When Do Young Stars Leave Home?

Synopsis

Methods: Using huge new censes of young stars in concert with new high-dynamic range maps of the distribution molecular gas and dust, we can answer several key long-standing questions related to the **timescales** of the star and planet formation process: *How long does a forming star stay with its natal core? How long does it remain associated with the "lower-density structure" (e.g. a filament in a dark cloud), or even the cloud complex where it originally formed? What kind of environment does a star-disk system need to keep accreting, or to produce an outflow, and when might that reservoir no longer be available to the system?*

The fundamental reason these questions have remained unanswered to date is a statistical one. In the past, limited datasets, particularly at mid/far-infrared and millimeter wavelengths have meant that most studies of star formation have had to concentrate on studying a small number of young stars and their immediate environment. However, recent simulations (see Table 1) and observations (see p. 4) suggest that the star formation process is potentially highly dynamical, so that *observations of the location and environment of a star "now" may provide little real insight into the conditions of the gas from which it formed*. Our proposed program uses data from very large, unbiased, new surveys both of the star-forming interstellar medium, and of the young stellar population itself, to investigate the secular evolution of a young star's environment in a statistical manner. This work will lay a critical foundation for research on the effects of the star-forming environment on the formation of planetary systems—once those systems can be detected around young stars.

The main analysis technique will be to establish the spatial distribution of gas density, and then to compare the spatial distributions of young stars in coarse age bins (e.g. <0.5 Myr, ~1 Myr, ~10 Myr) with the gas distribution. In sparsely populated regions, it will be possible—for the youngest stars—to associate individual YSOs with individual density peaks. In more complex regions, and for older stars, one-to-one correspondences are unlikely to be found, and our approach will be a statistical one, measuring the spatial frequency of YSOs of various types and comparing that with the spatial frequency of assorted density structures (e.g. where structures are defined as gas above a certain density threshold). Once assembled, our statistics, will suggest how far, how fast, and through what, stars of various ages may have moved since they began to form. Direct proper motion and radial velocity measurements for young stars will be used, in the rare cases where they exist, to evaluate the overall calibration of our more statistical "velocity" measurements.

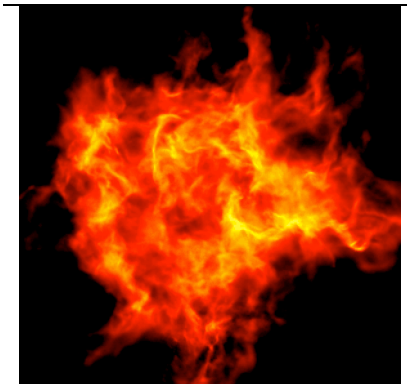
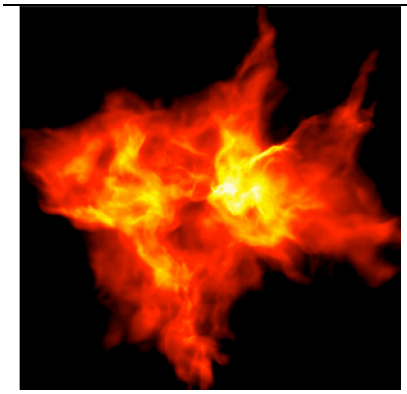
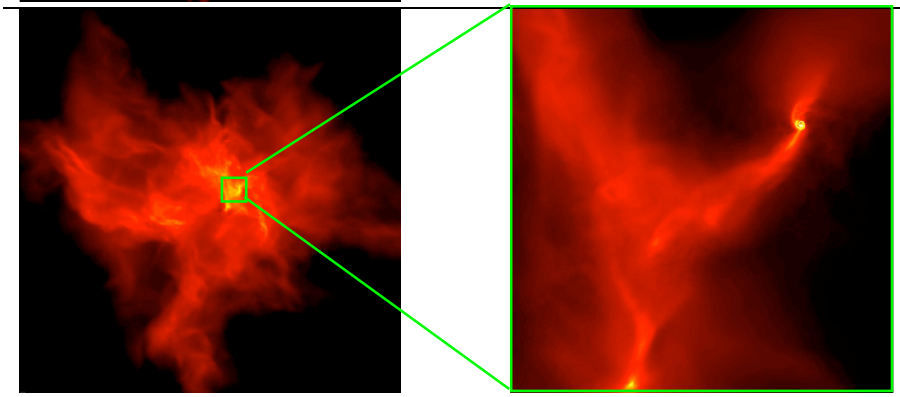
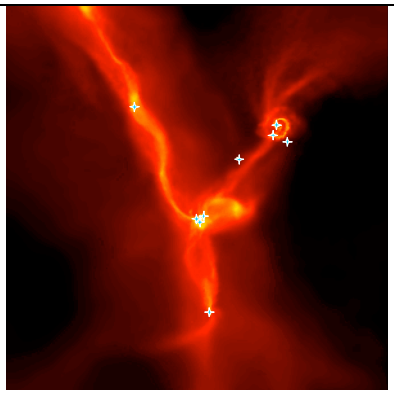
Data: For two >10-pc scale nearby star-forming regions (Perseus and Ophiuchus), we will use primarily a combination of X-ray (primarily ROSAT) and infrared (primarily 2MASS and Spitzer/c2d[1]) data to characterize the age and mass distributions of young stars. New molecular line and dust continuum observations from the COMPLETE[2] Survey, as well as extinction maps constructed from 2MASS and c2d color excess measurements will be used to understand the distribution and physical properties of high-density gas. Molecular line, sub-mm continuum, and wide-field Hα images will also be used to mark the presence of disks and outflows around the YSOs in our study areas, and the disk/outflow properties will be used to refine ages based on Spectral Energy distributions constructed from X-ray and near-IR data. The range in spatial scales of the data we will include will extend from ~0.01 to 10 pc, and we expect to be able to sort stars into (at worst) age bins of <0.5 Myr, ~1 Myr, ~10 Myr with less than 10% misclassification.

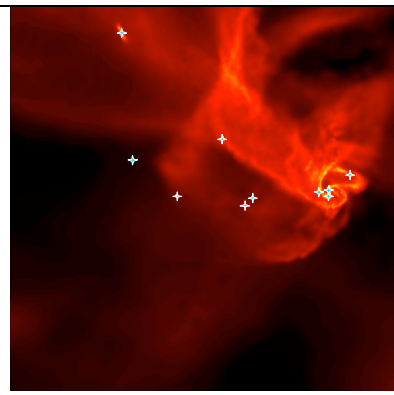
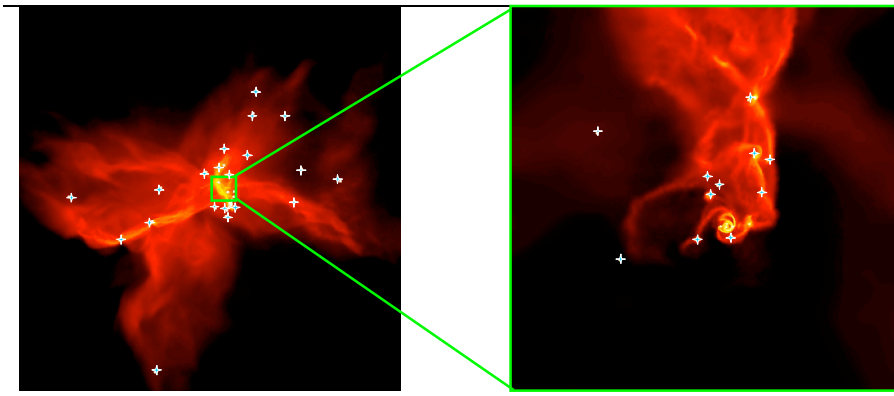
[1] **c2d** =From Molecular **Cores to** Planet Forming **Disks**, Spitzer Legacy Program, see Evans et al. 2003

[2] **CO**ordinated **M**olecular **P**robe **L**ine, **E**xtinction and **T**hermal **E**mission, see Goodman 2004.

Motivation and Background (Text begins on p. 3, and Table 1 is discussed on p. 4.)

Table 1: An Heuristic View of "Dynamical" Star Formation

Simulation Snapshots (based on Bate, Bonnell & Bromm 2003)		Time, Box Size
	An **overall dense molecular cloud**, before star formation ensues. Structures are largely transient, and determined by MHD turbulence (e.g. Ostriker, Stone & Gammie 2001). **Data:** COMPLETE (FCRAO, IRAS & 2MASS/NICER); Spitzer c2d/NICER	80,000 yr, 82,500 A.U. (=0.4 pc)
	A self-gravitating region of the cloud starts to emerge. Observationally such structures are associated with **"dark clouds"** or **"cores,"** depending on scaling. **Data:** COMPLETE (FCRAO & 30-m, SCUBA, 4-m class NICER maps)	160,000 yr 82,500 A.U.
		200,000 yr 82,500 A.U. *zoomed in to* 202,000 yr 5,156 A.U. (zoom is x 1/16)
The panels at right, and above right show **young stars** beginning to form from the **fragmenting core**. **Data:** *Gas/dust distribution* from COMPLETE (FCRAO & 30-m, SCUBA, 4-m class NICER maps); *YSO distribution* from ROSAT, 2MASS, Spitzer		210,000 yr 5,156 A.U. Star symbols (✦) in all panels show the positions of the young stars formed.

A large fraction of **stars are ejected** from their dense gas homes early on in their lives: many travel at several km s^{-1}. **Data:** *Gas/dust distribution* as above; *YSO distribution* as above; additional data will include proper motion measurements (Hipparcos, Tycho 2) and radial velocities from new IR spectroscopy		229,000 yr 5,156 A.U.
		253,000 yr 5,156 A.U. *zoomed out to* 266,000 yr 82,500 A.U. (zoom is x 16)

The prevailing (analytical) theoretical picture of star formation envisions stars forming inside dense cores, which are in-turn embedded in larger, slightly lower-density structures often called "dark clouds." A disk surrounds each forming star, and, when it is very young, the star-disk system produces a collimated bipolar flow, in a direction perpendicular to the disk. In its broad outlines, this paradigm is very likely to be right. In detail, though, many questions concerning the timing and physical scaling of this series of events remain.

In reality, star formation is potentially complicated by the fact that the young stars and the reservoir of gas from which they form move with respect to each other. The spatial density-velocity structure of the reservoir is changing with time, as it is a turbulent medium. The stars themselves are affected much more by gravity than by gas pressure (unlike the gaseous structures, which are affected by both), so they can easily move independently of the gas. And, to make matters worse, in dense "enough" regions, dynamical interactions (driven by gravity) amongst stars and dense clumps are statistically likely.[3] So, whether because a turbulent flow moves gas away from the star that formed it, or because dynamical interactions eject a forming star from its natal environment, it is likely that a star does not stay sheltered by its natal cocoon for very much of its childhood. The work proposed here will quantify the answer to the question of "When Do Young Stars Leave Home?", by defining "home" more carefully than has been possible in the past, and by creating a statistical description of a star's early environment, as a function of time.

[3] To put a scale to this discussion, keep in mind that for ten 0.1 pc clumps in a cubic parsec, and a purely random clump-to-clump velocity dispersion of 1 km s^{-1}, the mean free path for collisions is 3 pc, so the time between interactions is 3 Myr. However, the collision frequency increases linearly with the number of clumps and with the velocity dispersion. So, for 30 clumps, and a dispersion of 2 km s^{-1}, the collision frequency becomes 0.5 Myr, which is *equal to the dynamical (crossing) time*. When gravity is included, the collision frequency goes way up, as the simulation in Table 1 indicates.

The snapshots in Table 1 were selected from the animation of Bate, Bonnell & Bromm's (2003) simulation of the formation of young star cluster (animation available at http://www.ukaff.ac.uk/starcluster/). The conditions used in these simulations are extreme[4], so we do not offer these images (or their temporal and spatial scaling) here as a detailed quantitative illustration of how we think star formation typically proceeds, but instead as a heuristic for thinking about the key phases of a "dynamical" star formation process—even in a case where gravity is less important to determining gas-star motion than it is here. In the table, we point out the key physical attribute of each simulation snapshot shown and associate it with common semantic descriptions. The "**Data**" notes on which observations are useful in which regime are likely to be more useful to the reader as a reference guide, once the whole proposal is read.

The Intriguing Case of PV Ceph

We were inspired to write this proposal by the unusual case of the young star PV Ceph. A wealth of diverse observational evidence presented in Goodman & Arce (2004) implies a motion of ~20 km s^{-1} for PV Ceph relative to its surroundings. This velocity is an order of magnitude larger than what is "expected" (based on gas velocity dispersion measurements or on proper motions of stars seen projected on molecular clouds), and so is very surprising. The evidence for PV Ceph's motion is strong, but complex, and our space here is limited, so we beg any reviewers who find what we say below to be ludicrous, to see the Goodman & Arce (2004) paper in the ApJ.

The full history and current situation of PV Ceph is perhaps even more shocking than just its high velocity. It appears that PV Ceph was *dynamically ejected* from the ~100 $M_\odot$ cluster NGC7023, about 500,000 years ago. Then, it traveled across primarily low-density material until reaching the (otherwise non-noteworthy) molecular cloud in which in now finds itself, about 35,000 years ago. The star is currently surrounded by a disk and produces a giant (pc-scale) outflow—however, while there is a clump of ^{13}CO emission associated with the star, there is no N_2H^+. Thus, the PV Ceph outflow/disk system is surrounded only by a relatively low-density cocoon of material, and *not by the standard "dense core"* usually presumed necessary as a feeder disk accretion. Simple Bondi-Hoyle calculations show that a ~5 $M_\odot$ star like PV Ceph moving at ~20 km s^{-1} cannot gravitationally hold on to a dense core in the presence of so much ram pressure, but it can keep a disk. Careful modeling of the currently visible outflow shows it to be only 10,000 years old. Thus, it is very possible that what was ejected from PV Ceph was a star (with a bit of a disk) not yet finished forming, that somehow began forming again once it reached high-enough density gas.

We certainly do not believe that many young stars are zooming through the ISM at 20 km s^{-1} (only a handful of others have been found going this fast, all through serendipity), but our discovery of the unusual case of PV Ceph was what led us to question the importance of dynamical interactions in the star formation process, and in particular to wonder whether a young star "needs" to remain embedded within a very dense environment during its formation.

Current Thinking on "Dynamical" Star Formation: A Spectrum of Opinion

There are two extreme views when it comes to the relevance of star-cloud motion to the star formation process. In the "static" view, the only relevant motions are those of gas gravitationally-

[4] These simulations begin with 50 M⊙ of gas in a very dense and highly turbulent configuration. These conditions may be so extreme as to be unrealistic, and I have discussed this point with both Ian Bonnell and Volker Bromm, who admit that the BBB system was made unusually unstable in order to assure that interesting interactions would take place within the computing time available, but they stand by the qualitative import of the simulations.

infalling onto a forming star/disk system, which is forming at the center of highly symmetric system. This is the model that has been beautifully calculated by Frank Shu and his colleagues, beginning with the 1977 paper on the collapse of an isothermal sphere (Shu 1977). Taken at face value, the model's reservoir for star formation extends to infinity, and does not move in any systematic, non-self-gravity-driven or asymmetric way. At the other extreme, we have the "competitive accretion" model of star formation, where a density enhancement is produced in a chaotic turbulent flow and gravity tries its best to bring material to that enhancement in the presence of motions, which can either add or subtract material to this position. Qualitatively, this picture is best exemplified by the recent numerical simulations of Bate, Bonnell & Bromm (2003; c.f. Price & Podsiadlowski 1995), which are featured in Table 1.

In-between these two extremes is a confusing spectrum of other opinions. Consider, for example, the ongoing dispute between Hartmann and colleagues (Hartmann 2003; Hartmann, Ballesteros-Paredes, & Bergin 2001) and Palla & Stahler (Palla & Stahler 1999, 2000, 2002) over the timing of star formation in molecular clouds. Both groups note that nearly all of the "young" stars in the highly-filamentary Taurus molecular clouds, are closely associated in space with the gaseous filaments (see Hartmann et al. 2001 Figure 1), but they disagree vehemently over how that situation has been established. Ultimately, their dispute boils down to *whether the filaments provide a long-lasting "reference frame" valid for gauging the motions of stars over time, or whether the filaments are short-lived and so have only formed the stars we see associated with them right now.* The subtlety of the dispute also involves whether the filaments and stars move together, relative to the larger cloud, or not, for if they do not, it is hard to explain how any star that is not very young would still be associated with them. An alternative explanation for the star-filament association in Taurus is that stars are formed with a larger velocity dispersion than that of their natal gas (possibly due to dynamical interactions within the cloud), and that only the stars on the "slow" tail of the velocity distribution are still spatially associated with their birthplaces. This latter position is similar to that taken by Feigelson (1996), who sought to support this argument with the presence of a "halo" of X-ray sources around Taurus (Neuhäuser et al. 1995a, 1995b; 1995c). This idea has since been discredited, at least for Taurus, by Briceño et al. (1999; 1997), who have shown that many of the X-ray sources originally thought to be young by Feigelson (1996) are in fact very old. In light of our PV Ceph results though, we find the idea of a large stellar velocity dispersion very intriguing (albeit *a priori* unlikely). So, we are careful in the proposed analysis to make our young star search areas much broader than the clouds under study, so as not to exclude the possibility that a significant number of young stars have been thrown beyond the confines of their natal clouds by dynamical interactions.

The case of PV Ceph and the disagreements over the star-formation history in Taurus, seem to indicate that: (1) young stars seen projected very near a dense core of gas are likely to be extremely young; (2) young stars move along with the gas from which they form, even after they are formed; and/or (3) we have underestimated the velocity dispersion of young stellar populations, and have yet to find the widely dispersed population of young stars "ejected" from star-forming regions. We hope that the investigation we propose here will go some way to distinguishing between these scenarios.

Data & Analysis

If it were easy to measure the age of young stars, and the distribution of dense gas was unchanging with time, and we could somehow know which dense blob was the origin of each young star, then it would be easy to construct a history of "young stars leaving home," and to predict the amount and nature of the gas available for accretion by a young star/disk system as it forms. In reality,

though, measuring young stars' ages is imprecise and molecular cloud features are transient, so only statistical answers to the question of stellar dispersal are possible. In the "***Data***" portion of this section we show how we will use data from IRAS, 2MASS, Spitzer, and the various components of COMPLETE[5] to describe the distribution of star-forming gas, and data from ROSAT, Chandra, 2MASS and Spitzer, in conjunction with ground-based optical and infrared imaging to measure the spatial and temporal distribution of young stars. In the "***Analysis***" part of this section, we describe analysis methods for comparing these distributions which can statistically predict the motions of young stars with respect to dense gas.

The study proposed here will focus on two of the three >10 pc-scale regions under study in the ongoing large surveys known as "Spitzer/c2d" and "COMPLETE" (see below). Perseus, the first region, is a large complex at roughly 300 pc distance that contains two major star-forming clusters (NGC 1333 and IC 348) as well as many less "clustered" (a.k.a. boring, semi-isolated) regions of star formation. Ophiuchus, the other region, is closer (at 160 pc), and is dominated by the "ρ-Oph" cluster[6], but it also includes much filamentary gas where star formation is also taking place.

Data

Developments in millimeter and submillimeter receiver technology and in computing technology within the last 5 years have provided us with the ability to perform large-scale, high-resolution mapping of both dense gas (by observing molecular lines) and cold dust (via its submillimeter continuum emission) very quickly. The COMPLETE Survey exploits these technological advances, and includes high dynamic-range maps (resolution better than 40 arcsec, map size ~10 square degrees) of all of Perseus and Ophiuchus in ^{12}CO, ^{13}CO, and sub-mm continuum. In addition, many high-density peaks are being mapped with higher resolution (~10 arcsec) in higher-density-tracing molecular lines (e.g. N_2H^+) and mm-continuum. Also as part of COMPLETE, data from both ground- and space-based missions (see below) are being used to create extinction maps of Perseus and Ophiuchus. The careful combination of these data, which corrects for pitfalls like chance projections of unrelated velocity features and chemical depletion, can be used to create a very comprehensive map of the *position-velocity-density distribution of star-forming gas* at the present time.

Almost simultaneously with the advent of giant molecular-line and sub-mm continuum databases like those in COMPLETE, the Spitzer Space Telescope has at last opened up the mid- and far-infrared wavebands, where young stars emit most of their radiation, to unbiased observations of large regions. Combined with archival data from 2MASS and ROSAT, we are now in the exciting and unprecedented position of being able to *find and roughly age-tag all of the young stars* in huge regions of space. The Spitzer Legacy program c2d will fully cover all[7] of the Perseus and Ophiuchus clouds we propose to study here with IRAC and MIPS. In addition, tens of the young

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[5] The COMPLETE (**CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission) Survey, is an ongoing large international collaboration (see Budget Justification) led by the P.I. of this proposal, which is currently producing an unbiased database of multi-wavelength observations of three of the five star-forming regions (Perseus, Ophiuchus, and Serpens) being observed by Spitzer in the c2d Legacy program.

[6] Oddly enough, the "ρ-Oph" cluster is actually 1 full degree (2 pc) south of ρ-Oph, a B star that we have found to be surrounded by a shell of warm dust that impinges on the cluster from the North (see Schnee et al. 2004).

[7] The most famous clusters in the c2d program are already allocated to other observers through GTO time, but the SSC's plan, as we understand it, is to include the GTO data in the archive, along with c2d, as soon as the GTO data are published (2005-6).

stars are targetted for IRS followup, which will give very interesting information on the relationship between a star's SED and its disk properties.

Table 2 lists the sundry data products that we will utilize to perform our study and the information each dataset will provide us with. The paragraphs that follow the Table provide more insight into how each data set is used to derive physical quantities. Keep in mind that much of the data we will employ is already being analyzed, in the ways described, by the large teams of researchers who comprise the COMPLETE and c2d collaborations[8], so this project is not (quite!) as much work as it may appear. The "Analysis" section on p. 11 explains how these measures will be combined into answers to the question of "When Do Young Stars Leave Home?"

Table 2: Data Sets and Their Utility[9]

Data	Source	Information Provided	Scale (pc)
2MASS	Archival (NASA)	Dust distribution (using IR color excess) Near-infrared portion of SED for some stars	~0.1—10
ROSAT	Archival (NASA)	Unbiased census of X-ray emitting young stars	separations ~0.01
Hipparcos/ Tycho-2	Archival (ESA)	Direct measurements of proper motion and distance for a small number of young stars (mostly in Ophiuchus)	
IRAS/ISSA	Archival (NASA)/ COMPLETE	Dust temperature distribution Distribution of cold cores	~0.15—10
Spitzer	c2d Legacy Program +GTO cluster observations	Large scale dust distribution (from extinction mapping) Census of embedded sources Mid-infrared portion of SED □ disk frequency Other morphological age indicators	~0.02—10
FCRAO ^{12}CO and ^{13}CO	COMPLETE	Large scale distribution of moderate density gas Census of outflows (tracing young stars) Distribution of moderate density cores	0.05—10
FCRAO+IRAM N_2H^+ & CS	COMPLETE	Detailed distribution of density and velocity within dense cores	0.01-1
JCMT/SCUBA	COMPLETE	Finer scale density and velocity distribution in cores Identification of Class 0 protostars	~0.02—0.1
4-m IR imaging	COMPLETE	Finest scale dust distribution within cores	<0.01 to 0.1
OIR Surveys	Bally et al. Lada et al.	Census of HH outflows, used as age indicator Near-IR Spectroscopic & Photometric (FLAMINGOS) Survey of Perseus, used as age indicator	<0.01 to 10

2MASS: Using the NICER ("Near-Infrared Color Excess") algorithm (Lombardi & Alves 2001) developed by COMPLETE Co-I João Alves, on the 2MASS catalogue, we have already constructed moderate resolution (~2□ maps of the visual extinction in ~100 square degree fields around Perseus and Ophiuchus. This method of determining column density is extremely powerful, as it does not rely on any knowledge of the dust temperature or emissivity. The only

[8] A full list of the COMPELTE collaboration is given in the Budget Justification. The COMPLETE and c2d teams (Neal Evans, P.I.) are working closely together to coordinate their efforts, and we expect this happy collaboration to extend into the future of both projects.

[9] Note that this information is also included as cryptic comments on relevant "Data" in Table 1.

downfall of searching for dense material in extinction maps is that chance projections of material unrelated in velocity space can give high dust-column peaks just like "real" high (volume) density regions can. This is why we use NICER extinction maps *along with* spectral-line mapping when trying to describe the three-dimensional distribution of material.

Additionally, 2MASS provides us with a census of young stars that lie behind less than about 40 magnitudes of visual extinction, and for these, the near-infrared portion of the spectral energy distribution (explicitly the infrared excess) can be used to determine disk frequency (e.g. Lada et al 2000). Work on 2MASS data by Carpenter (2000) indicates that the two well-known young clusters in Perseus (NGC1333 and IC348) alone contain of the order of 500 young stars.

ROSAT: While K-band excess is strong evidence for the presence of disks, this criterion alone will miss "older" pre-main-sequence (PMS) stars (e.g. weak line T Tauri stars, WTTs and the elusive post-T Tauri stars, PTTS), which have shed much of their circumstellar material. WTTSs are well-known to have X-ray emission, and X-rays have the added advantage of being able to penetrate the high line-of-sight extinction towards regions of recent star formation (cf. Glassgold et al. 2000).

There are, however, other bright X-ray stars, and it is hard to weed out these interlopers without follow-up spectroscopy to measure other age signatures such as Li absorption or surface gravity. Some studies nonetheless suggest that X-ray selection is a very efficient (90% accurate) and robust way to detect the (potentially older) young stars, which K-band excess might miss (see Mamajek et al. 2002; Neuhäuser and Brander 1998). Meanwhile other results suggest that, for certain spectral types, X-ray strength cannot be used as a simple yardstick for age (see e.g. the study of F stars by Suchkov et al. 2003). In some dramatically bad cases, ROSAT "PMS" stars have been identified as young main sequence stars (~100 Myr old) after follow-up spectroscopy (Briceño et al. 1997, 1999). As discussed below, we will use X-ray identification in conjunction with other dating techniques to avoid some of the potential confusion associated with this technique.

Hipparcos/Tycho-2: The measurements of distance and proper motion made as part of the Hipparcos and Tycho-2 projects would be ideal for assessing the velocity distribution of young stars—if only those instruments had been a little more sensitive, or had worked in the infrared (where extinction would have been less of a problem). At present, Jonathan Foster[10], a Harvard graduate student working in the P.I.'s group is in the process of correlating ROSAT sources with sources for which a proper motion and/or distance is available from Hipparcos/Tycho-2. So far, we have learned that Perseus is essentially just too far away to find enough young stars with measured motion, but that Ophiuchus (twice as close) is very promising as a target for this kind of analysis. The utility of direct proper motion measurements for young stars, and of radial velocity measurements (made from the ground in the IR), is discussed further in the "Analysis" section, below.

Spitzer/c2d: The c2d Spitzer Legacy Program will use all three Spitzer instruments to observe sources that span the evolutionary sequence from molecular cores to proto-planetary disks in a wide range of star-forming environments. In particular, the program will use IRAC and MIPS (3.6—70 μm) to survey the entire areas of five of the nearest large molecular clouds, including the two regions which are the target of this program, for new candidate protostars and substellar objects as faint as 0.001 solar luminosities. The resulting data products will include a catalog of thousands of previously unknown embedded sources and multi-wavelength maps of about 20 deg^2

[10] As explained in the Budget Justification, no funding for Jonathan Foster is requested in this proposal. Nonetheless, Mr. Foster will work closely with the Science P.I. (Ridge) on the topic of this proposal for his thesis research.

of molecular clouds. The c2d catalog will facilitate determining the fraction of young stars with disks, as well as providing the mid- and far-infrared portions of the SED for stars detected at other wavelengths.

And, the catalog of point sources can also be used to construct maps of the extinction towards the molecular clouds, using similar methods to the NICER technique. The higher sensitivity compared to 2MASS is expected to produce extinction maps sensitive to structures as small as ~0.01 pc at the distance of Ophiuchus.

COMPLETE/ISSA: As part of COMPLETE, we have re-calibrated the zero points of the IRAS Sky Survey Atlas (ISSA) 60 and 100 μm images of the Perseus and Ophiuchus regions (Schnee et al. 2004). The recalibration method (see Arce & Goodman 1999) allows us to create column density and temperature maps based on these two flux bands that are usable down to very low emission levels. In both Perseus (Ridge et al. 2004) and Ophiuchus[6] (Schnee et al. 2004), the new ISSA-based maps reveal warm dust shells whose presence in these molecular clouds was not previously appreciated. Figure 2, which shows the shell in Perseus, clearly demonstrates why measures of "cloud" column density based solely on IRAS (or any far-IR) data are biased toward warm dust, which will always emit more, pound for pound, than cooler dust. To avoid this bias, we plan to use NICER (extinction) mapping (which is insensitive to temperature) to chart dust column density. Once dust column is specified from extinction mapping, then *dust temperature and emissivity* can be derived by fixing the total column density implied by emission to match that implied by extinction. In the study described here, the *ISSA data's primary utility will be in temperature mapping.*

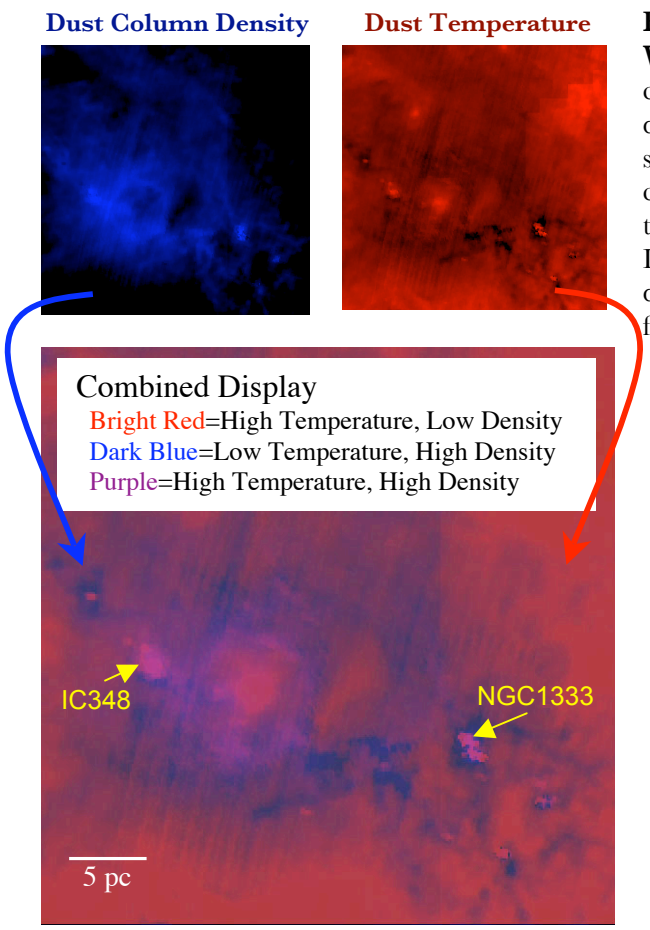
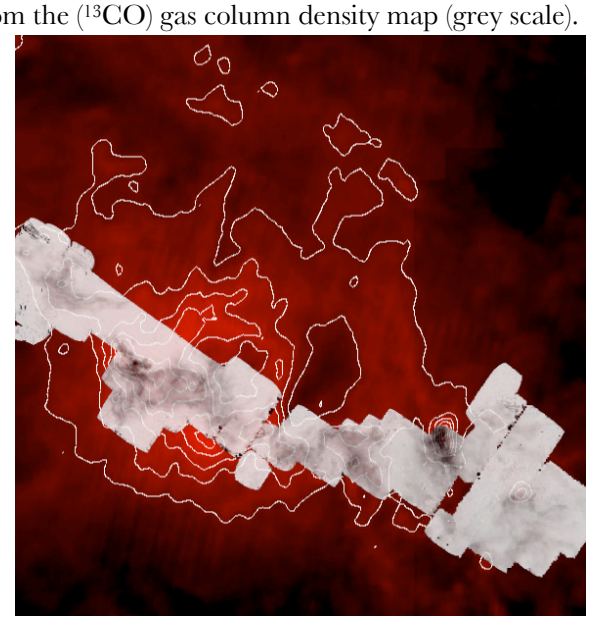


Figure 2: Neither Dust nor Gas Tracers Tell the Whole Story Alone. Panels to the left show how a combination of ISSA 60 and 100 μm-based column density and temperature maps of Perseus reveal a warm shell filled with hot gas superimposed on the chain of cold regions shown both by the dark blue blobs, and by the peaks in the map of ^{13}CO column density (below). In the panel below, note how different the column density map implied by ISSA alone (white contours) is from the (^{13}CO) gas column density map (grey scale).



COMPLETE/FCRAO: Central to COMPLETE are ^{12}CO and ^{13}CO maps at 45″ resolution obtained at the Five College Radio Astronomy Observatory (FCRAO) 14-m telescope. *Each map (of each tracer, for each region) contains >100,000 high-resolution spectra.* These observations will provide information on the motions of the star-forming gas on both small (dense core) and large (e.g. moderate density filaments) scales. One special use of the ^{12}CO data will involve a systematic search for outflows (using statistical tools like the Spectral Correlation Function (see Rosolowsky et al. 1999; Padoan et al. 2003)).[11] The existence and qualities of these outflows (and the concomitant HH flows discussed below) can be used to refine age estimates for the driving sources of those flows. Even though the ^{13}CO line traces denser gas than ^{12}CO, we will *not* use it to identify the highest-density cores, as it has been shown by several authors that carbon-bearing molecules freeze of the gas phase in cold dense star-forming cores (e.g. Tafalla 2002). Instead, we will use undepleted higher-density-tracing molecular species, being observed at FCRAO and at IRAM, along with mm (MAMBO) and sub-mm (SCUBA) data to map these high-density regions.

COMPLETE/IRAM 30-m: Dozens of the cores whose internal structure is not evident in ^{13}CO due to depletion are being mapped at the IRAM 30-m in non-depleted molecular tracers (e.g. N_2H^+), and in the mm continuum (with MAMBO). These observations (which have resolution ~20″) will be used to look for substructure within density peaks identified at lower resolution, and to measure the internal velocity distribution of core gas.

COMPLETE/JCMT: COMPLETE's JCMT observations will also provide maps of 850 μm thermal-continuum emission. Submillimeter continuum emission traces the structure of cold dust, and hence these data are particularly useful for identifying the coldest, densest cores, as well as the very youngest "Class 0" pre-main sequence objects from which no radiation escapes at shorter wavelengths (see below). However, these data must be treated with care, as the chopping technique required when making ground-based observations at these wavelengths introduces a spatial filter which suppresses any structure on scales larger than the largest chop-throw (90″ or 0.1 pc at the distance of Ophiuchus).

COMPLETE/4-m Ground Based: As part of the high-resolution portion of COMPLETE, we are mapping a handful of cores in our target areas in the near-infrared from the ground (at NOAO facilities in Arizona and Chile). The images will allow the NICER algorithm to create even higher resolution maps than those based on c2d. For the limited set of cores to be mapped in this way, these extinction maps will provide the finest scale view of the positioning of a forming source within the density peak that is forming it.

Wide Field Ground-Based Imaging: Nearly all current models of star formation suggest that the collimation and power of outflows from forming stars are greatest when those stars are young. Therefore, we will use results from published and ongoing narrow-band optical/infrared surveys of HH flows (e.g. Bally et al. 1996a; Walawender et al 2003, 2004) to aid our attempts to assign a rough age category to every "young" star in our sample. At the very least, any star showing evidence of driving a highly collimated powerful flow will be removed from the "old" young star age bin, and as our understanding of the flows improves, we may be able to design finer discriminants.

Ground-Based Near-IR Surveys: As luck would have it, Elizabeth Lada and colleagues (some of whom are also on the COMPLETE team) are currently engaged in a near-IR (FLAMINGOS)

[11] In a pilot study now underway, we have already demonstrated that the SCF is an excellent tool for detecting YSO outflows in spectral-line data cubes. We were able to approximately double the number of known outflows in Perseus using the SCF-based technique.

Survey of several star-forming regions, including Perseus[12]. Their photometric and spectroscopic data, which are publicly available through the NOAO Survey program, will be used, both by our team and theirs, for classifying the age and disk properties of young stars in Perseus.

Targeted Ground-Based Near-IR Spectroscopy: We are currently discussing the possibility of measuring radial velocities of optically-obscured young stars to better than 0.3 km s^{-1} with local experts Subu Mohanty, Kevin Luhman, and Lee Hartmann, and with soon-to-be-local expert Eric Mamajek. We do not expect we can measure velocities for very many stars in our target regions to this level of accuracy (even with NIRSpec on Keck), but we are continuing to investigate the feasibility of measuring enough radial velocities to get a YSO velocity distribution in a more direct way than what we propose here. Within five years or so (once FEPS[13] and other similar projects (e.g. Doppmann et al. 2003) are completed), we expect that high-resolution IR spectroscopy will contribute much to our understanding of the age and velocity distribution of young stars, but for now, we consider this angle on our proposed project purely exploratory.

Analysis

The easiest way to address the question of when, how far, and through what young stars move away from their birthplaces would be to measure the velocities and distances of gas and stars, in 3-D, as functions of time, inside molecular clouds. As we have explained above, though, this direct approach is far from possible, and only a statistical approach can offer the answer we seek.

The statistical approach we propose here relies on sorting stars into approximate age bins, and then estimating how far stars in each age bin have moved from their place of birth. The complications in this approach are essentially twofold. First, it is very hard to sort stars into age bins accurately. And, second, the gas distribution itself changes as a function of time, so much so that associating a particular star (especially an older young star) with a single "birth peak" is not possible.

The first problem, of age-sorting, will be overcome both by having coarse age bins, and by admitting, estimating, and factoring in the level of uncertainty in our age determinations. Given a large enough sample of stars, which we think this study represents, these errors should not erase underlying real differences in the spatial distributions of stars of "different" ages.

The second problem, of molecular cloud structures moving and even disappearing altogether, is harder to deal with. Our plan here is to use a "frames of reference" procedure, where we tie the motion of gas at higher and higher density thresholds to that at a lower threshold (e.g. CO to H I, N_2H^+ cores to ^{13}CO, etc.), and then finally derive statistical measures for the motion of gas with respect to itself on a variety of scales. These measures will be translated into a "scrambling" parameter for gas at different spatial scales. So, then when we compare the distribution of dense gas peaks "now" to the distribution of stars of various ages "now," we will factor in a measured amount of gas re-arrangement as a function of time. In other words, we can model the discrepancies between gas and stellar distributions as arising in part from the motions of stars with respect to the gas, plus some motion of the gas with respect to itself.

Below, we: 1) elaborate on the age indicators and disk diagnostics we plan to use to describe the stellar distribution; 2) discuss how the data described in the previous section will be turned into a description of the density-velocity distribution of gas (and dust) in space; and then 3) outline how we will put our analysis together to address the question of when young stars leave home.

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[12] see http://www.astro.ufl.edu/%7Elada/sfsurvey/2mfields/Perseus2m.html

[13] FEPS=Formation and Evolution of Planetary Systems, a Spitzer Legacy Project, M. Meyer, P.I. (see http://feps.as.arizona.edu/science.html)

Stellar Properties

SCUBA, ROSAT[14], 2MASS, FLAMINGOS and Spitzer will provide a complete, unbiased database of all the young stars and embedded sources in Perseus and Ophiuchus. The tricky part will be to characterize these stars by age. The general presumption we will employ in age dating is that the more opaque a disk an object has, and the more vigorously it is accreting, the younger it is. Our age bins will certainly be coarse, and we estimate that *at worst* we will be able to sort stars, to an accuracy of better than 10%, into categories of:

- Young: 0 to 0.5 Myr, big IR excess;
- Medium: 0.5 to 2 Myr, less IR excess, more evidence of a photosphere; and
- Old: 2 to ~10 Myr, mostly evident in X-rays and very little disk excess.

We expect that we will actually have five bins, though, so that our procedures will follow those established by others trying to sort stars into: "Class 0" (sub-mm only objects; André, Ward-Thompson & Barsony 1993); Classes I, II and III (progressively older PMS stars with less and less of a disk, as defined by Lada 1987); and a Class we call "W" which would include both WTTSs and post-TTS. Based on intercomparison of classifications in the literature, we expect we can sort stars into these five categories (rather than the even coarser three above) to an accuracy of 20%.

Much of the work we describe below will likely be done by (or in collaboration with) the c2d team, for the regions directly projected on the molecular gas. Our search for young stars will, however, go far beyond the confines of the traditional molecular cloud because we are searching for any stars that may have ever come from those clouds. Keep in mind that a 10 Myr-old star traveling at 1 km s^{-1} will have moved 10 pc away from its birthplace!

The X-ray sources will be cross-correlated with near-IR data, as well as with the literature to perform a rough sort of the stars in to the kinds of bins discussed above. Finer sorting will rely on more detailed looks at color-color diagrams, infrared spectra (where available from FLAMINGOS), and spectral energy distributions.

For stars detected in the infrared, the Spitzer and 2MASS data will provide us with sensitive photometry from 2—160 μm. It has been known for a few years that L-band excess is an especially reliable tracer of circumstellar disks, being less sensitive to variations in disk inclination and accretion rate than JHK excess, and also unlikely to be skewed by emission from HII regions or reflection nebulae (Lada et al 2000). Recently, Allen et al (2004) have shown that Class I and Class II protostars, traditionally identified by their near-infrared spectral energy distribution (SED), are well separated in a color-color diagram constructed from the four Spitzer mid-infrared (3-8μm) bands. So, we are confident that the combination of 2MASS and Spitzer (and, in Perseus, FLAMINGOS) data should provide us with a complete census of young stars with disks (Classes I, II and III).

To find the very youngest (Class 0) sources, we will rely on our own SCUBA imaging, as well as earlier sub-mm studies. For the oldest "W" sources, we will investigate the correlations between X-ray properties and optical line diagnostics further to attempt to weed out very old stars from the pile of candidate "old" young stars (which will be only X-ray, and not sub-mm or IR sources).

Gas and Core Properties

Each of our datasets provides us with a different insight into the structure of the star-forming material, allowing an unprecedented dynamic range in spatial scale from ~0.01 pc (2000 AU) to a

[14] Some subregions of our target clouds are also scheduled to be observed by Chandra, and we will use the Chandra data too, once they are made available.

few tens of parsecs. However, each of the techniques is subject to biases of sensitivity and resolution, and so can only trace part of the full picture we seek to assemble. As Figure 2 shows, for example, an IRAS-only measurement of column density for a random point in Perseus has a good chance of being very inaccurate. We will therefore need to use a combination of overlapping techniques to construct the statistical description of the position-position-velocity distribution of star forming material (both warm and cold) we seek.

As Table 2 outlines, on the largest scales (1-10 pc), we will identify clouds and filaments of moderate density material both in extinction maps and in CO maps (taking care to exclude chance projections of material at unrelated velocities). We can obtain temperatures for this material from the reprocessed ISSA maps. As we move to smaller scales (0.1-1 pc), dense clumps will be identifiable by their higher extinction, peaked ^{13}CO emission, and cold temperatures. At the smallest scales (0.01-0.1 pc), cold, high-density star-forming cores will be recognized by their high extinction, molecular line emission and sub-mm continuum emission. N_2H^+, which is not depleted onto dust grains, will trace the densest cores well. SCUBA observations, which are not sensitive to extended emission, will be ideally suited for identifying the small dense cores associated with active, ongoing star formation.

We will explore a range of techniques for cataloging the density peaks often called "clumps" and "cores," including the popular CLUMPFIND algorithm (Williams et al 1994). In many cases, we expect a large clump or filament present in data sensitive to lower column densities (2MASS, ^{13}CO) to break up into smaller sub-clumps or cores at higher densities. As explained below, though, a Fourier-style analysis of the distribution of material at various threshold densities may ultimately prove more useful than clump lists, as it is less arbitrary.

Putting it All Together

Many researchers, to whom we apologize for not having had the space to mention their work here, have tried to address the question of how young stars travel away from home. What distinguishes the analysis we propose here from what has come before is *our admission that the gas itself is moving*, and that the cloud structures we see now do not provide a legitimate fixed reference frame upon which to measure the motions of stars. (Table 1 shows an extreme demonstration of this statement.)

Our plan is to analyze the "cloud" and "stellar" data we describe above both in the spatial domain, and in a (Fourier transformed) frequency domain. In a scenario where stars do not move very far very fast, then some of the most intuitive plots we will be able to extract from our study will not require Fourier transforms, and will look something like the mock-up in Figure 3 (but with more informative and denser distributions of data points within and amongst the age bins[15]). In the Figure, we show the distribution of offset between young stars and the nearest density peak. (Note, though, that depending on how fast stars and cores move, the nearest density peak may or may not be correctly associated with a star's "birthplace.") Once this plot is created, if one assigns a time scale to the x-axis, then the slope of the correlation gives (offset)/(time), which gives a measure of the typical velocity with which sources move away from their homes[16]. Keep in mind, though, that the "homes" themselves are also moving, so the scrambling parameter discussed above would be needed to specify how much of the relative star-peak motion was due to the

[15] In a region like Perseus (Figure 5), there are of order 20 to 30 relatively isolated peaks associated with forming stars, as well as clusters each containing hundreds of forming stars (e.g. NGC1333 and IC348).

[16] To get a 3-D velocity from this 2-D measure, one needs to include a statistical model of the 3-D distribution (e.g. isotropic, sheet-like, filamentary, etc.) of material.

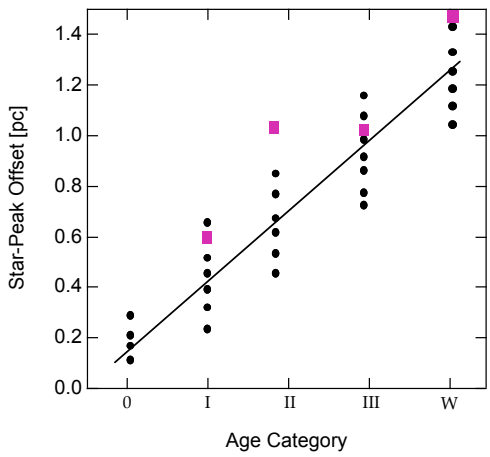

Figure 3: Plot to be used to Infer Stellar Velocity Distribution w.r.t. Gas

"peak's" motion with respect to a larger reference frame, and how much is due the star's motion with respect to the same frame. As a reality check, at least in Ophiuchus, we will also be able to compare the purely space/time derived stellar velocity distribution with the proper motion (Hipparcos/Tycho-2) velocity distribution we discussed above.

The magenta square points in Figure 3 are meant to represent stars we will have "tagged" as in some special category. A sample such category would include stars likely to have undergone some kind of dramatic event in their formative years, such as being overrun by an expanding shell or a nearby bipolar outflow. Sorting into categories we can hypothesize as physically interesting (e.g. proximity to a cluster, peaks with small/large internal velocity dispersions, stars with/without outflows, mass bins, cluster/non-cluster etc.) will be informative, but it is hard now, at the outset of the proposed project, to say exactly which physical properties will effect the implications of plots like Figure 3 most. That, after all, is part of what we seek to learn!

The spread of points around trends of offset with age, even when stars and peaks are sorted into physically-meaningful categories, will still be caused both by the uncertainty in our measurements and methods and by an underlying inherent distribution in velocities. It will be a challenge to separate the interesting, real, cosmic scatter in the velocities from the errors, but we have thought carefully about how to do this. For example, we can use a variety of methods to define "peak" positions and then test how much scatter the differences between methods introduce into the distribution of offsets. On the age-dating axis, in several cases we will be able to compare ages determined from SED modeling alone with age estimates that include other indicators, such as outflow collimation and/or outflow power, and/or IR spectroscopy for the YSO.

Plots similar to Figure 3, and their slightly less intuitive Fourier equivalents, will ultimately allow us to determine the age at which young stars are no longer associated with dense gas. In addition, more detailed analysis of the data will show whether stars located in moderate density gas can maintain significant accretion (as traced by a massive disk or outflow), and/or whether a high-density reservoir is required for the star-formation process to progress once a protostar has formed.

Implications of this Study

If we find that many stars move far outside their host "core" before they are "finished" forming, and/or that dynamical interactions (between forming stars, or between stars and gas) are important, our results will necessitate fundamental revisions in the modern paradigm for forming stars and protoplanetary disks. And, calculations of the star formation efficiency based on dividing the mass in stars by the mass in gas over a small region will need revision as well, since stars that formed in that gas once upon a time may no longer be around. If we find that stars do not seem to move far from where they started forming before they finish forming, then we as a community will need to investigate why the gas and stars move together, even though stars do not respond to gas pressure forces in the same way as the gas.

Management Plan

The P.I. (Goodman) will oversee the full project described here as part of her overall management of the COMPLETE Survey. The specific analysis described here will be supervised and largely carried out by the Science P.I. (Ridge). The large COMPLETE and c2d collaborations will provide much of the data needed here in final form, without additional work by either the P.I. or Science P.I. The new work under this proposal involves interrelating these data in a statistically meaningful study designed specifically to look at the question of "when young stars leave home."

Goodman & Ridge are part of the COMPLETE group at the CfA, which currently includes two postdocs (Ridge and Di Li (who is funded outside of COMPLETE)), and two Harvard Astronomy graduate students (Scott Schnee and Jonathan Foster). Schnee, a fourth-year student, will finish in 2006, and so will only contribute to the earliest phases of what is proposed here, and no funding is requested for him. Foster, who is a first-year student, is currently working on the initial phases of the project described in this proposal, and he would like to pursue it for his thesis. In the interest of keeping our budget in-line with the Origins program, we have proposed to fund Mr. Foster through an NSF grant, even though he will work closely with the Science P.I. on *this* Origins proposal.

In the first year of this project, we will concentrate our analysis, and develop its methodology, first on Ophiuchus, and then extend the analysis to include Perseus toward the end of the first year/beginning of the second year. The initial paper in our project will describe our methods and offer statistical descriptions of the spatial frequency of gas and stars in Perseus and Ophiuchus. *All the catalogs and maps created will be posted to, and maintained at, the COMPLETE website, which is linked to and from the c2d website.* (At least two) papers produced during **the second year** will focus on the inter-comparisons of these distributions, and begin to consider the implied stellar velocity distributions. One of the second-year papers will include a comparison with extant measured proper motions and radial velocities.

During the second year of the program, we will host an **Origins Workshop** here at the CfA, with the title **"How Dynamical is Star Formation?"** The plan for that workshop will be to invite 12 "established" researchers whose work is most relevant to this question, along with 12 students or postdocs invited by the 12 established invitees whose presence will liven up the workshop and extend its impact to a broader community.

Inspired by the results of the workshop, we plan to spend the **third year** of this project thinking and writing about the deeper implications of stars forming in "non-traditional" environments. We will be able to contemplate questions like how frequently "PV Ceph-like" events take place, and so how often we need to worry about stars with disks and outflows having no apparent associated high-density reservoir to draw upon.

And, finally, we will be able study the relationship between star and/or disk mass and the star-forming environment. This relationship may ultimately have dramatic ramifications for the planet-forming potential of young stars with disks. In the not-too-distant future, when enough extrasolar planets have been detected in a range of interstellar environments, our study will be used to examine the question of how much of an effect a star's place of birth, and the conditions there, have on its ability to form particular kinds of planets and planetary systems.

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