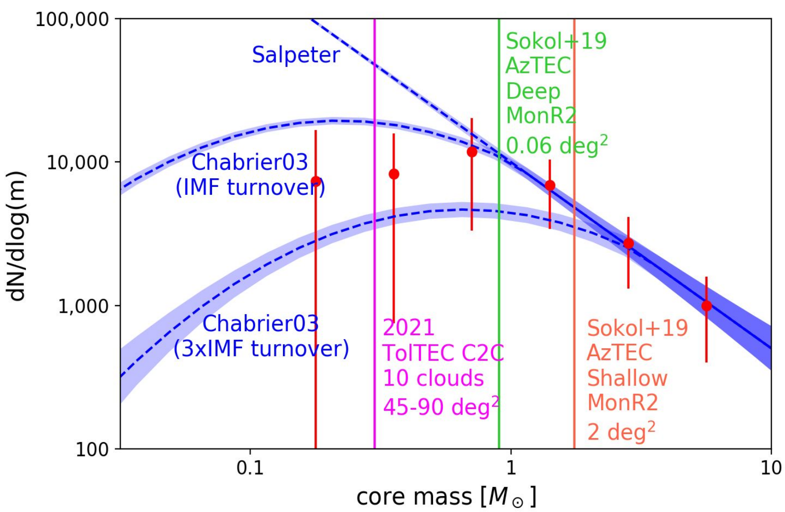
It is imperative that we expand beyond core masses and build distributions of other observable properties such as mean densities, radial profiles, and clustering to develop a diverse set of constraints for next generation simulations of star formation. Follow-up spectral and polarization mapping are required to measure gas motions and magnetic fields within and around cores to constrain nonthermal support against collapse. These observations go hand-in-hand with full-physics simulations of forming stellar clusters, which can provide a theoretical framework to understand the role of various physical processes in core formation, test the impact of different initial conditions on core properties, and explore time-dependent evolution (Offner et al. 2014, Chen & Ostriker 2018, Chen et al. 2019). Post-processing models to create "synthetic observations" is an essential step to identify physically meaningful observables and correct observations for biases (Beaumont et al. 2013, Mairs et al. 2014, Koch et al. 2017).

Constrain the effects of environment and feedback on cores

Most stars form in the presence of other recently formed stars. While the destructive impacts of high-mass stars are widely known (though not adequately constrained), a less well considered and considerably more common influence comes from low-mass stars. They can have considerable feedback on their environment in the form of bipolar outflows and accretion-fed UV output (Federrath 2015, Cunningham et al. 2018). Given the strong penchant for primordial clustering of low-mass stars during formation (e.g., Lada & Lada 2003, Bressert et al. 2010), these processes can combine to yield net energy and momentum input into nearby gas, driving turbulence and producing warming that will affect the formation of subsequent generations of cores (Krumholz et al. 2014, Offner & Liu 2018).

Individual core properties vary substantially, thus large samples are required to characterize distributions of core properties with sufficient constraining power to demonstrate compelling evidence of impact from a given set of environmental factors (Fig. 2). As with setting the base empirical distributions of core properties, large samples of cores (e.g., hundreds per mass bin) located within regions of distinct environmental differences (greater feedback, higher gas density/temperature, different B-field strength/alignment) are paramount and can only be met by sensitive high spatial dynamic range continuum surveys, with line and polarization follow-up, for numerous star-forming regions. The need to press into more active regions for this purpose places particular emphasis on the need for fine angular resolution observations afforded by interferometers.

However, to differentiate large numbers of cores by environment, we must also systematically characterize the thermal, kinematic, and B-field structure of a large numbers of core formation sites as well as accurately identify sources of feedback. Such an effort requires high spatial dynamic range (large area, small beam) surveys of low to medium density gas tracers (e.g. 12CO, 13CO, HCO+, HCN). Historically, due to the complexity of the gas structure, feedback has been identified in both continuum and line data through visual inspection. A complete census of feedback requires new statistical and computational techniques, such as machine learning, which can identify and quantify feedback signatures efficiently and reproducibly (Boyden et al. 2016, Xu & Offner 2017, Van Oort et al. 2019).



<u>Figure 2</u>: Core mass functions, present and future. Sokol et al. (2019) CMF for the MonR2 cloud is shown in red points (scaled up by 10x to match models) with three sigma error bars. Large statistical uncertainties and limited depth result in weak constraint on the low-mass end of the CMF. Predicted CMFs (Salpeter 1955, Chabrier 2003) scaled to the size of a planned large survey of ten nearby giant molecular clouds, the TolTEC Clouds to Cores (C2C) Public Legacy Survey, are plotted in blue. Survey completeness limits (90%) for the Sokol et al. (2019) and TolTEC C2C surveys are red, green and magenta vertical lines, respectively.

Physics of core formation and evolution

Since the mass of the bound material in a core is larger than that of the star that it will eventually form, it is generally believed that as a core evolves, a significant fraction of the gravitationally bound gas surrounding the forming star is dispersed. Estimates of the lifetime of different stages of protostellar evolution indicate that the embedded stage lasts about 0.2-0.5 Myr (e.g. Dunham et al. 2015; Kristensen & Dunham 2018). This shows that cores are dispersed in only a few 10^5 yr after the protostar is formed. In regions of low-mass star formation outflows are the most likely (or the only) source of dense gas dissipation —a process that can regulate the efficiency of star formation in cores and clouds (e.g., Federrath et al. 2014). Perturbations to the core by outflows may affect the mass of the forming star, and hence have an influence on the IMF (Offner et al. 2014, and references therein). Furthermore, by injecting energy and momentum into the gas, outflows may maintain the turbulence that can then counteract the gravitational infall of gas and regulate the core's star formation efficiency (Offner & Arce 2014; Offner & Chaban 2017). Although theoretical studies and numerical simulations have shown the potential effects of outflows on core and star formation, observations are crucial for testing the mechanisms proposed and the assumptions adopted by these models (e.g., outflow power, degree of collimation, mass outflow rate, outflow evolution and lifetime, etc.). Observational studies indicate that outflows play a major role in the mass-loss process of circumstellar material (e.g., Zhang et al. 2016). However, the details of how protostellar winds drive turbulence, entrain and disperse the dense core gas and how these processes evolve are still uncertain.

High spatial dynamic range, multi-line observations of molecular clouds and cores with different environments and at different evolutionary stages are needed to build a statistically sound sample that will allow a thorough investigation of how cores evolve. Combined interferometer and large (30-50m diameter) single dish (i.e., total power) observations are essential for producing molecular line maps that are sensitive to a wide range of scales, from ~100 AU to a few pc (e.g., Kong et al. 2018). This is important for tracing the structure and kinematics from the dense inner core —where the gas either involved in the formation of a future protostar, or the main mass reservoir of a existing protostar is found— all the way to the lower density regions of molecular clouds, where the flows of gas that are expected to feed onto the cores. Development of codes that can easily, efficiently, and properly combine interferometer and single dish data are essential to be able to produce a large set of combined maps.

Multi-line maps are important as different molecular species probe distinct density regimes and different velocity structures. For example, ^{12}CO is useful for tracing the entrained outflow gas, and with it one can estimate the total mass, momentum and energy injected by the outflows into the parental cores. Emission from ^{13}CO traces the medium-density (~10^3 cm^{-3}) gas and cloud structure, and it is essential for estimating opacity of the ^{12}CO line in order to obtain reliable estimates of the outflow mass, momentum and energy. The $C^{18}O$ probes the kinematics of the outer circumstellar envelopes gas (with n~10^4 cm^{-3}), while N-bearing and deuterated molecules like N_2H+, N_2D+, NH_3 and NH_2D trace cold gas, with densities of about 10^4 to 10^5 cm^{-3} (or more), and can be used to study the structure and kinematics of inner envelopes in the central parts of starless or protostellar cores. Indeed, the presence or lack of these species offers valuable astrochemical and thermal constraints.

Detailed polarization maps over scales ranging from molecular clouds to cores and disks will be needed to determine the role of magnetic fields in directing gas accretion onto protostars, providing support against gravitational collapse, and regulating the angular momentum of cores and disks. This effort will require extremely sensitive single-dish polarimeters, with better than 10'' FWHM resolution to both resolve core fields in nearby GMCs, and overlap in spatial coverage with ALMA polarization capabilities.

Summary

The study of dense cores is primed to bring valuable new insight into the star-formation process in the coming decade by leveraging i.) growing observational capabilities for high spatial dynamic range imaging and spectroscopy from the IR to mm from both interferometers and single dish telescopes, ii.) commensurate improvements in physical simulation quality and quantity, and iii.) new advancements in data analysis techniques that unite the two by means of “synthetic observations” and machine learning. We anticipate building core catalogs of sufficient scale to constrain the fundamental shape of the CMF and other reference physical property distributions for cores, uniformly identify regions of stellar feedback in star-forming regions, and measure the effects of that feedback on core masses, local gas mass flows, magnetic field morphology, and other properties. We will also explore in greater detail the efficiency of star-formation through detailed observations of cores, probing how gas mass flows from diffuse cloud structures, through filaments and clumps, to the cores, down to disks and protostars within, and back out through outflows.

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