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STAR FORMATION RESEARCH IN CANADA: A WHITE PAPER FOR THE 2010 LONG RANGE PLAN

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1. EXECUTIVE SUMMARY AND RECOMMENDATIONS

Star formation research in Canada is presently in very good shape. The international competition is, however, fierce and Canada must continue to put significant energy into this field in order to maintain our excellent standing. The four recommendations below will make sure that this area of expertise continues to shine on the world stage.

1) Access to Post-Docs. Hiring post-doctoral researchers remains the biggest hurdle for the star formation community. The field has evolved to a point where large coordinated efforts, producing massive data volumes, play an extremely important role and thus consortia are required for their effective analysis. Dedicated post-doctoral fellows are needed but their funding is extremely difficult to obtain. Star formation astronomers are not alone in finding this one of the weakest aspects of the Canadian funding model.

2) Access to Observatories. Canada must be prepared to use ALMA as early as 2011! Since all proposals will compete internationally, an extremely strong Canadian participation is possible. While ALMA is the clear future for star formation studies, the JCMT Legacy Surveys are critically important and must be completed before the JCMT is closed. This requires funding for about five years of continued JCMT operations.

3) Access to Computational Resources. Canada must keep up with the steady advance in computational resources if we are to remain competitive with the international community. Powerful computational tools are required both for theoretical and observational studies.

4) Coordination. Synergy across wavelengths and across theoretical models is a must. The benefit of a small but strong star formation community in Canada is the possibility for effective coordination on research problems. A funding mechanism, similar to the CIAR Cosmology and Gravitation program, that encourages collaboration and interactions, especially between the theorists and the observers, would immediately produce significant dividends and help vault Canadian star formation research to the top of the international scene.

2. INTRODUCTION

The study of star formation in our Galaxy is centred around the physical and chemical processes that take place as matter accumulates within molecular clouds, settles within dense clumps and cores, and finally collapses into protostars (and their disks). Understanding this processing is crucial to unraveling the mysteries of the Initial Mass Function (IMF) of stars and the star formation efficiency (SFE), two important constraints on the evolution of galaxies both in the past and in the future - the unwinding of the Universe through time.

Astronomers studying star formation aim to understand both the formation of individual isolated stars as well as stellar aggregates and star clusters. We aim to uncover how all stellar objects form, from brown dwarfs to massive stars. Thus, the study of star formation covers a wide selection of underlying environments and an enormous range of physical scales.

Star formation is inherently complex because the physical processes continually feed back on themselves, creating an extremely non-linear theoretical problem. These problems are often best studied through numerical simulations, essentially the 'experimental' component of astrophysics. Such studies, however, severely test the computational power of today's computers. The lack of well defined, discrete objects and 'perfect tracers' for the underlying physical conditions throughout the star formation process complicates both observations and analysis.

Despite the complexity of the theoretical problem and the limitation of the observations, we are making excellent progress in understanding star formation. At present there is no *ab initio* theory of star formation from which initial conditions within the cloud can predict the IMF produced and the efficiency with which the gas is turned into stars. There are, however, many excellent models for how star formation proceeds and detailed observations with which to compare. As witnessed by the figures referenced in this paper, Canada has expertise and leadership across the full spectrum of star formation research, including theory, computation, multi-wavelength observation, and instrumentation development.

Advances since LRP2000 have unearthed a new dynamical approach to star formation. Molecular gas is highly supersonic and dynamic. Supersonic motions and gravity compress the gas into dense filaments and 'cores' out of which individual stars form. As well, stars typically form as members of groups or clusters and not in isolation. Together, these facts overturn the basic premises of previous star formation models which emphasized quasi-static isolated star formation. Understanding the origin of the IMF and the SFE are now realistic goals. Achieving these milestones will require close coordination between observers, computational experts, and theorists.

Note that star formation studies extend beyond the Galaxy (see WP by P. Barmby). The star formation process feeds directly onto the initial conditions within circumstellar disks and stars (see WPs by B. Matthews; R. Jayawardhana et al.). Finally, the formation of molecular clouds is intimately coupled to the ISM, both in our Galaxy and external galaxies (see WP by S. Ellison).

3. HOW STAR FORMATION IN OUR GALAXY IS STUDIED

The star formation process is exceedingly complex due to the large range of physical scales involved (e.g., size, density, magnetic flux) and the dynamic feedback between scales. Thankfully, physical laws and chemical diagnostics provide powerful tools which combine with observations and simulations to aid our sleuthing.

3.1. *Physical Conservation Laws*

As with all fluid dynamics problems, understanding star formation requires recognition of the underlying physical conservation laws: mass, energy, and momentum. Mass flows onto a molecular cloud from the diffuse ISM, providing an important initial condition for present star formation studies (Fig. 1). While theoretical molecular clouds are often assumed to be in equilibrium, there is growing observational evidence that cloud lifetimes are short, requiring the nature of the formation of the cloud to be included in the analysis of the cloud evolution. One appealing model under investigation is the formation of molecular clouds at intersections of hot, supersonic, diffuse gas flows where sufficient shock compression produces quick and efficient cooling to molecular gas. A ramification of this is that large-scale gravitational instabilities within the shocked molecular gas may be an important source of the observed turbulence mediating global cloud collapse (Fig. 2). Within any molecular cloud a fraction of the gas must continue to flow into ever denser structures, clumps and cores (Figs. 3 & 4), until reaching a scale on which gravitational instability produces collapse to a protostar (Fig. 5). The forming protostar ejects a large fraction, perhaps 50%, of its mass back out to larger scales through powerful jets, winds, and outflows (Figs. 6 & 7).

The formation of a star requires a flow of mass to ever smaller spatial scales. This process is undoubtedly aided by the gravitational potential supplied by the massive molecular cloud. Indeed, if it were not for non-thermal support mechanisms, the entire cloud would be unstable to gravitational collapse. Thus, star formation requires a careful analysis of the energy sources and sinks within the cloud - gravitational, turbulent or bulk motion, magnetic field strength, and thermal. Is the apparent equipartition of the first three energy sources a clue to the ordered evolution of molecular clouds or simply a consequence of the cloud's dynamic evolution? Such theoretical questions are likely best examined computationally. Heating and cooling of the gas and the conversion of gravitational energy into ordered or turbulent motions likely play extremely important roles in defining the appropriate Jeans mass for gravitational collapse (Fig. 8).

Finally, the flow of unbalanced force, momentum, leads to supersonic motions (Fig. 9) which drive shocks within the cloud where energy is readily dissipated and dense structures can form quickly. Oblique shocks within the cloud produce eddies and turbulence on large scales, possibly leading to disks and jets around protostars on small scales (Figs. 10 & 11).

A particularly complicated area of research centres around magnetic fields in star-forming regions (Figs. 12, 13, & 14), which despite being extremely hard to understand remain a key ingredient of star formation.

3.2. *Chemistry*

Observations of star forming regions have revealed an astonishing inventory of both simple and complex molecular species. Many of these molecules play essential roles in defining precise heating and cooling rates, which ultimately may set the Jeans mass for collapse to stars. The availability and formation of complex molecules is also important for astro-biology studies.

Specific molecules can be used as precise tracers of physical conditions (e.g., density and temperature) and thus are observationally appealing and require concerted theoretical understanding (Fig. 15). As well, the form of matter (e.g., atomic, molecular, ionic) plays an important role in revealing the conditions within star-forming regions, especially in regions of massive star formation where energetic photons are numerous and can destroy molecules and ionize atoms.

Finally, the composition and evolution of dust is extremely important since dust emission (and extinction) maps are the most powerful tools for probing the column density structure within molecular clouds. At present our understanding of the dust is rudimentary (Fig. 16) and our uncertainty in the conversion from dust emission (extinction) to column density is at least a factor of two!

4. THE TOOLS WE USE TO STUDY STAR FORMATION

Very little star formation research can now be obtained with just pen, paper, and thought. To remain competitive, star formation researchers must have access to world-class facilities and powerful computers, both for data reduction and numerical calculations.

4.1. *Observations*

The study of star formation requires a coordinated, multi-wavelength approach. Understanding the formation of molecular clouds is aided through radio observations of the diffuse ISM, such as the CGPS. Molecular clouds themselves are cold and dusty and best observed at millimetre and submillimetre wavelengths where the dust and molecules emit strongly. To study the youngest embedded stars requires mid-infrared instruments which can punch through the optically opaque cloud. Classification of young stars is best performed through their Spectral Energy Distribution from the near infrared through mid-infrared, especially when searching for disk diagnostics. More massive stars produce copious UV photons which ionize the regions around them, producing forbidden line emission often observed with traditional optical and IR telescopes. Finally, young protostars are often x-ray emitters. Despite the need for observations across all these wavelengths, the bulk of observational star formation studies are carried out from mid-infrared through radio wavelengths.

Canadians have benefited significantly through their access to the submillimetre JCMT (see WP by G. Joncas). Previous SCUBA surveys of star-forming regions (Figs. 3 & 4) have leveraged Canadians into prominent roles within the SCUBA-2 Star Formation Legacy Surveys. These surveys will provide unprecedented detail on the nature of the dense material within clouds - essential for comparison with theories. The unfortunate and prolonged delay of SCUBA-2 is disappointing but the science remains extremely relevant and timely. Without continued involvement in the JCMT Canada's leading role in these surveys will suffer significantly.

More positively, ALMA will soon be the premier instrument for detailed investigations of star formation (see WP by C. Wilson) and Canada has unfettered access to all North American time. The community must be ready for ALMA Early Science beginning in 2011 and full operations in 2013. ALMA will provide powerful insight into the detailed nature of nearby pre- and proto-stellar cores (Fig. 17), resolving even the circumstellar disks - a scale only barely accessible with current interferometers. At greater distances in our Galaxy, regions of massive star formation will be analysed using techniques developed at the JCMT for nearby clouds. To date, the lack of spatial resolution and the additional complexity of powerful feedback has limited the study of massive star formation (Fig. 10). ALMA provides an excellent opportunity to bring the low through high-mass star formation communities together (as it also connects Galactic and extragalactic star formation).

The Herschel Space Observatory provides a rare opportunity to probe the far infrared, a region only accessible above the atmosphere. Canadians are actively involved in large imaging surveys (Fig. 18) as well as detailed investigations into the chemical structure within star-forming regions (Fig. 19). These observations will expose the evolution from cores to stars, especially when combined with the SCUBA-2 surveys. With a short 3.5 year mission lifetime, the community has focused on maximizing the impact of this limited opportunity. As well, smaller experiments, like the balloon-borne BLAST continue to provide niche opportunities (Fig. 20) and should be continued. In particular, the polarimetric possibilities of these telescopes are extremely intriguing for testing the importance of magnetic fields.

Canadian astronomers should continue to utilize the excellent NRAO Green Bank and EVLA facilities available through NAPRA (Figs. 15 & 21). The ground-based mid-infrared capabilities of Gemini have not yet been exploited by Canadian star formation researchers. Development of the relevant expertise should be encouraged.

Further forward, JWST will provide access to the mid-infrared from Space (see WP by J. Hutchings). JWST will be an enormously capable successor to Spitzer, itself a real work-horse for star formation studies. JWST will probe the physical environment around young forming stars, their disks, and their jets. Canadians must be ready to exploit JWST, either as follow-up to JCMT and Herschel surveys or in combination with dedicated ALMA investigations.

Astronomers are already envisioning the next generation submillimetre survey instrument. With a larger aperture than the JCMT and a drier location, this telescope would allow fast, high resolution mapping of the sky at short wavelengths presently only reached from space. Such measurements would significantly constrain the dust properties (Fig. 16) which are needed both to calibrate masses and determine heating (cooling) within clouds. Canada should remain vigilant about joining a consortium such as CCAT (see WP by M. Fich) in order to leverage our competitive advantage gained at the JCMT. It is also likely that SPICA, the joint European and Japanese successor to Herschel will be built providing further access to space-based far infrared observations of star-forming regions (see WP by M. Fich).

In the future, star formation astronomy will benefit directly from development of the SKA, as it provides details on the ISM. As well, it is hoped that the next generation extremely large optical telescopes will retain mid-infrared imaging and spectroscopic capabilities.

In LRP2000 Canadian star formation astronomers recognized the overwhelming need for ALMA. With the ALMA era about to begin, Herschel launched, and JWST nearing completion, the near to mid-term future of observational star formation looks excellent. The most glaring complication is the need to keep the JCMT operating through the next five years in order to successfully exploit the essential science within the star formation Legacy Surveys.

4.2. *Computation*

The overall future computational needs for Canada are addressed elsewhere (see WP by D. Bohlender). Star formation simulations will continue to tax the computational resources as highly as any other field of astronomy. The range of physical processes - including gravity, turbulence, molecular and atomic cooling, radiative transfer and feedback, magnetic fields, ionization processes by cosmic rays and X-rays - all require sophisticated algorithms and enormous amounts of machine time. Most computational work by Canadian theorists is done on networks - e.g., Westgrid, SHARCnet, ACEnet, - which must also serve a large and diverse computational community. Leadership in computational aspects of star formation research requires ongoing investment in updating hardware, and in providing support staff.

Future computational research will need to follow two paths. First, there will be a continued exploration of the detailed physical (and chemical) processes required for the formation of molecular clouds, the formation of structure within clouds, and the formation of individual stars and stellar systems. Each of these processes can then be matched against detailed observations of the same phenomenon. Second, there is a growing need to produce suites of simulations for careful comparison against the ongoing large surveys within molecular clouds.

5. SYNERGY – THE WAY FORWARD

Surveys of star forming regions are now routinely producing powerful observational diagnostics, such as the fraction of material within dense structures, mass distributions, and evolution timescales. Numerical simulations of star formation are also sufficiently advanced, providing strong theoretical predictions. Future star formation studies must bring these two approaches together in order to effectively progress.

One powerful, but under-utilised, technique is to take statistical information from the observations to constrain the possible theoretical models (Fig. 22). Such attacks present a very compelling direction for future Canadian star formation studies, requiring greater interaction and focus between the researchers across the country.

Canada can also boast an impressive cohort of theorists, observers, and instrument scientists dedicated to magnetic field research, a complex and therefore oft overlooked key component of star formation studies. Coordination, however, is paramount in order to fully exploit this strength and play a leadership role internationally.

The modest size and large breadth of the Canadian star formation community lends itself well to a comprehensive approach, requiring dedicated focus, workshops, and post-docs. This focus would significantly enhance our attempts to uncover the mysteries of the IMF and SFE.

6. ACKNOWLEDGMENTS

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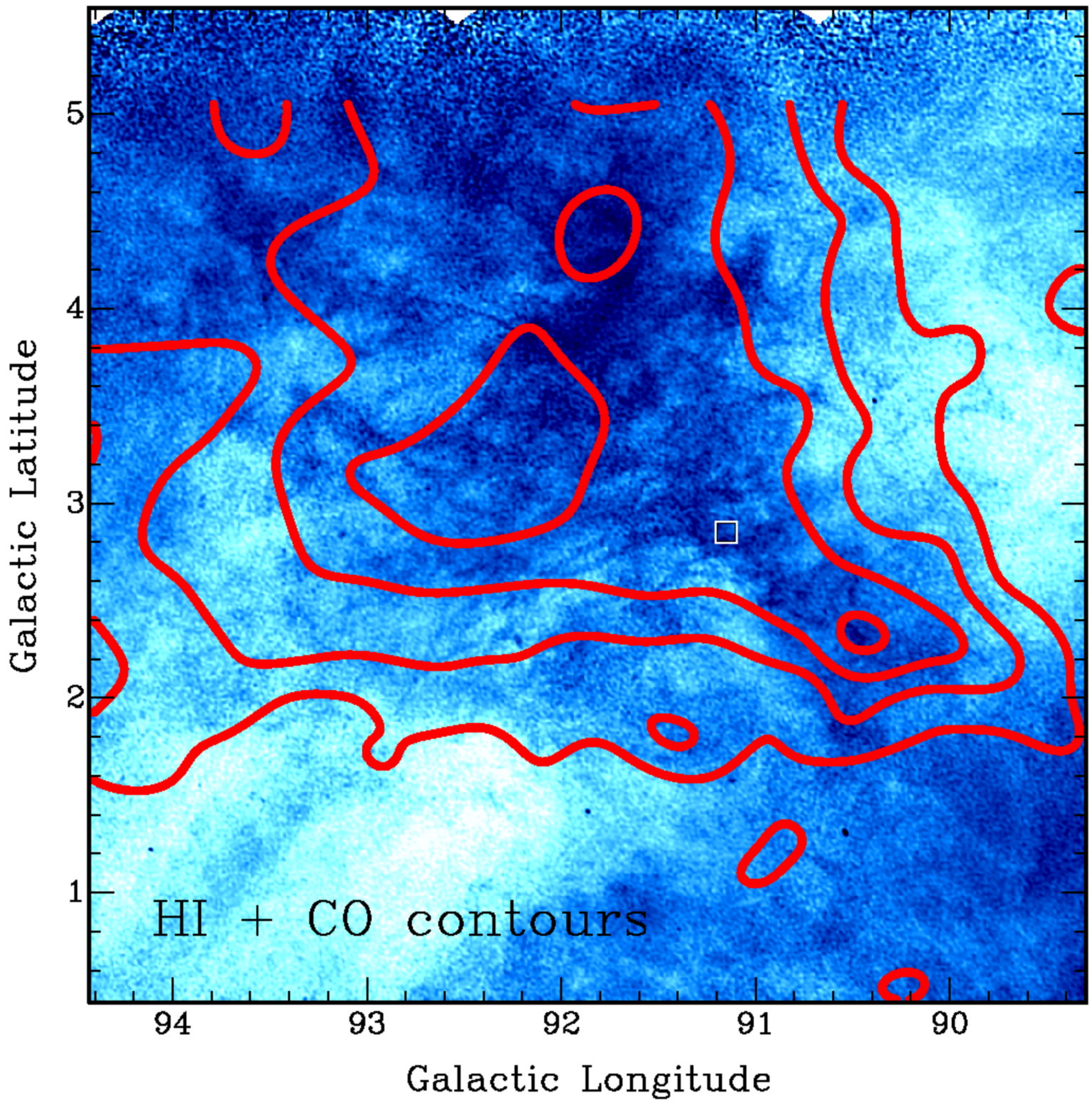

FIG. 1.— Molecular clouds are intimately connected back the the larger ISM in the Galaxy. One way in which cloud formation can be analysed is through the spatial and kinematic correlation between molecular gas, traced by CO, and the atomic HI. Dense regions of HI which become self-absorbed (HI Self-Absorption: HISA) can be cataloged from large Galactic surveys such as the Canadian Galactic Plane Survey (CGPS), providing a powerful diagnostic of molecular cloud boundary conditions.
The figure presented here shows the central cold HI concentration in the nearby giant molecular cloud Cyg OB7, as revealed by HISA in this (l,b) channel map with v_{lsr} = -3 km s^{-1}. The colour image indicates HI brightness with ^{12}CO J = 1–0 emission from Dame et al. (2001) at contour levels of 1, 2, 3, and 4 K. The intensity range is 0 to +130 K for the HI. See Gibson et al. (2005) for further details.

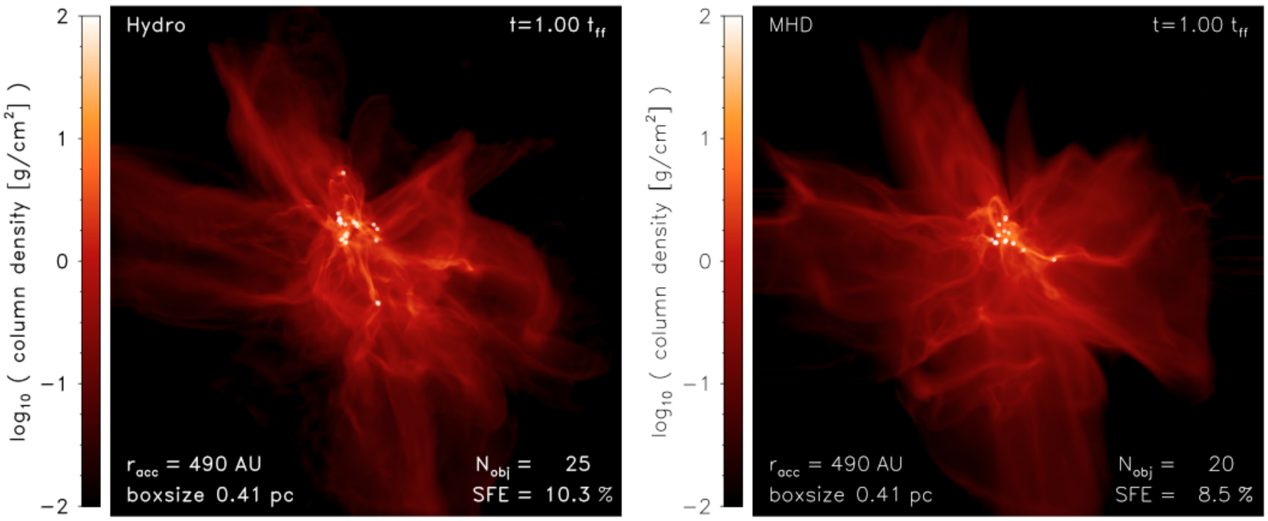

FIG. 2.— Simulations of star formation in molecular clouds now have the capability of following many important physical processes including turbulence, cooling from molecules and dust, magnetic fields and ambipolar diffusion of these fields, as well as basic elements of radiative transfer and feedback. Simulations robustly show that turbulence creates a highly filamentary structure that is studded with denser cores. The mass distribution of the cores, known as the core mass function, is often found to be lognormal in form, which replicates the observations reasonably well. State of the art simulations must include magnetic fields and radiative transfer from the more massive stars, since both of these agents are known to reduce the fragmentation of the gas.
The figures presented here show snapshots from the collapse of a 100 $M_{\odot}$, initially turbulent, clump. The initial density model is a uniform 'top-hat' sphere. The simulation on the left shows the evolution with just gravity and hydrodynamics, while the simulation on the right includes the effects of magnetic fields. See Duffin et al. (2010b) for further details.

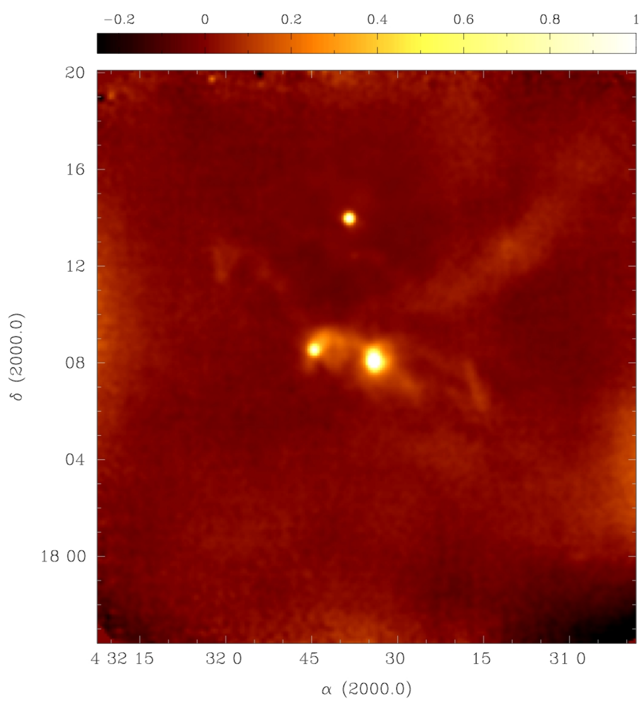

FIG. 3.— The high density material within molecular clouds is observed to be fragmented into filaments and cores. A particularly powerful way to observe this fragmentation process is through submillimetre continuum observations of the thermal dust emission, using instruments like SCUBA (and SCUBA-2) at the JCMT. Such studies have been significantly enhanced through large collaborative surveys and dedicated archiving of all observations. An excellent example is the SCUBA Legacy Catalogue, produced from *all* CADC archived observations taken with SCUBA. See Di Francesco et al. (2008) for further details.
The figure presented here shows a SCUBA Legacy Catalogue image of the L1551 region in Taurus. The two central sources are embedded protostars driving outflows, which are visible to the left and right through the swept up dust at their extremities. To the northwest is a faint filament in which the earliest stage of star formation is proceeding. To the north lies the more evolved protostar HL Tau. See Moriarty-Schieven et al. (2006) for further details.

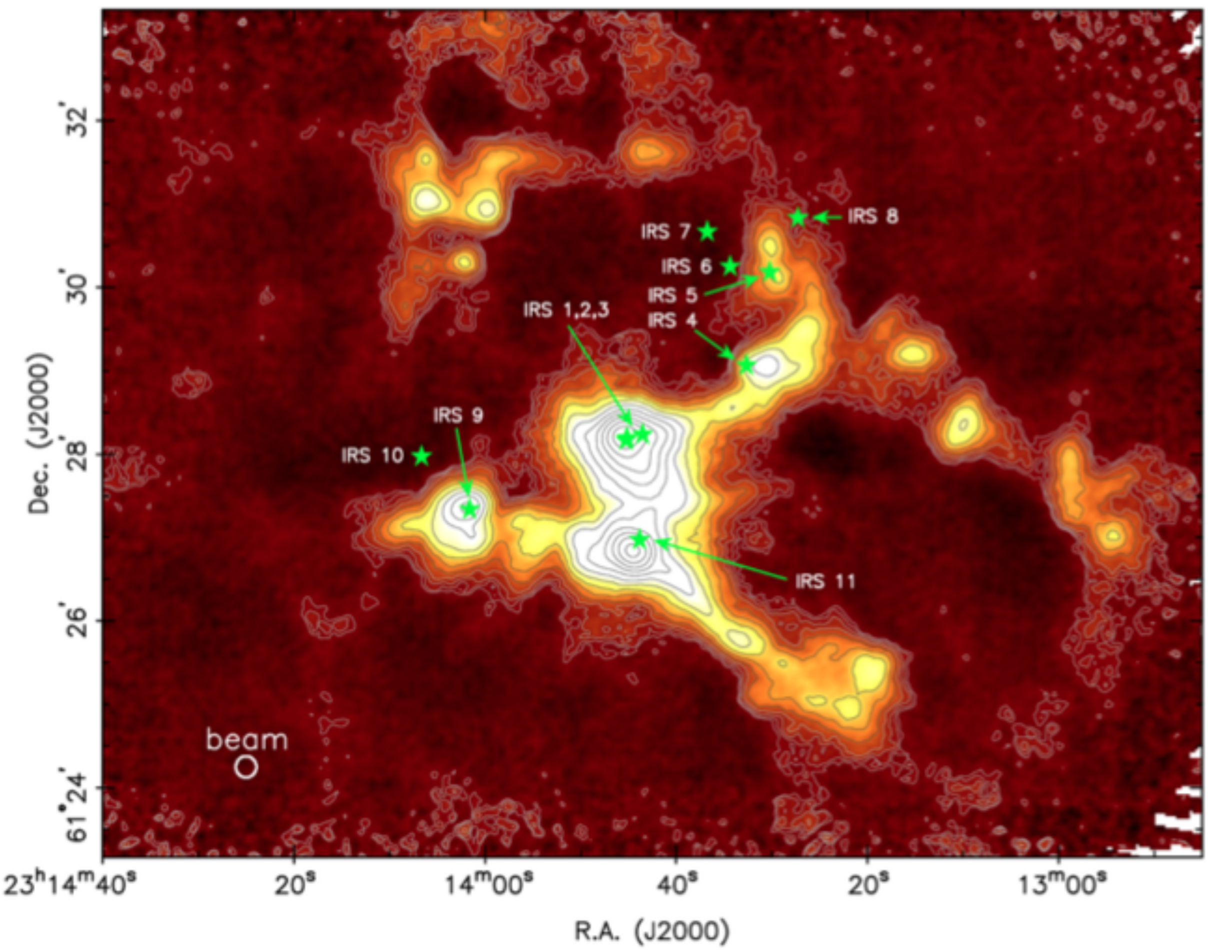

FIG. 4.— Submillimetre mapping of dust emission has proven to be a powerful tool for understanding the mass distribution of dense material within molecular clouds. For nearby star-forming regions the mass function of the cores can be probed to fractions of a Solar mass, and with SCUBA-2 the detection limit will reach the lower limit for the formation of a star. Nearby star-forming regions, however, do not harbour massive stars and thus observations of more distant regions are required to test whether the star formation process is similar across all scales. Present observations of massive star-forming regions are limited to larger and more massive clumps by instrument sensitivity and angular resolution. The ALMA era, however, will very quickly change this situation.
The figure presented here shows an 850 micron map of the nearby massive star-forming region NGC 7538, taken with SCUBA at the JCMT. At a distance of only 2.8 kpc, each bright clump in the image is a possible precursor of one or more massive stars, or even a cluster of stars. The positions of some known forming or formed massive stars are shown with green stars. See Reid & Wilson (2005) for further details. Figure 10 reveals more detail about the forming massive star, IRS 1.

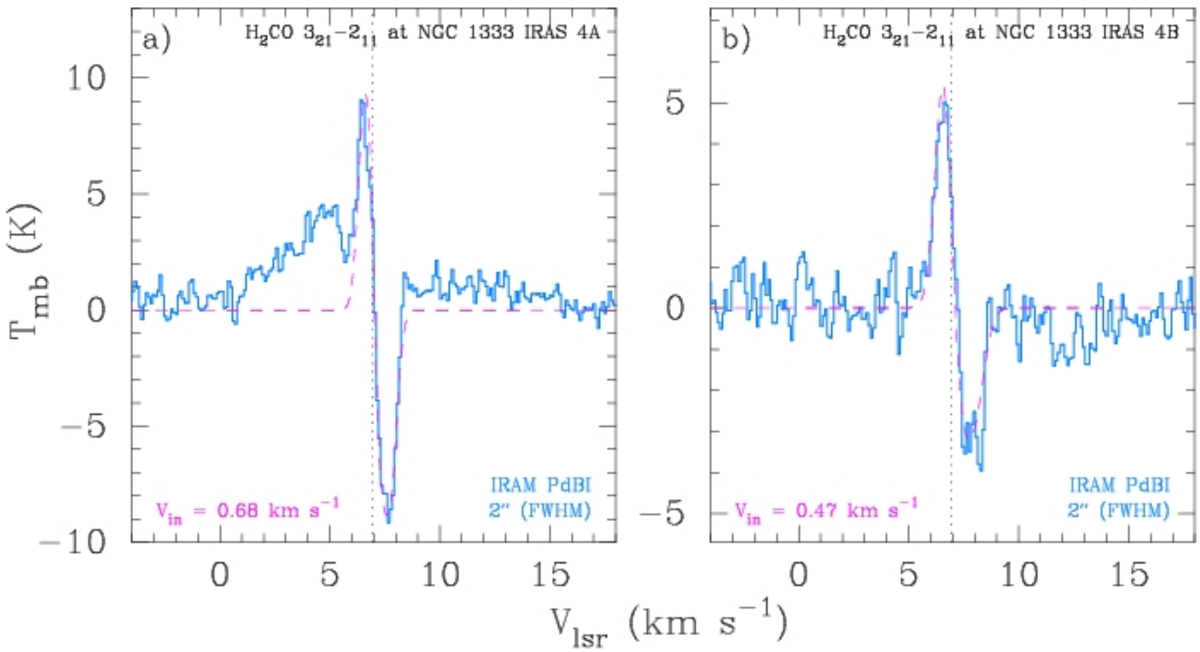

FIG. 5.— The formation of a star requires the collapse of material down to stellar scales. All theories for star formation posit gravitation as the dominant inward force, responsible for the implosion of the core to a star. The importance of thermal pressure, turbulence, angular momentum, and magnetic fields in obstructing the collapse is highly debated and will only be definitively answered through observations of the conditions surrounding collapsing cores.
The figure presented here shows profiles of H_2CO 3_{21}-2_{11} toward two protostars in the Perseus molecular cloud, IRAS 4A and 4B. The profile shows an "inverse P-Cygni" configuration of blueshifted emission and redshifted absorption arising from inward motions of dense gas toward the protostars along the respective lines of sight. Such profiles are unambiguous tracers of infall motions and from these data mass infall rates of $\sim 10^3$ $M_\odot$ yr^{-1} can be estimated. See Di Francesco et al. (2001) for further details. Similar data should be routinely obtained with ALMA.

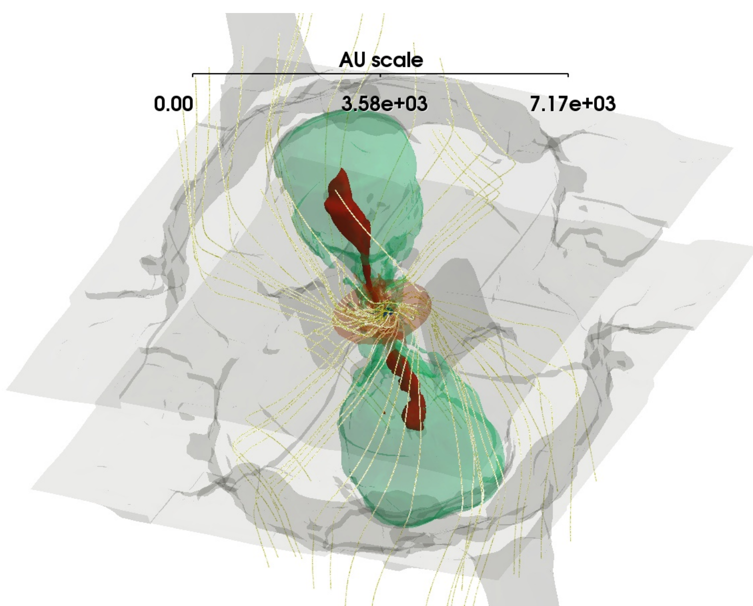

FIG. 6.— The presence of outflows and disks around young stars is ubiquitous. There is good evidence that they are also tightly coupled. Outflows are particularly powerful during the early stages of collapse, before a star has acquired most of its mass and while the disk is being built up (the Class 0 phase). In the absence of magnetic fields, all collapse calculations of rotating cores only produce disks from which the bulk of the star's mass is ultimately accreted. In the presence of magnetic fields however, simulations show that gravitational collapse and disk formation lead to very powerful outflows. Such outflows could clear a substantial portion of the infalling envelope. Outflows also extract a significant fraction of the angular momentum of the underlying disk, enabling disk accretion. New capabilities at ALMA, together with JWST, will allow us to test whether outflows originate on disks or are tightly associated with the interaction of a stellar magnetosphere with the disk.
The figure presented here shows an outflow that arises from a collapsing Bonnor Ebert (BE) sphere that has initial perturbations and a threading magnetic field. The outflow is about to burst through the radius of the initial sphere. A sink particle at the centre of disk allows the collapse and outflow to be followed for hundreds of thousands of years. Grey denotes the BE sphere (100 K contour), green (red) shows the 1 $km\,s^{-1}$ (5 $km\,s^{-1}$) gas, orange (blue) shows the dense 10^{-16} (10^{-15}) $g\,cm^{-3}$ gas, and yellow denotes the magnetic field lines. See Duffin et al. (2010a) for further details.

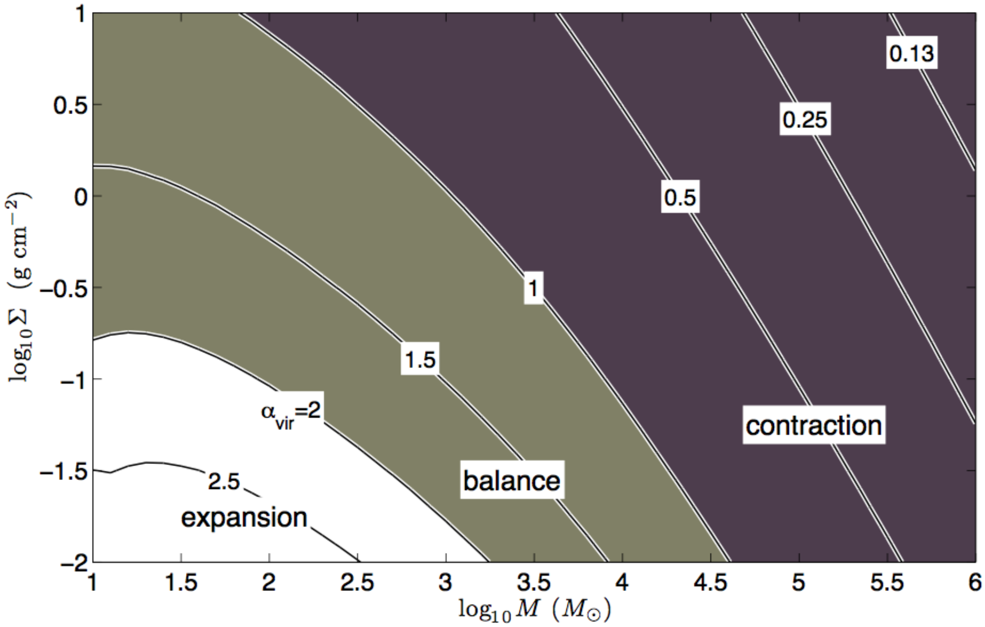

FIG. 7.— The powerful outflows from forming stars replenish the turbulent energy in the molecular cloud and may be an important mechanism for slowing down, or reversing, the star formation process. Such complex feedback mechanisms are common in star formation studies and require careful consideration.
The figure presented here shows the various regimes of turbulent feedback from protostellar outflows in a model for star cluster formation. Depending on its mass and mean column density, the cluster-forming region can either be overwhelmed by gravity (dark grey area), in a state of mechanical balance between turbulence and gravity (light grey area), or pushed into expansion by outflows expanding within it (white area), as delineated by the gravitational parameter $\alpha_{\rm vir}$. Even in a state of balance, matter is continually lost due to the eruption of outflows (Matzner & McKee 2000) and unstable pulsations are expected. See Matzner (2007) for further details.

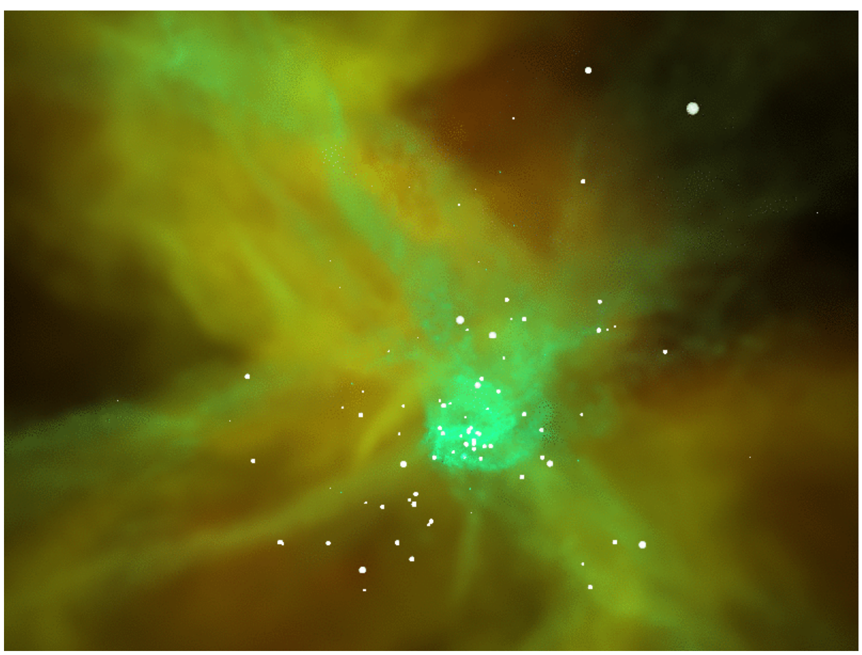

FIG. 8.— Numerical simulations of star formation must follow carefully the heating and cooling of the gas in order to determine the importance of gravitational fragmentation.
The figure presented here shows a snapshot from a simulation, including heating and cooling, of a collapsing 50 $M_\odot$ cloud in which dense cores are converted to star particles that act as sinks to accrete additional mass (white dots). The star particles are plotted with size indicating closeness to the viewer. At this stage of the collapse around 15% of the mass has been converted into stars. Similar to the polytrope results of Bate et al. there are many low mass stars formed. See Petitclerc (2009) for further details.

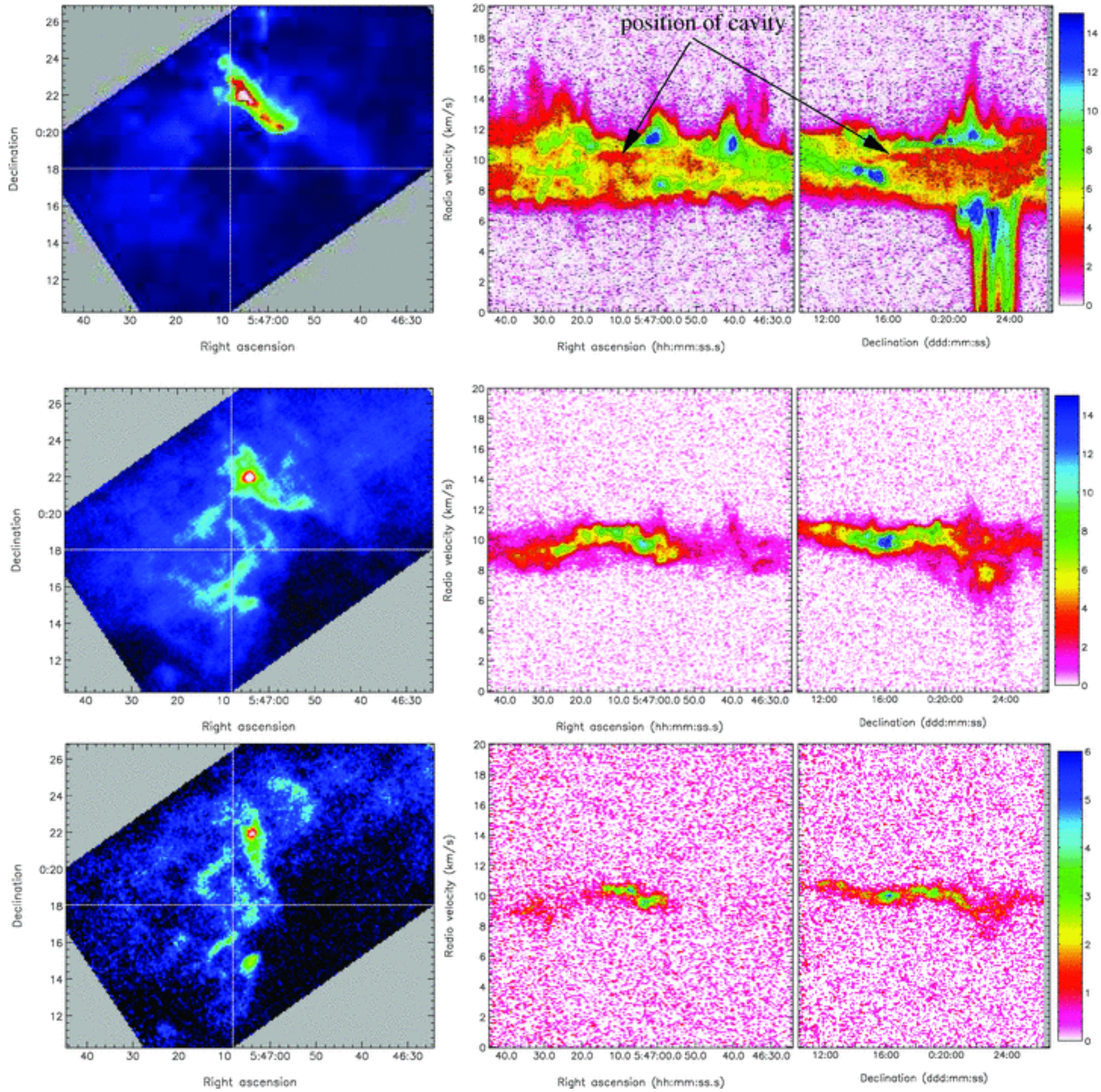

FIG. 9.— Understanding the large-scale velocity field of molecular clouds is necessary in order to constrain theoretical models of star formation. Surveys of CO emission throughout clouds remain the best technique for discerning the kinematic fingerprint and heterodyne array receivers, such as HARP at the JCMT, have significantly enhanced mapping speeds.
The figure presented here shows integrated intensity maps from HARP of CO in dense regions within the Orion B Molecular cloud, along with position-velocity plots showing the supersonic motions within the gas. These data will be combined with SCUBA-2 observations, as part of the JCMT Gould Belt Legacy Survey (Ward-Thompson et al. 2007), in order determine both the mass and kinematic properties of the dense material. See Buckle et al. (2010) for details.

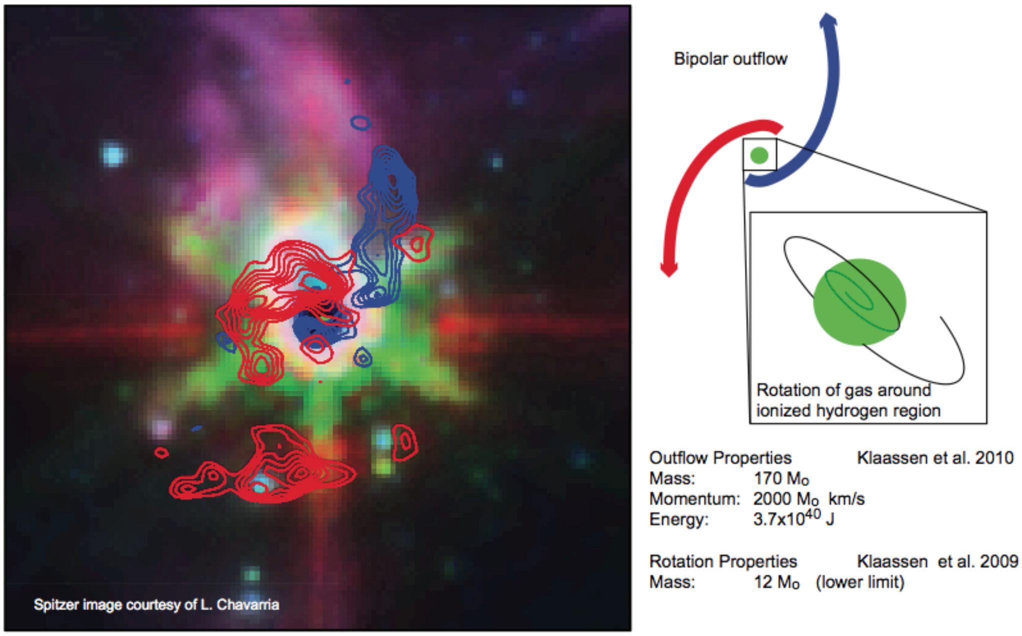

FIG. 10.— Massive stars form at large distances from the Sun and are therefore difficult to analyse with moderate resolution single-dish telescopes. In order to understand the manner in which massive stars form, high spatial resolution interferometric observations are required. The figure presented here shows molecular gas kinematics in the massive star forming region NGC7538 IRS1. Shown on the left are the red and blue shifted outflow lobes from the massive protostar being formed at the centre of the image. Only gas that has been accelerated to more than 6 km s^{-1} from the rest velocity of the source is shown. The molecular gas, traced by CO, has been observed at a resolution of $1''$(2700 AU at the distance of this source) by combining data from two different configurations of the Submillimeter Array (SMA) along with larger scale structure observed with the JCMT. These observations have 15 times the resolution of the observations in Figure 3 (only the sources labeled IRS1, 2, 3 are shown here), allowing for determination of the outflow source. The background image is a colour composite from the three highest energy bands of the Spitzer IRAC camera, which are highly saturated by this bright massive star forming region. On the smallest scales there is evidence of rotation within the warm molecular gas around the HII region (as traced by OCS and SO_2). The spatial resolution of these observations do not allow for studies of disks in massive star forming regions. ALMA, however, will make such observations routine. See Klaassen et al. (2009, 2010) for further details.

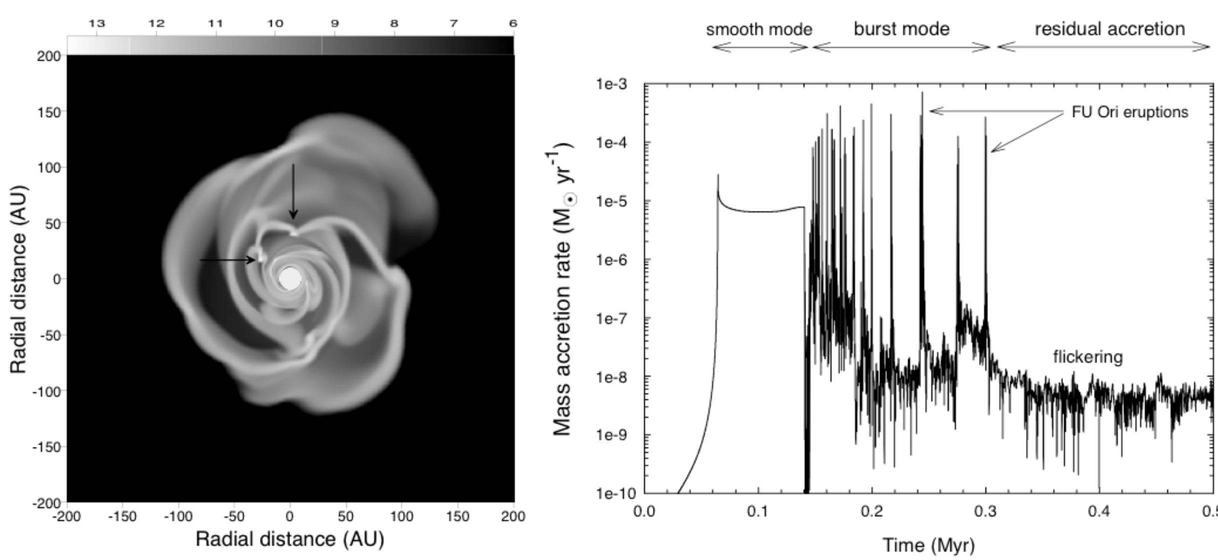

FIG. 11.— Detailed numerical simulations of the infall onto a star-disk system reveal a stochastic system in which strong outbursts are present. The connection between these events and observed FU Ori eruptions in star-forming regions is extremely intriguing.
The figures presented here show: (Left) An image of the gas volume density distribution within a circumstellar disk immediately preceding a mass accretion burst. The protostellar/protoplanetary embryos with $n \gtrsim 10^{13}$ cm^{-3} are indicated with arrows. The scale bar is in cm^{-3}. A bright circle in the image represents the protostar plus some circumstellar matter. (Right) A plot of the temporal evolution of the mass accretion rate in the same model. The central protostar is formed at approximately 0.06 Myr. A log scale is used to emphasizes the low-amplitude flickering between the bursts and in the late evolutionary stage. See Vorobyov & Basu (2006) for further details.

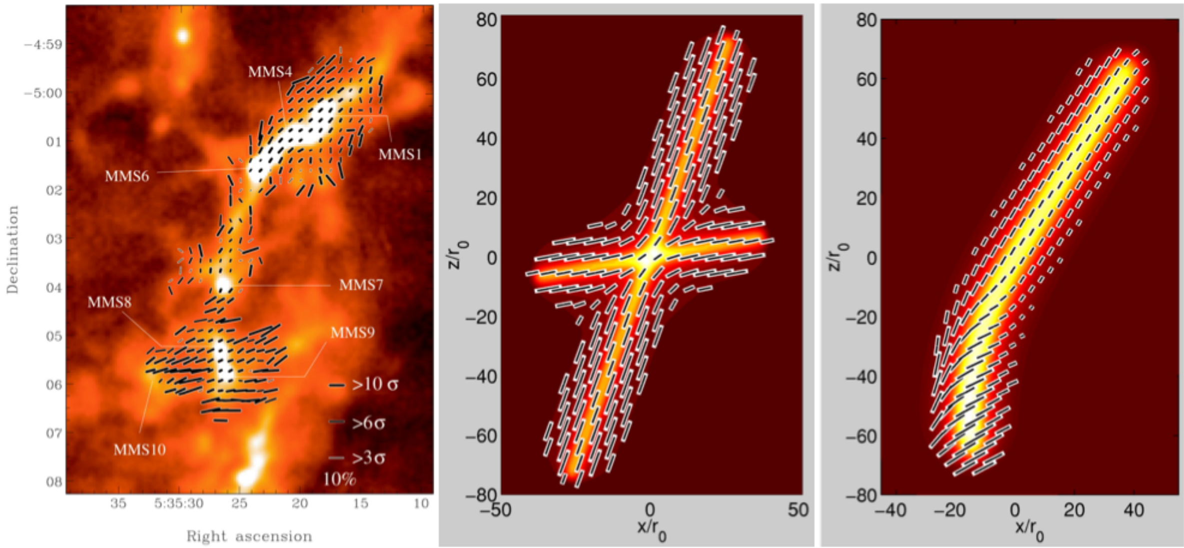

FIG. 12.— Observations of the linear polarization of submillimetre dust emission from dense regions provide extremely important geometric detail on the importance of magnetic fields within molecular clouds. The SCUBA polarimeter produced many excellent maps across a wide range of star-forming regions. The SCUPOL Legacy Catalogue, reconstructed from *all* CADC archived observations taken with the SCUBA polarimeter, provides many excellent examples. See Matthews et al. (2009) for further details.
The figures presented here show linear polarization of dust grains in the OMC-3 region of the Orion A molecular cloud. The 850 μm data from the SCUBA polarimeter (left) reveals a polarization pattern (length $\propto$ polarization percentage and orientation gives the position angle, degenerate to 180 degrees) of considerable complexity. Simple interpretations of deriving the magnetic field direction from a 90° rotation of the polarization vectors have often been done when only a small region is mapped, but larger regions with denser vector coverage immediately reveal the flaws in this approach. Two qualitative models based on a helical magnetic field threading the filament are also shown. In the first case centre, two crossed filaments generate the variation observed in polarization vector direction; in the second right, a bent filament is used to produce the observed pattern. See Matthews, Wilson & Fiege (2001) for further details.

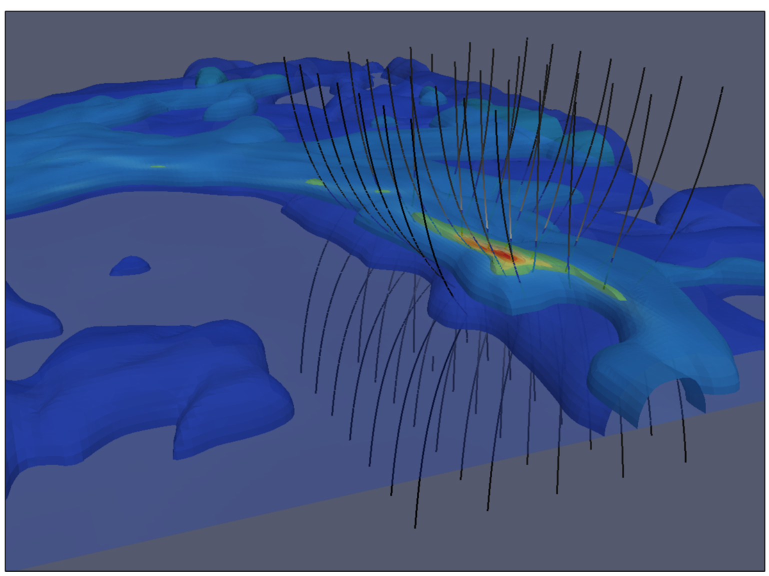

FIG. 13.— Numerical simulations which include magnetic fields during the star formation process can be used to compare theoretical ideas and observations. As shown in Fig. 12, the geometry of the polarization can be an excellent diagnostic.
The figure presented here shows an image of gas density and magnetic field lines from a simulation of star formation within a sheet-like molecular cloud. In this particular model, gravity, turbulence, and magnetic pressure compete to compress and support the dynamic cloud. See Basu et al. (2009) for further details.

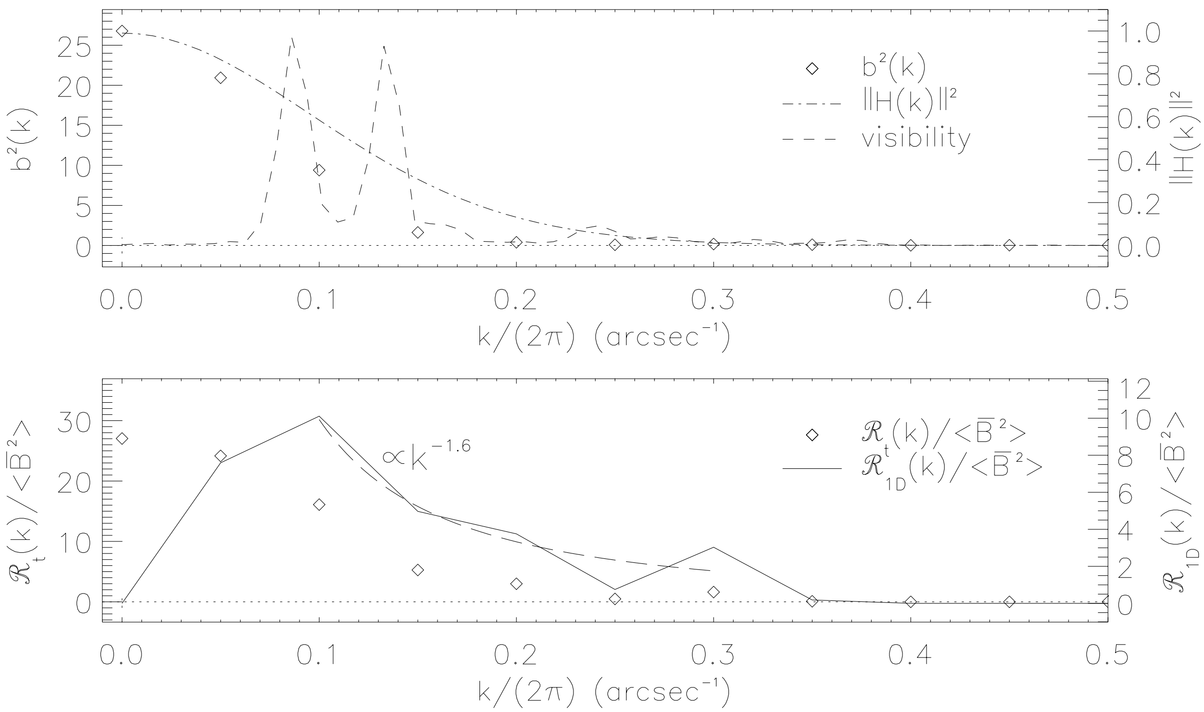

Fig. 14.— The importance of magnetic fields in the star formation process is extremely hard to quantify due to the extreme difficulty in making the relevant measurements. Submillimetre polarimetry of dust emission provides only a measure of the geometry of the field and does not measure the actual field strength. One promising method for measuring the importance of the magnetic field from such observations, however, assumes that the underlying variations in the geometry relate to a magnetized turbulent distribution.
The figures presented here show an analysis of the magnetized turbulent power spectrum (MTPS) of Orion KL with a high resolution 850 micron polarization map obtained with the Submillimeter Array (SMA). The top graph shows telescope beam filtered MTPS (symbols) obtained from the Fourier transform of the dispersion function of polarization angles, i.e., the mean of the square of the difference in polarization angles between two points separated by a given distance (Houde et al. 2009; Hildebrand et al. 2009). The telescope visibility (i.e., dirty beam), which fundamentally limits the frequency extent of the spectrum, and the synthesized beam ($||H(k)||^2$) are also shown. In the bottom graph the underlying MTPS (symbols) is revealed after the removal of the beam filtering through deconvolution. The corresponding one-dimensional MTPS is also shown (solid curve) along with a power law fit of its profile ($\propto k^-1.6$) to an equivalent Kolmogorov-like turbulent spectrum (broken curve). See Houde et al. 2010 for further details.
This type of analysis will be useful to directly test potential turbulence theories using polarization data, as well as for determining important parameters that define the role of magnetized turbulence in the process of star formation. One such parameter is the location of the high frequency cut-off of the MTPS, which is probably due to turbulent ambipolar diffusion. Because of the significant increase in spatial frequency coverage they will bring, future facilities such as ALMA and CCAT will greatly improve on the results currently achieved with available facilities.

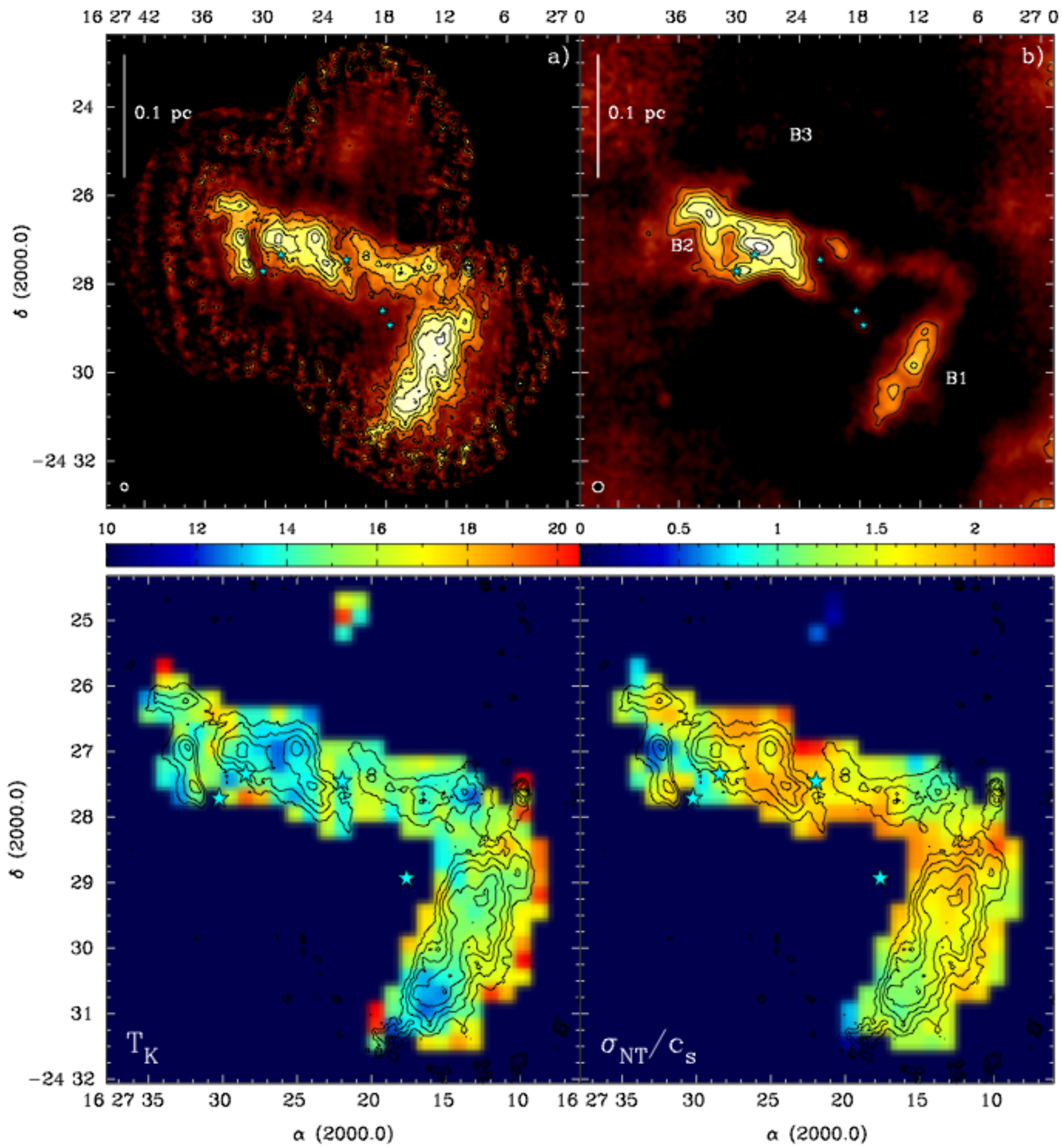

FIG. 15.— For some molecules such as NH_3, observations of a few transitions and/or hyperfine structure can be used to determine the physical properties of the gas, such as temperature and density.
The figures presented here show conditions within the star-forming B Core in the Ophiuchus molecular cloud. (Top) Comparison of NH_3 (left) and submillimetre continuum emission (right). The NH_3 image shown is a combination of data taken with the NRAO Green Bank Telescope, Very Large Array, and the Australia Telescope Compact Array, and reveals locations of high density gas. The continuum image was observed with the JCMT. In both plots, stars denote locations of Class I protostars, which are young and remain embedded in their natal dense gas. (Bottom) Determination of the gas temperature (left) and the ratio of the non-thermal to thermal motion of the gas (right) derived from the NH_3 spectra. See Friesen et al. (2009) for further details.

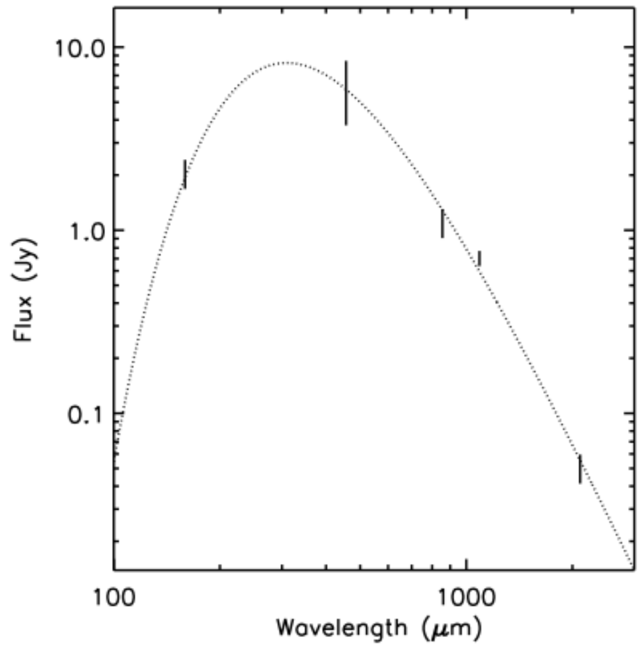

FIG. 16.— The interpretation of observations of dust emission at far-infrared to millimetre wavelengths is complicated by uncertainty in the dust emissivity as a function of wavelength, variations in the dust properties along the line of sight, and the unknown gas-to-dust ratio. The figure presented here shows the dust emission from the starless core TMC-1C. The data points come from Spitzer (160 microns), JCMT - SCUBA Legacy Catalogues (450 & 850 microns), IRAM 30m/MAMBO (1.2mm) and CSO/Bolocam (2mm). Over-plotted is a fit to the observed SED, with column density of 10.2x10^{21} cm^{-2}, dust temperature of 8.9 K and an emissivity spectral index of beta = 2.3. See Schnee et al. (2010a) for further details.

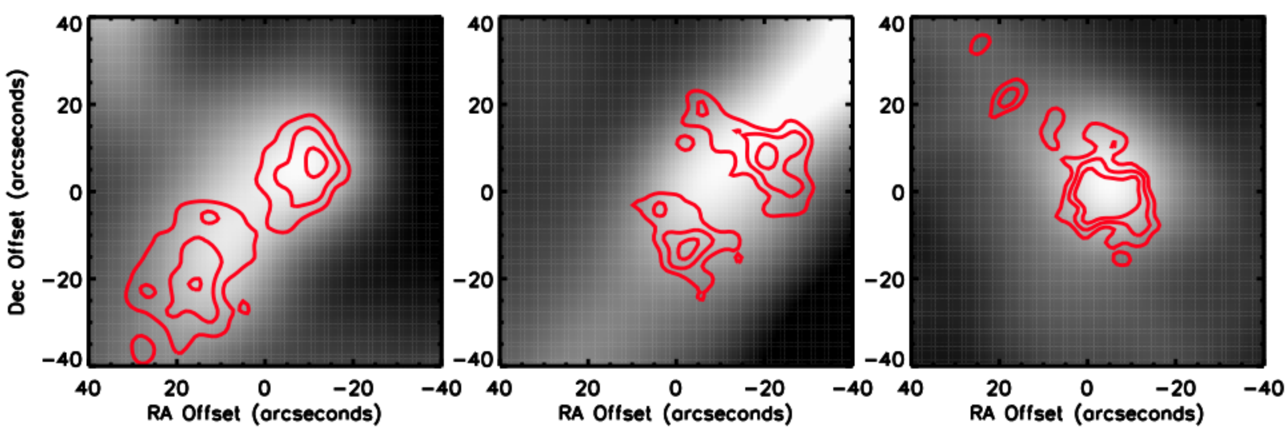

FIG. 17.— The breakup of starless cores has important implications for the conversion of the core mass function into the stellar initial mass function. Present interferometers allow us to tackle this issue within only the nearest and brightest cores. The high resolution and sensitivity of ALMA, however, will make large, detailed, systematic studies of this type possible.
The figure presented here shows the JCMT SCUBA 850 micron emission (greyscale) and 3mm continuum emission (contours) for three starless cores in the Perseus molecular cloud. Note that at the $\sim 5''$ resolution of the 3mm map (observed with CARMA and the SZA) two of the three cores are seen to have multiple components while at the $\sim 15''$ resolution of the JCMT each core is identified as being a single object. See Schnee et al. (2010b) for further details.

Fig. 18.— Far-infrared image of the Rosette Molecular Cloud obtained recently from the Herschel Space Observatory. The image combines 70 μm (blue), 170 μm (green) and 250 μm (red) continuum data observed with the PACS and SPIRE instruments. The image is the first of several expected of high-mass star forming molecular clouds from the Herschel OB Young Stellar Objects Key Project (PI: F. Motte). In particular, the image shows an obvious temperature gradient from right to left with increasing distance from the O-stars in NGC 2244, the Rosette Nebula. A preliminary analysis reveals that this image contains ~300 compact starless and protostellar cores. See Di Francesco et al. (2010) for further details.

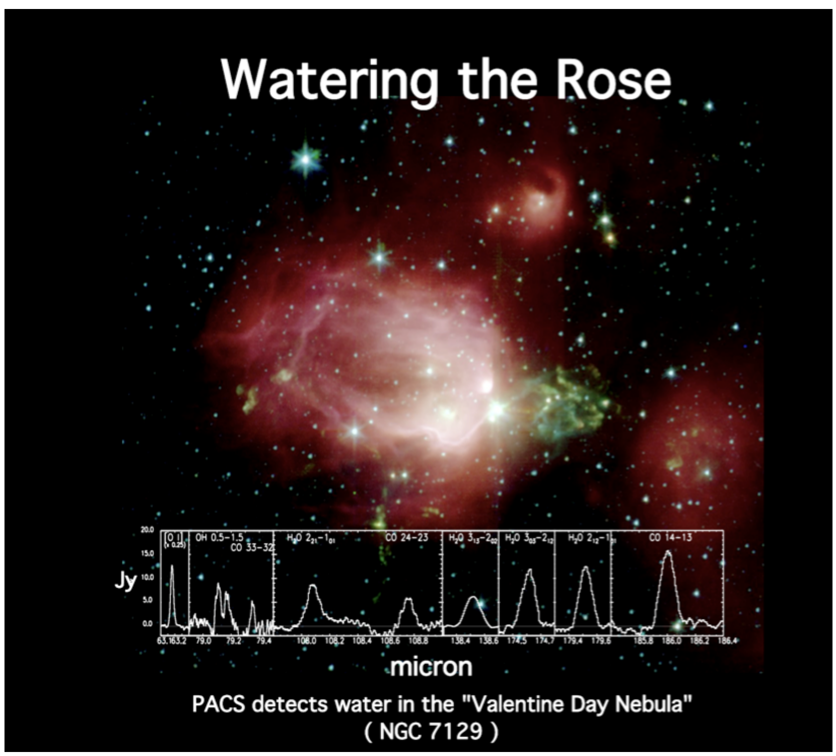

Fig. 19.— Access to the far infrared spectrum allows for observations of water lines which can be the dominant radiative coolant in dense star-forming regions. These transitions are obscured by the Earth's atmosphere and must be taken from space.
The figure presented here shows the first Herschel observations of an intermediate mass star-forming region by the WISH project team, revealing strong lines from highly excited water and high-J rotation levels of CO. These lines, if thermally excited, would indicate temperatures of over a 1000 K and high densities (typically 10^8 cm^{-3}). If the density is much lower, substantially higher temperatures are required. It is likely that much of this emission arises from a series of shocks near the central protostar. See Fich et al. (2010) for further details.

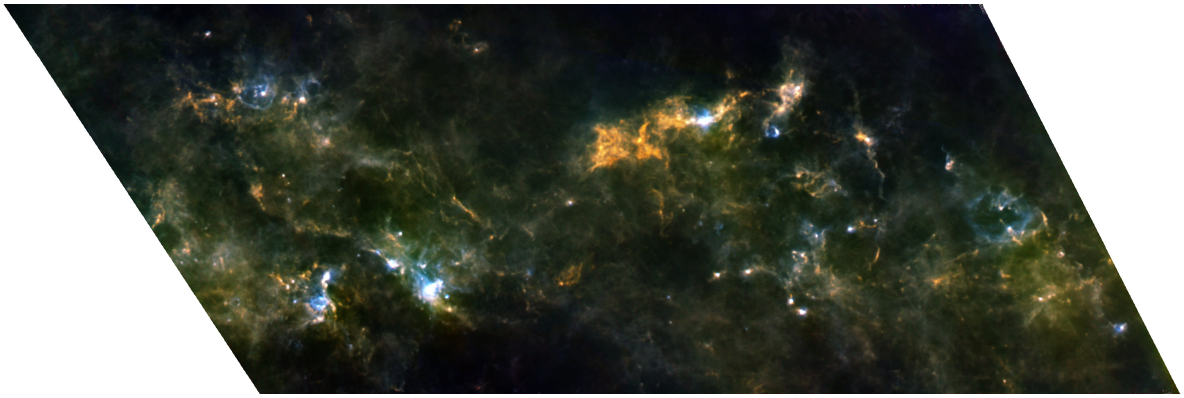

FIG. 20.— A 3-band submillimetre image of the Vela star-forming region taken with the balloon-borne BLAST. The image covers about 50 square degrees and shows a wide range of morphologies associated with recent and on-going star-formation. The combination of filters spanning the thermal peak for cold sources means that one can literally see temperature in this image. See Netterfield et al. (2009)for further details.

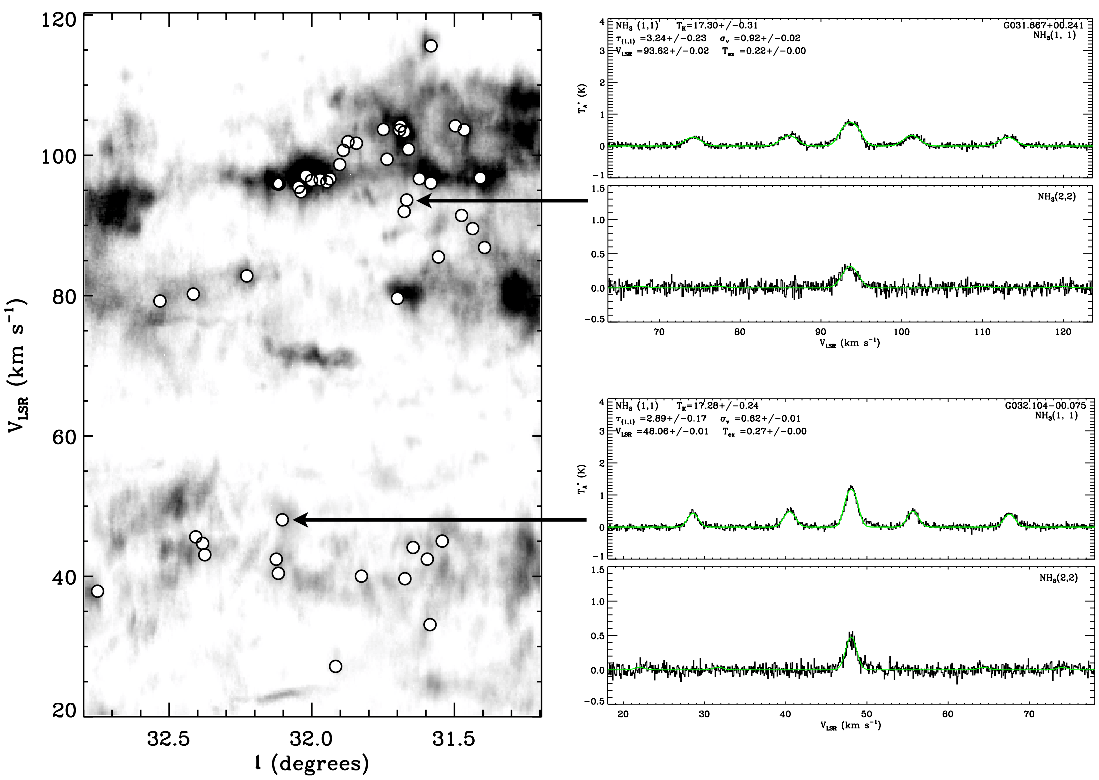

FIG. 21.— Large systematic surveys covering the physical properties of star-forming regions are a key ingredient to any collaborative effort to produce a unified star formation theory.
The figure presented here shows ammonia emission from Galactic plane sources. Recent (sub)millimetre continuum studies of the Galactic plane provide wide-area surveys of dense gas over many square degrees of sky. These surveys serve as excellent finding charts for studies of dense gas properties using line emission. Spectral line studies are critical for measuring the line-of-sight velocity to a source of continuum emission to asses its properties. This figure shows a longitude-velocity diagram of ^{13}CO emission from the BU Galactic Ring Survey with the locations of millimetre continuum sources from the Bolocam Galactic Plane Survey overlaid. The locations are known because of complementary ammonia observations with the GBT, for which the spectral data of two sources are shown on the right. These observations enable the measurement all the bulk properties of a dense gas feature, including temperature, non-thermal line width, and, when the distance ambiguity can be resolved, the size and mass of the objects. Owing to improvements in radio and submillimetre instruments, such combined surveys will become common over the next decade, enabling spectral line studies in multiple tracers to assess the dynamical and chemical state of star forming clumps throughout the Galaxy. The broad surveys begin to study Galaxy-wide star formation from the perspective of a population of objects rather than a detailed study of a few objects. See Rosolowsky et al. 2009 for further details.

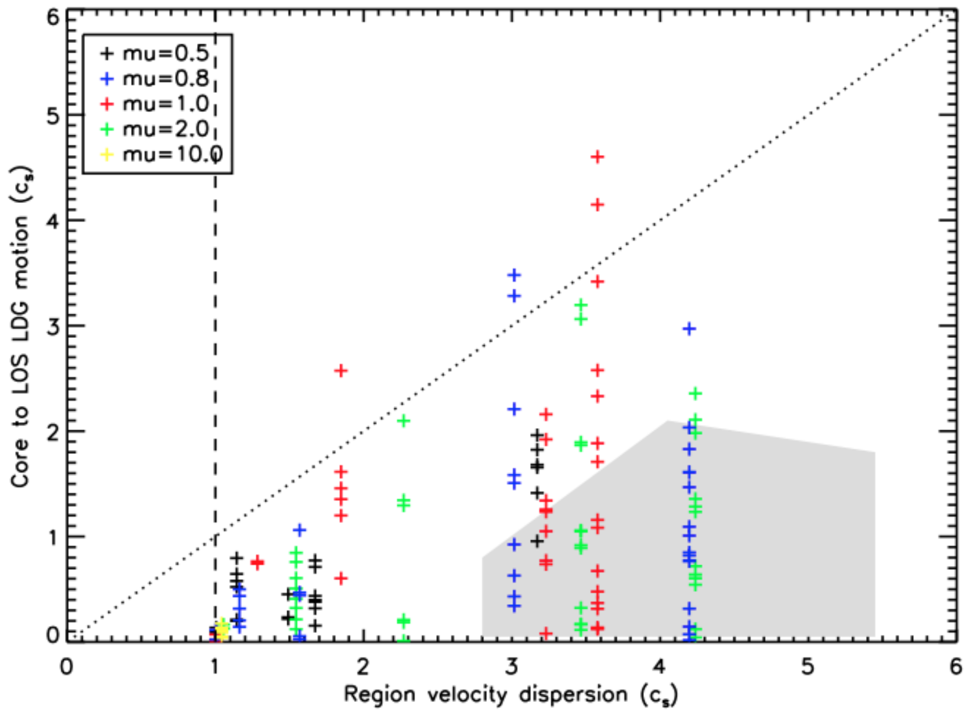

FIG. 22.— Detailed comparison between the observations and the numerical simulations is required in order to constrain and validate theories.
The figure presented here shows comparison between dense core motions observed in the Perseus molecular cloud and those 'observed' in a suite of thin sheet magnetohydrodynamical simulations (such as Fig. 13). The horizontal axis shows the velocity dispersion of the large-scale ($\sim$1 pc) region in which dense cores are located (e.g., B5, NGC 1333), providing a measurement of the turbulence in the environment. The vertical axis shows the difference in centroid velocity found between the dense core gas (traced by N_2H^+) and its lower density surroundings (traced by $C^{18}O$). Both axes are in units of the sound speed (0.23 km s^{-1} for a temperature of 15 K). The grey shading indicates the region of the plot where the observed cores are found(Kirk, Johnstone, & Tafalla 2007), while the coloured symbols indicate the simulated observations, with different colours corresponding to different initial magnetic field strengths. Symbols lying along a common vertical line originate from the same simulation. The simulations which have enough large-scale turbulence to match the observations over-predict the typical motion between dense cores and their local less-dense surroundings (points in upper right portion of plot). See Kirk, Johnstone, & Basu 2009 for further details.