COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 04-2

NSF 04-2

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

AST - GALACTIC ASTRONOMY PROGRAM

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Harvard University
1350 Massachusetts Ave.
Cambridge, MA. 021383826

NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE

Harvard College Observatory

PERFORMING ORGANIZATION CODE (IF KNOWN)

5300006452

ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE

Harvard College Observator
60 Garden Street
Cambridge, MA 02138

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS

☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **How Dynamic is Star Formation in a Dynamical Time?**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 497,733	36 months	07/01/04	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.A)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ________
☐ HUMAN SUBJECTS (GPG II.D.6)
Exemption Subsection ________ or IRB App. Date ________
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
☒ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)

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CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 04-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix C of the Grant Proposal Guide.

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(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

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Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME **Susan H Roudebush**	**Electronic Signature**	**Nov 19 2003 4:45PM**

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PROJECT SUMMARY

Our investigation will use the wealth of new data being produced by large, new, surveys of star-forming regions to address the question: *How Dynamic is Star Formation in a Dynamical Time?* The central principle of the project is to empirically define a reference frame on one scale (e.g. a giant molecular cloud) to study the motions of the objects within (e.g. dense, star-forming cores), on smaller scales. This "frames of reference" principle is applied to the study of star and gas motions on scales all the way from ~30 to 0.01 pc.

The motivating **("Intellectual Merit")** goal of the project is to assess the physical importance of dynamic interactions between and amongst star-forming gas and stars, under a variety of physical conditions. To do this, we will determine the positions, velocities, and space-densities of gaseous structures and stars throughout three very large molecular cloud complexes. Each target complex is simultaneously home to both "isolated" and "clustered" star formation. We will use the motions and masses we infer to assess the likelihood of several kinds of potentially significant interactions as functions of time and energy. Those interactions include, but are not limited to: stars coming close enough to each other so as to alter their futures (e.g. ejection from a cluster, loss of a disk); bodies (either stars or gaseous clumps) tidally removing mass from one and other (e.g. "competitive accretion"); fertile star-forming density peaks stars being overrun by outflows from young stars or expanding shells from older stars; and the unbinding of forming clusters. Understanding the frequency with which these interactions occur will go far toward settling current disputes over the time scales associated with: forming molecular clouds; forming stars in those clouds; and dispersing the stars and clouds. For example, do all clouds, as Bruce Elmegreen has suggested, really "form stars in a dynamical time"?

The ongoing COMPLETE Survey of Star-Forming Regions (P.I., Alyssa Goodman) will provide us with: atomic and molecular-line maps of gas density and velocity distribution; extinction maps of dust column density; and thermal-emission maps of dust column density and temperature, for three nearby star-forming regions: Perseus, Ophiuchus, and Serpens, each of which covers ~100 square parsecs of sky. The upcoming SIRTF "Cores-to-Disks" (c2d) Legacy Survey (P.I., Neal Evans II), along with several recent and upcoming ground-based surveys (including 2MASS) will offer enough information to deduce positions and approximate ages for hundreds of the young stars forming in these same clouds.

For each cloud complex, the position-velocity distribution of the gas measured (by COMPLETE) on large scales will be used to define a reference frame for the motion of the objects within (and near) the complex. We can measure the motions of density peaks, also using COMPLETE data, with respect to that frame. And, by measuring offsets between those peaks and the associated stars whose ages we can determine, we can estimate the velocity of the stars with respect to the peaks. It is only with the advent of a data set as large and unbiased as COMPLETE's, which contains hundreds of identifiable density peaks and forming stars, that the kind of statistical analysis we propose has become possible.

COMPLETE has already had a **"Broad Impact"** on both the astronomical community, and on the public at large. The COMPLETE data, like the SIRTF c2d data, are being made available on the internet as soon they are taken and verified. Through the P.I.'s affiliation with the National Virtual Observatory (NVO) initiative, COMPLETE is the test-bed for new NVO interfaces being designed for quick and intuitive access to spectral-line data. The specific project proposed here is only one of several going on within the COMPLETE consortium, and only one of hundreds facilitated by the data set our COMPLETE team is making public. The P.I. has given several public lectures on COMPLETE, and through her talks and the project's web site, many laypeople are now keenly interested in the project, and following its progress closely. In addition to the postdocs and graduate students working on COMPLETE at Harvard, two undergraduates and one high-school student have been substantially involved.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

1 RESULTS FROM PRIOR NSF SUPPORT

Notes: In this section, I discuss only the work directly motivating the current proposal, rather than giving a full review of recent accomplishments. Scientific results from the COMPLETE Survey, which are key to what we propose here, are discussed in §2, and the survey's funding history is explained in the Budget Justification.

1.1 Development of the Spectral Correlation Function

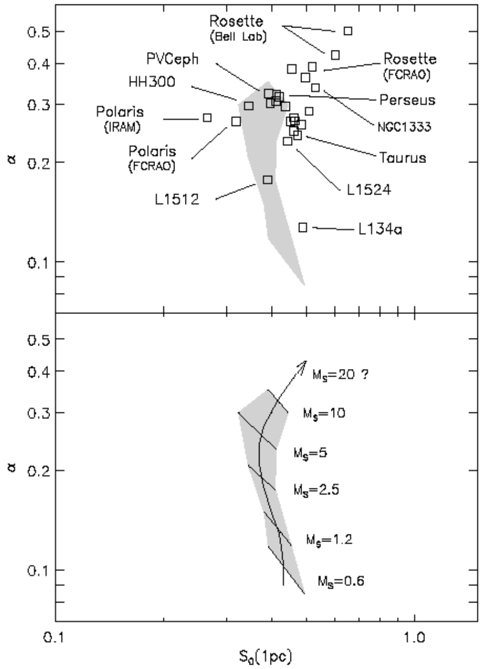

Figure 1: Summary of SCF analysis comparing MHD simulations and ^{13}CO maps of molecular clouds. (Padoan, Goodman & Juvela 2003)

Under my previous NSF Galactic Astronomy Grant (*Watching the Interstellar Medium Move: Testing Simulations*, AST-9721455, $260,038 duration 1998-2002), I developed a new tool for describing spectral-line data cubes called the "Spectral Correlation Function," or "SCF." The goal of this work was to develop a statistic to describe spectral-line maps that would be both more intuitive *and* more discriminating than those usually applied. In collaboration with Paolo Padoan[1], who was hired as a postdoc under the grant, and (now) graduate student Erik Rosolowsky[2], the SCF code was developed into a powerful tool that has been put to a wide variety of uses (Ballesteros-Paredes, Vázquez-Semadeni, & Goodman 2002; Padoan, Goodman, & Juvela 2003; Padoan et al. 2001b; Padoan, Rosolowsky, & Goodman 2001c; Rosolowsky et al. 1999).

While some of the SCF's applications, such as using it to map out the thickness of a face-on galaxy (Padoan, et al. 2001b) were unanticipated, we also managed to do exactly what we set out to do: to learn which numerical simulations, if any, were most like what kinds of molecular clouds.

The plots in Figure 1 show the SCF-derived parameter "α," which measures how quickly spectra de-correlate as a function of spatial scale, versus S_o, which measures the overall level of correlation amongst all the spectra in a map. In the upper panel, the open squares show where a variety of molecular clouds, observed in ^{13}CO, lie in this S_o-α space.[3] In the lower panel, diagonal line segments show, for each Mach number (M_S) indicated, the range of results obtained from "super-Alfvénic" numerical models over a range of possible magnetic field inclinations (see Padoan & Nordlund 1999). The grey-filled shape in both panels shows the range of parameter space covered by the simulations for the range of Mach numbers it is currently possible to simulate, maxing out at 10. The fact that several clouds lie "above" the grey range (upper panel) implies that higher Mach number simulations--which require the simulation of a larger dynamic range in density, and thus more computing power--are needed to model the most turbulent clouds.

Our SCF work was the first to show and quantify *disagreement* between numerical models and observations, including some that had earlier been shown to "agree" according to less stringent tests (e.g. comparisons of the distributions of various spectral moments (e.g. Falgarone et al. 1994)). The models that came closest to reality in our SCF comparisons (Figure 1) utilized non-LTE radiative transfer codes in calculating synthetic spectra (e.g. Padoan et al. 1998). Our SCF work has now convinced the modeling community that it necessary to include radiative transfer calculations when generating synthetic spectral-line maps of molecular clouds for comparison with observations, and the upcoming generation of synthetic cloud observations we look forward to in §2.4 will do just that.

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[1] Dr. Padoan has recently been appointed to the faculty at UC San Diego and is affiliated with their Supercomputer Center.
[2] Eric Rosolowsky began working with me when he was an NSF/REU (undergraduate) intern at SAO. Now, he is a graduate student at UC Berkeley, working with Leo Blitz on projects that include applying the SCF to new maps of the molecular gas in M33.
[3] We fully appreciate that this highly-derived parameter space is likely to be unfamiliar to some reviewers, but we choose to include the figure here to show that not even the best simulations are yet up to the task of "matching" reality.

The SCF will be used in the coming years to test this next generation of models. The expectation is that the numerical models will mature to the point where physical inputs can be adjusted so as to model special kinds of regions, enabling statistical comparisons (e.g. via the SCF) of observed and simulated properties of various physical regimes. In §2.3.4, below, we describe our recent success in using the SCF as an automated outflow-finding algorithm.

1.2 Discovery of a "Speeding Young Star"

The quest to understand the motion of the Herbig Ae/Be star PV Ceph was by the far the most fun I have had as an astrophysicist in the past several years. My former student, Dr. Héctor Arce[4], and I have just submitted a paper to the *Astrophysical Journal* laying out a wide variety of evidence that implies a motion of ~20 km s^{-1} for PV Ceph relative to its surroundings (Goodman & Arce 2003).

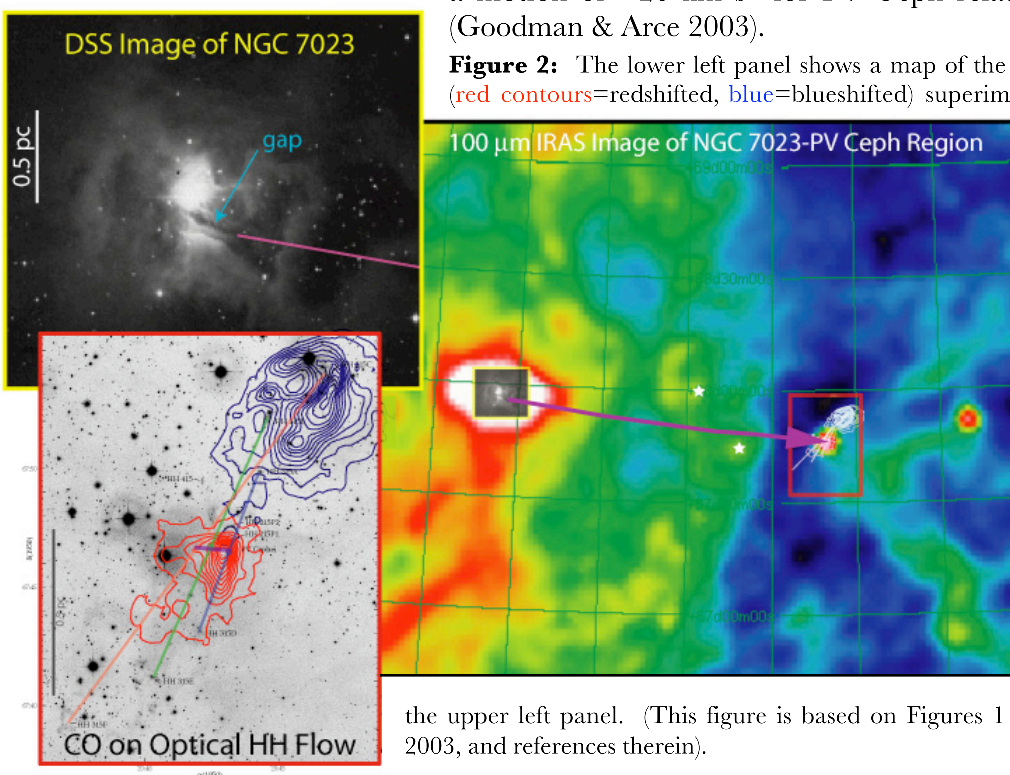

Figure 2: The lower left panel shows a map of the CO outflow from PV Ceph (red contours=redshifted, blue=blueshifted) superimposed on an optical image showing the positions of HH knots, with each knot pair connected by a colored line. The positions of the bisectors of these colored lines imply a motion for PV Ceph of ~20 km s^{-1}, along the direction shown by the tiny purple line segment. The colorful panel (an IRAS map) shows that an extension of PV Ceph's motion (long purple arrow) back in time leads directly to the young cluster NGC7023, and specifically to the gap in the nebulousity shown in the upper left panel. (This figure is based on Figures 1 and 6 of Goodman & Arce 2003, and references therein).

It took nearly three years of work to convince ourselves that PV Ceph is moving at this high speed, so I am not likely to be able to convince you in just a few paragraphs--but I shall try[5]. In studying PV Ceph in two earlier papers (Arce & Goodman 2002a, 2002b), we noticed that the Herbig-Haro (HH) knots in the flow (Reipurth, Bally, & Devine 1997) could not be connected pairwise along lines passing through the source. Instead, the bisectors of lines connecting knots at similar distances from PV Ceph seemed to move East as the knot pairs got farther from the source (see Figure 2). After applying a plasmon model (see Cabrit & Raga 2000 and references therein) of the deceleration of a clump of gas (an HH knot) moving through other gas (a molecular cloud), we fit the observed positions of the HH knots in PV Ceph's flow with a model where a jet is ejected at 350 km s^{-1} from a source moving, from East to West, at *22 km s^{-1}* with respect to its environs. This is a perfectly reasonable jet velocity, but rather an insane stellar velocity. Then, though, we realized that we could also model the tilt of the wiggling CO jet we

[4] Héctor Arce had an NSF minority fellowship as graduate student, and he is currently an OVRO postdoctoral fellow at Caltech and a member of the COMPLETE team. He and COMPLETE postdoc Naomi Ridge are leading the effort to find and understand the outflows recently discovered and mapped in the COMPLETE Survey.

[5] As of this writing, PV Ceph is likely to be featured in a Press Conference at the upcoming AAS meeting in Atlanta. So, perhaps by the time you read this either our result will be familiar to you, or you will have already formed a strong opinion about our capabilities, or sanity.

had discovered earlier (Arce & Goodman 2002a) with the same kind of plasmon formalism. This would give us an independent estimate (using only the radio CO data, and not the optical HH knot positions) for the velocity of PV Ceph, and it gave *21 km s^{-1}* for the same jet velocity of 350 km s^{-1}. What is more, upon inspection of the molecular line maps of PV Ceph at various velocities, it becomes clear that PV Ceph is leaving a wake-like trail behind itself, in exactly the direction the plasmon modeling implies.

When we began to show our most expert colleagues the evidence for PV Ceph's speeding, they usually (to our astonishment) believed our story, but they always asked the same question: "Where did it come from?" Accepting the likely answer to this question--that PV Ceph was ejected from NGC70233--requires that one cast aside the traditional model of stars forming in the molecular cloud where they are observed, and it is a *very* hard pill to swallow. If one traces the motion implied for PV Ceph by the positions of the HH knots back, along a 10-pc-long segment of a great circle (the long purple arrow in Figure 2), one hits the young star cluster NGC7023 dead-on. Not only that, if one looks closely at the optical image of NGC7023 (inset in Figure 2), it is apparent that PV Ceph's backtrack extends directly into a linear *hole* in NGC7023. If PV Ceph was not ejected from NGC7023 (which is also at the same distance as PV Ceph), this is the one of the cruelest tricks the Universe has ever played on observers.

So, the story we can piece together is that about 500,000 years ago, something--probably a forming star with a circumstellar disk--was ejected from NGC7023. Then, it traveled West through much lower-density space until, about 30,000 years ago, it hit the molecular cloud (visible in the IRAS image of Figure 2 as a sideways-V collection of green filaments) in Cepheus in which "PV Ceph" now finds itself. Our modeling shows that the age of all of the outflowing material associated with PV Ceph now is only 10,000 years, so there is no temporal inconsistency.

The inconsistencies are with the prevailing theories of star formation. How, exactly, does a star manage to hold on to enough material--or gather up enough new material--to continue forming and generate a giant outflow, while moving at 22 km s^{-1}? We *certainly do not believe* that many young stars are zooming through the ISM at this kind of speed, but we do hope that PV Ceph[6] serves as a wake-up call to our community, prompting a re-examination of the role of dynamical interactions in the star-formation process. For now, PV Ceph has inspired us to submit this proposal, aimed at investigating these interactions.

1.3 The National Virtual Observatory

I serve as P.I. on an $0.5M and a co-I on a $10M NSF grant to develop the National Virtual Observatory (NVO). Most of our efforts in this regard to date involve software development, which it is not appropriate to describe here. Instead, I call out the connections between the NVO, COMPLETE (see §2.2), and the work proposed here throughout the remainder of the proposal.

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2 HOW DYNAMIC IS STAR FORMATION IN A DYNAMICAL TIME?

2.1 Motivation and Background

The prevailing theoretical picture of star formation envisions stars forming inside of dense cores, which are in-turn embedded in larger, slightly lower-density structures. Each forming star is surrounded by a disk, 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 of this series of events remain. For example, how long does a 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) 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

[6] In our paper, we show that PV Ceph is one of six young stars to have been serendipitously discovered to travel at speeds >10 km s^{-1} (see Goodman & Arce 2003 and references therein).

longer be available to the system? (witness PV Ceph, §1.2). Does a bipolar outflow have any effect on star formation nearby? How much influence do spherical winds (e.g. SNe, B-star winds) from previous generations of stars have on the timing of star formation? How often is a star in the process of forming likely to encounter an external gravitational potential (e.g. from another forming star) strong enough to alter its formation process?

The complicating issue underlying all of these questions is that it is hard to define and understand the long-lasting properties of the reservoir from which a star forms if the reservoir itself is highly dynamic.

2.1.1 Frames of Reference

To define how "dynamic" a system is requires a frame of reference in which to measure motions. The fitted rotation curve of the Galaxy provides a reference frame for the motions of the stars, or the large molecular cloud complexes, within it. The "peculiar" motions of stars or cloud complexes with respect to the rotation of the Galaxy tells us about their dynamics on scales less than the size of the Galaxy. Differences between the motions of stars and molecular cloud complexes with respect to this Galactic rotation reference frame tells us about the *relative* motions of the gas and the stars. This proposal relies upon extending these ideas to smaller scales. The position-velocity distribution of an entire molecular cloud complex provides a reference frame within which we can measure the motions of star-forming dense clumps and of the forming stars themselves. Differences in the position-velocity distribution of clumps and forming stars, with respect to the larger-scale cloud, tells us about the relative motions of clumps and stars. Not all of the relevant parameters (e.g. stellar velocity) for such an analysis are easily measurable directly, and the structure of molecular clouds on large scales changes with time, so one must be especially clever and careful about how one applies this "frame of reference" analysis in star forming regions.

In this proposal, we explain how the new data from our[7] "COMPLETE" Survey (§2.2), which maps out the density, position and velocity distributions of all of the molecular clouds in three star forming regions, used in concert with new (e.g. SIRTF) and existing measures of the distributions of young stars near and within these complexes, allows us to measure how "dynamic" the star formation process is in these clouds, using the "frame of reference" logic described here.

2.1.2 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-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, hereafter BBB; c.f. Price & Podsiadlowski 1995), which show the formation of a (small) star cluster to be a highly chaotic process featuring several energetically important gravitational interactions between forming stars (striking movies of this view are at http://www.ukaff.ac.uk/starcluster/).

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

[7] A full roster of the COMPLETE team is given in the Budget Justification.

filaments (see Hartmann et al. 2001 Figure 2), 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 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.

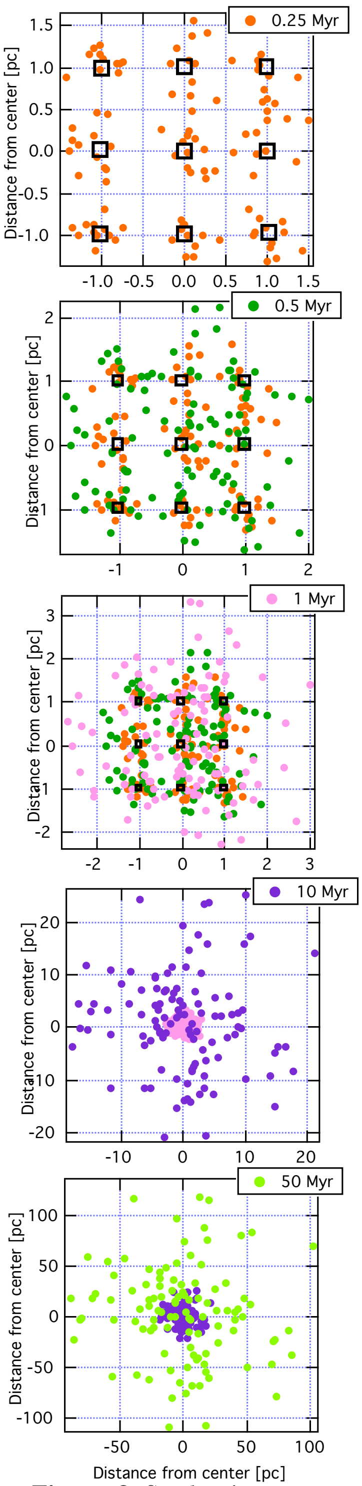

Figure 3: Stochastic Evolution of Stellar Positions

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 (Neuhaeuser et al. 1995a, 1995b; Neuhaeuser et al. 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 (§1.2), 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 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.

For reviewers who have not followed these complex disputes over the past several years, consider the following simple calculation for context. Stars that move with a mean random velocity (σ) similar to that found in the gas where they form will move a distance σt in a time t. **Figure 3** shows a Monte Carlo calculation where we have allowed 108 stars, initially arranged into 27 tight (0.01 pc) 4-star clumps, spaced at 1 pc intervals inside a 3 pc x 3 pc x 3 pc box, to move in straight lines in 3-D (no gravitational effects are included) with random initial orientation and a gaussian velocity distribution with σ=2 km s^{-1} (i.e. typical of Taurus). The small black boxes visible in the upper 3 panels show a grid of 0.2 pc x 0.2 pc squares separated by the original clump spacing of 1 pc. *If clumps did not move* relative to the larger cloud "reference frame," but stars did, one could think of these black boxes as boundaries of clumps. (It is, however, likely that the clumps *do not* stay still.) The figure shows 2-D projections of the evolution of this system at: 0.25 Myr (approximately the latest time at which clumping remains visually apparent); 0.5 Myr; 1 Myr; 10 Myr; and 50 Myr. (Note that all stars from the previous snapshot are repeated in panels at later times, for reference, and that *the scale of the box changes in each panel*. By the time just 0.5 Myr has gone by, the original spatial distribution of the stars is erased, and by 10 Myr, the stars--which all originated within 3 pc of each other--are scattered over more than 40 pc on the sky.

Thus, no matter who is "right" about Taurus, it is clear that: (1) young stars seen projected very near dense gas are 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.

2.1.3 How long do forming stars have to interact?

In Bruce Elmegreen's *Star Formation in a Crossing Time* (Elmegreen 2000), his central thesis is that a wide variety of empirical evidence shows that the *duration* of star formation in any region is less than or about equal to its crossing time (a.k.a. a "dynamical time"). Thus, in a 20-pc scale region like Taurus, with a typical velocity dispersion on that scale of 2 km s^{-1}, star formation should last for no more than about 10 Myr. Similarly, star-formation in a 1-cubic-pc clump with a velocity dispersion ~1 km s^{-1} should last only ~1 Myr. Elmegreen concludes that these rapid star-formation time scales support a picture where stars essentially "freeze out" of gas above a critical density threshold as fast as they can, thus preserving, at least for a while, the spatial distribution of the gas from which they formed.

While both Elmegreen and Palla & Stahler would argue that the stellar distribution we see now looks like the clouds from which the stars formed, Elmegreen believes that the clouds are short-lived whereas Palla & Stahler believe the clouds wait a long time (~10 Myr) before producing stars in the "accelerated" (~1 Myr) burst we see today. Since about half of all density peaks (cores) harbor young stars (Beichman et al. 1986), it is hard to see how most clouds could "wait" for so long as Palla & Stahler want them to before forming stars. Both Hartmann et al.'s work with numerical simulations of molecular clouds (Ballesteros-Paredes, Hartmann, & Vazquez-Semadeni 1999), as well as our own (Padoan et al. 2001a), imply that the star-forming density peaks in molecular clouds form rapidly, at shock interfaces or in colliding streams in turbulent flows, and that they dissipate rapidly if they are not sufficiently dense to collapse into stars. While we suspect that Elmegreen, Hartmann et al., and others who have argued for short-lived dense clouds are likely to be right, the interesting open question is: *how dynamic is star formation in a dynamical time?*

Elmegreen argues that star formation in molecular clouds is typically so rapid that it does not last long enough for dynamical interactions amongst the forming stars to matter. Nonetheless, simulations like BBB, which show dozens of energetically-significant interactions in the formation of just a small star cluster, inspire us to *measure,* using the large, unbiased set of cloud and star measurements we describe below, just how dynamical stars formation could be in a dynamical time.

In a stochastic system, the probability of one "particle" interacting with another depends on the number density (N), the velocity distribution, and the "cross-section" of the "particles." *If forces (e.g. gravity, magnetic fields) between the collision partners can be neglected* so that just the geometric cross-section (πa^2) is most relevant, then the mean free path between interactions is given by $l=(N\pi a^2)^{-1}$. And, the time between interactions (τ) depends only on the mean free path and the typical velocity (v) of particles, as $\tau=lv^{-1}=(N\pi a^2 v)^{-1}$. For a density of ten 0.1 pc clumps in a cubic parsec, and a clump-to-clump velocity dispersion of 1 km s^{-1}, the mean free path is 3 pc, and the time between interactions is 3 Myr, which is three times the crossing time of the cubic-parsec box[8]. So, for a region like Taurus, or the outskirts of Perseus or Ophiuchus, where the clump density does not usually exceed ten per cubic parsec, it would perhaps appear Elmegreen is right that dynamical interactions are unlikely to alter the formation process of any individual star.

If, however, one either includes the effects of gravitational focusing (meaning cross-sections are more than geometric), and/or increases the velocity dispersion, "clump" size, and space density of clumps, dynamical interactions do begin to matter. For example, *even ignoring gravitational focusing*, if we boost clump size, velocity dispersion, and clump space density each by a factor of two in the example above, the mean free path drops to 0.2 pc and the time between interactions is only 200,000 years, meaning a clump could have *five* interactions in a crossing time.

In the BBB simulations, which begin with 50 $M_\odot$ of gas and a very dense and highly turbulent configuration, dynamical interactions and gravitational focusing play central roles. As a result, the velocity dispersion of the objects formed is very high, and several stars are ejected from the forming system, at velocities as high as 5 km s^{-1}, with no correlation between stellar mass and velocity. In

[8] These parameters give nearly the same mean-free-path and collision time as those (N=4 pc^{-3}, v=2 km s^{-1}) used in Figure 4, and either set is realistic for portions of nearby star-forming molecular clouds.

addition, the protostellar disks in these simulations are truncated to be <20 A.U. This very dynamic picture is clearly at odds with the Elmegreen or Palla & Stahler views. And even though the BBB simulations support the idea favored by Hartmann and colleagues, that stars form in colliding streams of gas, the BBB picture surely does not explain stars staying with their natal gas for millions of years.

One can argue, as I would, that the initial conditions in the BBB simulations are so unstable as to be unrealistic even for a forming cluster[9]. While the BBB simulations are unrealistic in other ways as well (e.g. no magnetic fields are included), it is clear even from just the stochastic arguments above that a regime can plausibly exist in molecular clouds where dynamical interactions *are* likely to influence the star formation process.

2.1.4 Working Hypothesis: Boats Adrift in a Dynamic Sea

The hypothesis we seek to test is one that lies in-between the purely static approximation of Shu et al. and the highly dynamic view offered by the BBB simulations[10]. In 1998, we published two papers (Barranco & Goodman 1998; Goodman et al. 1998) showing that dense cores appear to be what we called "islands of calm in a turbulent sea." The islands, which we named "coherent cores," exhibit near-constant spectral line width, whilst their surroundings (the sea) show a line width which increases with size scale. Within these cores, we imagine that a "static" star formation scenario, like the one described by Shu and colleagues, could play out. None of the cores we studied were in clusters, but similar ideas, featuring quiescent regions embedded in a turbulent flow, have been put forth for clusters as well (e.g. Myers' "kernels"; Myers 1998). The "island" analogy is alright as long as one's thinking is restricted to a single "coherent core," and that core serves as a (fixed) frame of reference. But, in a larger frame of reference, in which the coherent cores themselves move around as entities, then "boats adrift" in a dynamic sea is a better analogy. (Islands don't move.)

Before beginning our study, is our <u>guess</u> that dynamical interactions do *not* matter when "boats" (density peaks qualifying as coherent cores) are separated by more than about half a mean free path (*l*) worth of "sea", but that interactions definitely do matter when islands are spaced much more closely than a mean free path (e.g. in clusters). We also guess that this generality may be modified when a star-forming region is overrun by either an expanding shell coming from an older star (e.g. a B-star wind or SN), or perhaps by a powerful molecular outflow from a nearby young star.

The hardest, and most interesting, question our study will address is: *In what way(s), exactly, do dynamical interactions manifest themselves in the star-forming process?* The best we can do for now is to design data-based tests (§2.3) of a variety of physically-motivated guesses as to the answer. Even if our guesses are wrong, the unbiased tests we propose will produce valuable results (e.g. unbiased censes of: outflows; of clumps; and of young star SEDs), which we feel makes the risk associated with this work worth taking.

2.2 Data Overview: COMPLETE, c2d, and More

COMPLETE The COMPLETE (**CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission) Survey of Star-Forming Regions is now well into its second year of data collection, and it is rapidly producing a bounty for the star formation community beyond what even I (as P.I. of COMPLETE) had anticipated[11]. In order to carry out the investigation proposed here, we require a tremendous amount of information on the velocity and density distribution of star-forming material over a wide range of physical conditions, and only a survey as large and unbiased as COMPLETE, which was designed for such purposes, can offer this. We also need an unbiased sample of the young

[9] I have discussed this point with both Ian Bonnell and Volker Bromm, both of whom 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.

[10] We do not mean to imply that Shu et al. or BBB hold either of these regimes in mind as purely realistic, we are just using the models to represent endpoints of a philosophical spectrum.

[11] The COMPLETE data are being made available to the public without restriction, as they are verified, at cfa-www.harvard.edu/COMPLETE.

stellar population in, and near, the complexes we will study, and only huge, systematic, surveys like 2MASS and the upcoming c2d (Cores-to-Disks) SIRTF Legacy Survey[12] can provide that.

The three target regions for our study (Perseus, Ophiuchus, and Serpens) are the three that will be covered fully under both the COMPLETE and c2d Surveys. Each target (located at distances between 150 and 300 pc) covers of order *100 square parsecs* on the sky, and can be thought of as fully encompassing a whole molecular cloud complex (see cfa-www.harvard.edu/COMPLETE for maps and details).

All of the spectral-line data we will use to analyze atomic and molecular gas kinematics will come from the COMPLETE Survey. The density fields we have already begun to derive are based on combining COMPLETE's re-processed IRAS data (Goodman et al. 2003b) with 2MASS-based extinction maps (Alves, Goodman, & Schnee 2004), and they will later be updated to include information from COMPLETE's JCMT/SCUBA program and c2d's SIRTF and CSO/BOLOCAM programs (see Table 1). The data we shall employ in locating and "age-dating" pre-stellar and stellar point sources comes from a combination of 2MASS, ground-based, and SIRTF near IR observations, JCMT/SCUBA sub-mm, CSO/BOLOCAM mm, and ROSAT and Chandra X-ray fluxes[13]. Since Perseus will be the first target to be fully studied with the methods we describe below (§2.3), we offer a list of the Perseus observations we shall employ in Table 1[14].

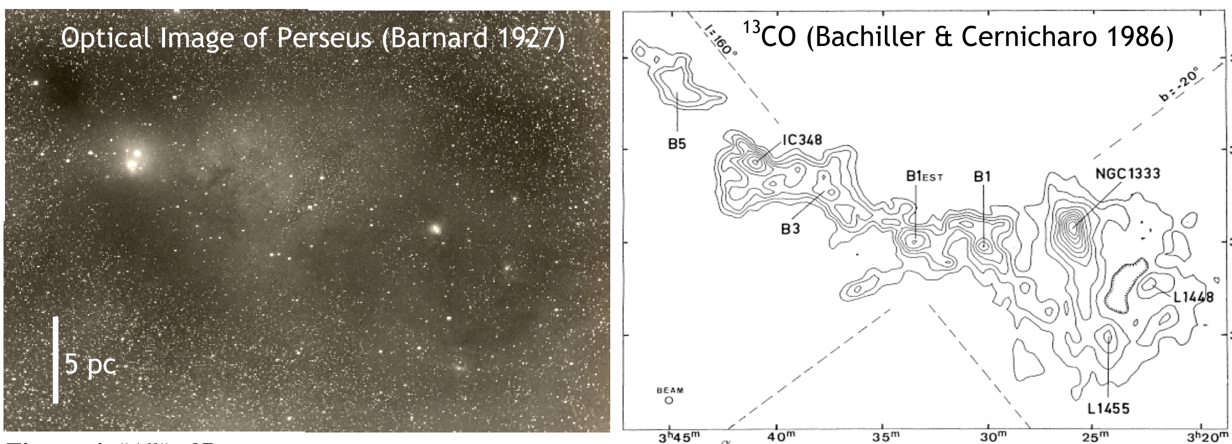

Figure 4: "All" of Perseus

It is hard to appreciate the density of data COMPLETE is producing when viewing any wide-field image of its 100 square parsec targets[15]. Figure 4 shows both Barnard's 1927 optical image of Perseus and Bachiller & Cernicharo's classic ^{13}CO map of the same field (Bachiller & Cernicharo 1986, hereafter BC). The new COMPLETE Perseus ^{13}CO map (see Table 1) has 7 times the linear resolution of BC. In other words, there are fifty pixels in COMPLETE's *lowest* resolution molecular line maps for each "BEAM" area labeled in the lower left corner of BC's map (Figure 4). Each COMPLETE ^{13}CO spectrum is twice as sensitive, and has five times the velocity resolution of the BC data. It is COMPLETE's high data density and quality that allows us to audaciously claim that we can find "every" outflow or "every" self-gravitating density peak in the regions under study.

[12] Neal J. Evans II is the P.I. of c2d, which includes using nearly every instrument on SIRTF to study the star-forming material and young stars in Perseus, Ophiuchus, and Serpens. Over the past two years, since the inception of COMPLETE, we have been working closely with Neal and his team to coordinate the data-collection in the two surveys, as well as the planned analysis.

[13] This age-dating will be primarily carried out by COMPLETE postdoctoral fellow Naomi Ridge, who is currently applying for a SIRTF fellowship, in large part to sponsor that project. Her age-dating scheme is described in detail at cfa-www.harvard.edu/~nridge.

[14] Table 1 is intended to offer expert reviewers the opportunity to understand the unprecedented wealth of unbiased data we have to draw upon. For anyone less familiar with our sub-field, we apologize for all the acronyms.

[15] Figure 7 is a minor graphical crime- showing COMPLETE's ^{13}CO integrated-intensity map, which has 73,000 independent pixels, in just a few square inches.

Table 1: Summary of Recent, Ongoing, and Near-Future Observations in Perseus

Survey[16]	**Full Coverage of Perseus**[17]	**>5 mag Peaks in Perseus**	**Selected Regions**	**Relevance Gas, Dust, ★Stars**	**When?**
^{13}CO FCRAO	COMPLETE	←[18]	←	G	**Now**
^{12}CO FCRAO	COMPLETE	←	←	G	**Now**
"Pilot" N_2H^+ & CS FCRAO			COMPLETE	G	**Now**
N_2H^+ & CS FCRAO		COMPLETE		G	2004[19]
N_2H^+ & DCO^+ IRAM 30-m		COMPLETE		G	2004[20]
H I, GBT	COMPLETE			G	2003/4[19]
NICER 2MASS-based extinction map	2MASS/ COMPLETE	←	←	D	**Now**
NICER SIRTF-based extinction map	**c2d**/ COMPLETE	←	←	D	2005[21]
NICER ground-based (8-m) extinction map			COMPLETE	D	2004/5
Zero-point corrected IRAS far-IR	COMPLETE	←	←	D	**Now**
JCMT/SCUBA 850 μm		COMPLETE	SCUBA archive	D ★	2004[22]
CSO/BOLOCAM 1 mm			**c2d**	D ★	2003/4[23]
30-m/MAMBO 1 mm		COMPLETE		D ★	2004[24]
SIRTF near through far IR imaging	**c2d**	←	←	D ★	2004/5
Ground-based photometric near-IR Cluster Surveys			NGC1333[25] IC348[26]	★	**Now**
Ground-based near-IR spectroscopic Surveys			NGC 1333[27]	★	**Now**
2MASS near IR images	2MASS	←	←	★	**Now**
"Catalog" of PMS objects[28]	2MASS	←	28	★	**Now**
ROSAT X-ray images	RASS	←	←	★	**Now**
Chandra X-ray images			NGC1333[29]	★	**Now**

[16] Any "Survey Data" listed in this table is, or will be, available in digital form, and has been taken using methods where observational selection biases are clear and easily understood.

[17] In some cases, "full" coverage for c2d means all the regions not in the GTO SIRTF program. Most GTO data will be available to us as well.

[18] Left-pointing arrows (←) emphasize that the subregions will be *included* in the wider survey.

[19] Observations approved, scheduled for Winter 03/04.

[20] High-density tracer, high resolution, observations will be proposed to the 30-m by the COMPLETE team in February 2004. The regions to be mapped will match those we are observing with MAMBO at the 30-m.

[21] The NICER algorithm will be applied to the c2d point-source catalog as soon as it is available, and this star-count based extinction map will have finer resolution (owing to the larger number of sources detected) than the map we have recently made from the 2MASS data.

[22] Observations approved, now in progress at the JCMT.

[23] Observations, by Caltech student Melissa Enoch (advisor: Anneila Sargent, c2d co-I), are ongoing at the CSO.

[24] Observations approved, to be scheduled Winter 2003/4.

[25] Lada et al. 1996

[26] Muench et al. 2003

[27] Aspin 2003

[28] While Carpenter's (2000) 2MASS survey gives (nearly) full coverage of Perseus, the point source population of the heavily extinguished clusters is better probed by the targeted near-IR cluster surveys (e.g. Lada et al. 1996; Muench et al. 2003; cf. Luhman et al. 2003) . Also the NGC1333 region of 2MASS is still unreleased.

[29] Getman et al. 2002

For the other two regions under study in COMPLETE and c2d, the coverage and quality of observations is similar, or in some cases, better, than for Perseus. For example, in Ophiuchus, we have nearly finished mapping most of the >5 mag cloud area with SCUBA, and we have already learned that dense peaks are more clustered than was previously appreciated, from just those data (see Johnstone, DiFrancesco, & Goodman 2003).

2.3 Analysis Plan

Motivated by the question: *How dynamic is star formation in a dynamical time?*, we seek to quantify the ways in which dynamical interactions manifest themselves in the star-forming process.

The easiest way to address this question would surely be to measure the velocities and distances of gas and stars, in 3-D, as functions of time, inside molecular clouds. Unfortunately, only our numerical simulation colleagues get to do this. We observers usually only get to measure the plane of the sky distribution of the radial velocity of gas at particular densities, averaged in an indirect way by radiative transfer, and the positions of stars on the plane of the sky and their spectral energy distributions, at a single point in time.

When we are unusually lucky, we can also measure stellar radial velocities and proper motions to determine stars' 3-D motions and distances. The luck is associated both with nature--optically-visible or IR-bright stars are needed for radial velocity or proper motion measurements--and with time allocation committees, who are not fond of giving away time on 8-m telescopes for radial velocity or proper motion surveys that devote hours of time to a handful of stars. Thus, with some exceptions (see §2.3.5), we will rely on *indirect* determinations of the stars' motions with respect to the gas in order to determine the significance of dynamical effects.

2.3.1 Offset vs. Age

Some of the most intuitive plots we will be able to extract from our study will look something like the mock-up in Figure 5, but with more informative and denser distributions of data points within and amongst the age bins[30]. In the Figure, we assume that we can design a legitimate measure of the plane-of-the-sky offset between a young star and the density peak from which it most likely originated. This is trickier than it may sound, so we will test a variety of methods, both for associating stars and peaks, and for defining the peaks themselves (see §2.3.2). We also expect that we can age-date the stars well enough to sort them into categories equivalent to "Class 0, I, II, III and Older (W)" stars[31]. 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[32]. (It does *not* measure how much the homes (boats) themselves move, which is an important additional question, addressed in §2.3.3, below.)

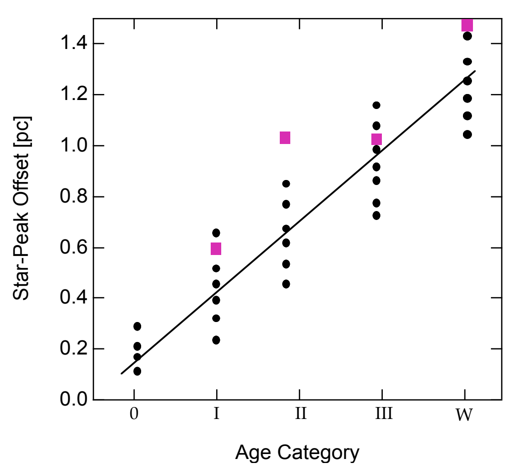

Figure 5: Plot to be used to Infer Stellar Velocity Distribution w.r.t. Gas

[30] In a region like Perseus (Figures 4 and 6), 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).

[31] Consultation with several members of the c2d and FEPS (P.I. Michael Meyer) SIRTF Legacy teams, as well as our own past research, has led us to believe that this is not an overly optimistic assumption. The Class designations here refer to those (I, II, III) originally defined by Lada (1987), with the addition of the youngest protostars "Class 0" (André, Ward-Thompson & Barsony 1993), and older sources we designate as "W".

[32] 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.

The magenta square points in Figure 5 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. 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 5 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 (see below) 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.

2.3.2 Boats at Sea

Many existing studies of relationships between stellar ages, positions, and velocities make one critically incorrect assumption. They assume, either explicitly or implicitly, that the molecular cloud distribution, as seen today, is an enduring pattern over long time scales. This is not physically likely, and we will not make this assumption *a priori* in our analysis. As we mentioned earlier, we once likened molecular cloud cores to "islands of calm" in a "turbulent sea" (Goodman et al. 1998), but we now think the cores are really better thought of as "boats," adrift on the turbulent sea.

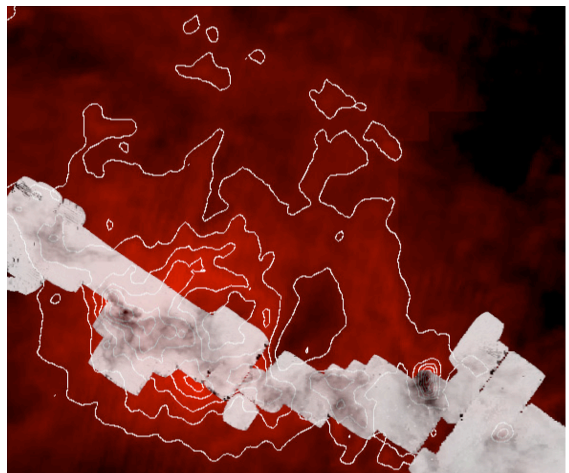

Figure 6: Warm Dust and Cold Gas in Perseus (Goodman et al. 2003a)

Thus, in order to *properly* measure the motion of stars with respect to their ancestral homes (boats), we need to measure how much the boats move as well. Both in order to do that, and in order to create plots like Figure 5, we need systematic ways of finding, and consistently defining, the "boats."

Refining the Meaning of "Boat"

Our recent work using the COMPLETE data set has shown us, in even starker contrast than we expected, the different, and very biased, answers one gets about the density distribution of star-forming clouds when it is derived from different observational measures. Figure 6 shows our velocity-integrated map of ^{13}CO in Perseus (greyscale) overlaid on our new, zero-point corrected, IRAS-based dust column density map (red w/contours). Examining Figure 4 as well, the astute reader will notice that while Barnard's image looks more like a ^{13}CO map (either ours or BC's), it has some of the IRAS look to it as well. A quantitative analysis of these results reveals that the IRAS column density map is confused by the presence of a previously underappreciated huge shell of *warm* dust, which emits more strongly than the *cold* dust associated with the *cold* gas traditionally thought of as the Perseus molecular cloud complex (Goodman et al. 2003a). The presence of this shell is of interest on its own (Goodman, et al. 2003b), especially as a "special" event of the kind alluded to in §2.3.1, but our point here is that the shell skews one's view of the cloud density distribution so that an IRAS-only measurement of column density for a random point in Perseus has a good chance of being very inaccurate as a result.

On the other hand, if one *also* has a temperature-independent measure of the dust column density, as we have in our COMPLETE/2MASS extinction maps (Alves, et al. 2004), then one can *use* the temperature sensitivity offered by far-IR thermal emission to separate density structure from temperature structure.

To find the "boats" (a.k.a. peaks) small enough to be associated with individual stars or binaries, the IRAS map's resolution is far too coarse, and SIRTF's far-IR maps will be saturated. Therefore, we will use the SCUBA and MAMBO dust-emission mapping which samples all areas in the COMPLETE target clouds where A_V>5 mag, in concert with extinction mapping based on SIRTF/c2d's point source catalog and COMPLETE's ground-based large telescope near-IR observations (see Table 1), to map out the density and temperature distribution of peaks with a resolution better than 0.03 pc in Ophiuchus, and 0.05 pc in Perseus and Serpens. Maps of the internal structure of the peaks themselves will have resolution twice as fine.

Seaworthiness

To survive in a turbulent flow for a long period of time, a "boat" needs to be seaworthy. In our case, we will interpret seaworthiness to mean having at least as much inward as outward pressure. We will evaluate the gravitational energy associated with each boat (density peak) based on its density and size, and we will evaluate its kinetic energy based on the line width observed for a density-commensurate spectral line mapped in COMPLETE (see Table 1). Only if the core appears "bound" will it be declared seaworthy. We will not define so-called pressure-confined clumps (Bertoldi & McKee 1992) as seaworthy, as their state is likely to change as they move through the turbulent sea.

Some pairs of versions of Figure 5 will differ only in whether or not we require "seaworthiness" for a density peak to qualify as the possible ancestral "boat" of a young star. If, for example, we believe that outflows put so much energy into cores as to unbind them (Arce 2003), then one can argue that seaworthiness should *not* be a necessary quality for inclusion in the list of "cores" used in producing a meaningful "Figure 5" plot.

Other ways to define boats

Choosing "boats" to be bound or unbound density peaks is only one of several ways we will experiment with in defining the relevant ancestral boats of young stars. For example, in our original work on "coherent cores," we found these cores as plateaus in spectral line width surrounded by a line width that decreased with scale size. We can use the COMPLETE data to search for such line width plateaus within valleys and define "boats" that way.

Also, since we have maps with ~100,000 spectra at our disposal, the Spectral Correlation Function (§1.1) can be (and is being) used in a wide variety of ways to find "boats" as well as to find special storms in the sea (see §2.3.4).

2.3.3 Defining Reference Frames

To define a reference frame relevant to a particular scale, we can make use of the VFIT algorithm for finding velocity gradients in spectral-line data cubes (Goodman et al. 1993). We will use a fit of the gradient in a core's lower-density (e.g. ^{13}CO) "environs" to predict what the velocity of the dense gas (e.g. N_2H^+) at a particular position would be if it matched the lower density gas (a boat adrift). The difference between the mean velocity of the dense gas associated with the core and the velocity predicted by VFIT for the core's environment at the core's position is then the velocity of the "boat" with respect to the "sea." This calculation can be made on a variety of scales, depending on how big a reference frame (sea) one wishes to consider. On the largest scale to be studied, we will define an atomic reference frame using narrow H I self-absorption features we are mapping with the GBT as part of COMPLETE.

We will use these measurements of the core-environs velocity difference to study how much cores (boats) move with respect to their environment (the sea). This motion is critical to factor into our overall characterization of the distribution of relative star-core motion, and we are particularly interested in learning whether core-environs velocity difference varies with physical conditions, such as ambient density, core mass, stellar mass, radiation field, outflow proximity, shell passage, etc.

2.3.4 Finding Outflows and Shells

In order to assess the influence of bipolar outflows and shells on star-core-cloud dynamics, we need to be sure to find and characterize "all" the outflows and shells.

We have begun a program in Perseus (Ridge et al. 2004) to combine the SCF and new visualization tools to identify "all"[33] of the large bipolar outflows in our 73,000-spectrum ^{12}CO COMPLETE data cube. This program has been remarkably successful thus far. We have recovered all of the known pc-scale outflows (~6), and discovered at least five more. In addition, we have discovered several patches of very bizarre spectra in Perseus that may be related to how the giant shell in Figure 6 relates to the molecular cloud complex.

The IRAS re-analysis included in COMPLETE turned up not just the giant Perseus shell visible in Figure 6, but also a 2-pc-wide shell, in Ophiuchus, produced by either the B-star ρ-Oph or by a non-famous, but apparently compact object-like ROSAT source associated with a cluster of young X-ray sources which also lies inside the shell (see Goodman et al. 2003a, b)[34]. The "real ρ-Oph cluster" we have identified inside the shell is actually a full *degree* (2 pc) North of what is *known as* the "ρ-Oph cluster." So, the shell is actually impinging on the dense molecular gas associated with the cluster, making it possible to compare the properties of gas and stars likely vs. unlikely to have been influenced by this shell. Both the Perseus and Ophiuchus shells will be fully-mapped in ^{12}CO and ^{13}CO at FCRAO, as part of COMPLETE, by 2005.

Thus, when the results of our already-in-progress outflow and shell projects are incorporated with the results of what is proposed here, we will indeed both be able to *identify* the regions likely to have been impacted by an outflow or shell, and to *assess the kinematic effects* of those impacts.

2.3.5 Proper Motions and Radial Velocities

We have discussed this project with many colleagues, several of whom are very interested in helping us to add some new radial velocity and proper motion measurements to this study. These measurements would have obvious utility as an addition to, and a check on, the indirect methods we shall principally rely upon. Lee Hartmann and colleagues[35] plan to use the new HectoEchelle instrument on the MMT to measure radial velocities of young stars (to ~0.5 km s^{-1}) accuracy, and they are amenable to including some COMPLETE targets in their program.

We have also been in contact with Eric Mamajek, who is in the process of investigating the feasibility of proper-motion-based estimates of distances and plane-of-the-sky velocities for stars in the COMPLETE fields--and (since young stars might have a large velocity dispersion) their surroundings. And, my graduate student, Jonathan Foster, has determined that there are a handful of young stars in Perseus whose proper motions are already measured accurately enough so as to make them interesting as calibration points. He is continuing to investigate what cataloged astrometry can do for our project (cf. Steenbrugge et al. 2003; Wichmann et al. 1998).

2.4 How Dynamic is Star Formation in a Dynamical Time?

Once the steps outlined above are taken, we will be able to tie all our measured reference frames, and the velocity distributions within those frames together, to statistically describe the motions of young stars with respect to their natal clumps, and the motions of those clumps with respect to their environments. We will be able to calculate, for particular physical conditions, an empirically-based

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[33] We will, of course, have to quantify the meaning of "all" by calculating both our sensitivity limitations due to the 40" resolution of the COMPLETE FCRAO survey as well as the effects of confusion within dense star clusters.

[34] We (Goodman, Schnee, Gaensler, Lada & Wolk) have time in the XMM queue to followup this discovery

[35] One of these colleagues is Dr. Subu Mohanty, who is especially interested in contributing to COMPLETE, possibly even as the postdoc to be funded with this grant (see §2.5).

likelihood that any particular kind of dynamic interaction (e.g. stars interacting gravitationally with other stars, clump being overrun by an outflow, etc.) will take place within any specified length of time, including the infamous dynamical time. In addition, the combination of time scales and cloud/stellar distributions we will measure will allow us to make realistic "star formation efficiency" calculations, including considerations of the time variation in the stellar and gas content in a particular region of space.

It will also be very interesting to compare our results with those of futuristic simulations that might fall in the region pointed to by the arrow in Figure 1—where Mach numbers are high enough to match reality. If all kinds of parameters—not just the SCF—match between simulation and observation (imagine that the stellar and gas density distributions also came out right!), then one could actually use the matching simulations to go forward and backward in time, and see where our empirically derived version of the star-gas-motion story fits in the whole history of a star-forming region. We would even be able to legitimately *calculate* the statistical likelihood of an event like PV Ceph being thrown out of NGC7023. Wouldn't that be great?

2.5 Personnel and Management Plan

It would be impossible for me to accomplish what is proposed here alone, or even with just the one postdoctoral fellow I seek to fund with this grant. As explained above, I am the P.I. of the COMPLETE Survey of Star-Forming Regions, which gives me ten expert collaborators (see Budget Justification) who are already in the process of deriving much of what is needed for this study from our data. Here at the CfA, there are currently two postdocs, two graduate students, one undergraduate, and one high-school student working on COMPLETE. They are:

Dr. Naomi Ridge (**Postdoctoral Fellow** funded by P.I.'s Harvard funds) *Research Interests:* COMPLETE Outflow Survey; Age-dating of Stellar Population revealed by 2MASS, c2d, and ground-based NIR imaging

Dr. Di Li (**Postdoctoral Fellow** funded by SWAS/NASA until 2004) *Research Interests* Mapping HI in COMPLETE fields, thus measuring velocity offsets and line-of-sight distribution of atomic and molecular gas.

Jonathan Foster (1st Year Harvard **Graduate Student**, funded 2003/4 by NSF/GBT grant and applying for NSF GSRF) *Research Interests:* Determining stellar motions in star-forming regions.

Scott Schnee (4th Year Harvard **Graduate Student**, funded by NSF/GSRF through 2006): *Research Interests*: Measuring the true density and temperature distribution in star-forming molecular clouds by combining thermal dust emission maps and optical and near-IR extinction maps.

Michelle Borkin (2nd Year Harvard **Undergraduate**, funded by P.I.'s Harvard funds) *Research Interests:* COMPLETE web site and database; COMPLETE Outflow Survey.

Jason Li (**High-School Student**, Great Neck, NY) *Research Interests:* COMPLETE IRAS dust-emission mapping.

In addition to these COMPLETErs here at the CfA, we have two SIRTF Legacy c2d co-I's (Drs. Phil Myers and Lori Allen) along with the P.I. of IRAC (Dr. Giovanni Fazio) and his team. My group and I have been in very close communication with the c2d team, in planning COMPLETE and in planning this proposal. I recently gave a presentation on COMPLETE at c2d's pre-launch workshop, and COMPLETE is called out in the c2d documentation as providing essential "ancillary" observations.[36] While the Legacy data (including c2d) will be made public "immediately," our cooperation with the c2d team will give us access to "beta" versions of the c2d data (and we will provide beta COMPLETE data to c2d as well)[37].

Thanks to these collaborative efforts, we can expect to have (at least) beta versions of the most essential pieces of the plan outlined above in place, for Perseus and probably Ophiuchus, by late 2004 (see detail in Table 1).

[36] See c2d's web site, at http://peggysue.as.utexas.edu/SIRTF/.

[37] For example, in one direct collaboration, the c2d team is relying in large part on the COMPLETE collaboration (J. Alves in particular) to carry out the careful extinction mapping that the c2d point source catalog will enable.

The assembly of those pieces into an answer to the question we have promised to address in this proposal requires new work, in collaboration with the postdoctoral fellow we request here, to begin in 2004. We estimate that it will take six months to understand the limitations of the data we will have available for Perseus and Ophiuchus, and hopefully improve it (e.g. by designing better data-reduction algorithms or taking additional data where quality is variable), before we can use it in the scheme outlined above.

After the data are verified, we estimate that it will take about one year to make the calculations required to offer, and properly qualify, the first answer to "How dynamic is star formation in a dynamical time?" and to publish a paper by that name. Concurrently, our group will submit several other papers featuring the fully-processed and analyzed COMPLETE data sets included in Table 1. (See "*'s" in the References.)

For the remainder of the grant period, the postdoc, students, and I, will incorporate the Serpens data (which should be ready by 2005) and compare results with those in Perseus and Ophiuchus. I expect that we will publish a summary paper on the dynamics of star formation, in 2006, near the end of the grant period.

2.6 Broader Impact

The broad impact of our work falls into two categories. The more obvious one is COMPLETE's lasting impact on astronomy. We are presently working on securing private funding to assure the accessibility and longevity of the COMPLETE database (see Budget Justification). I am the P.I. of a $0.5M NVO grant here at the CfA, and a co-I on the $10M grant administered by Caltech and Johns Hopkins. Neither I or COMPLETE receives any funding from these grants, but I am using my NVO connections to turn COMPLETE into a testbed for data archiving and visualization tools specific to spectral-line data cubes. Right now, the COMPLETE "archive" consists of FITS files freely available through our extensive web site (at cfa-www.harvard.edu/COMPLETE), but we are determined to improve this in the very near future. In addition, our URL is emblazoned on 1000 blue plastic rulers we had made last year, 800 of which we have now distributed around the world.

COMPLETE's less obvious impact has been on the public. I give about ten large public lectures per year on my work. In the past year, I have focused these lectures on COMPLETE. In the past two weeks alone I spoke to hundreds of people, first at the University of Michigan's "Cosmic Origins" series, and then at the Harvard College Fund Assembly. In both cases, the public's fascination with just how we can put information from so many unfamiliar (non-optical) techniques together with the optical data they understand was inspiring for me. Through my web site (http://cfa-www.harvard.edu/~agoodman/) one can find on-line versions of all of these talks, as well as a link (at http://cfa-www.harvard.edu/COMPLETE/news.html) encouraging amateur astronomers to contact us with questions. I have many e-pen pals as a result! The video of the NASA/SIRTF Press Briefing where I served as the "Star and Planet Formation" expert on the Science Panel is online at http://www.jpl.nasa.gov/webcast/sirtf/30.cfm, minutes 13-20.

At Harvard, I teach a course entitled "The Visual Display of Quantitative Information," and I am deeply committed to making all astronomical data, not just COMPLETE, accessible and understandable by experts and non-experts alike.

I also enjoy writing about science for the public. I have recently agreed to follow up the Sky & Telescope cover story (*Recycling in the Universe*) I wrote a few years ago with a long piece on *Dynamical Star Formation*, based in large part of the issues discussed in this proposal, to appear in 2004.

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BIOGRAPHICAL SKETCH FOR ALYSSA A. GOODMAN, NOVEMBER 2003

Education

Sc.B. in Physics, MIT, 1984; A.M. in Physics, Harvard, 1986; Ph.D. in Physics, Harvard, 1989

Recent Academic Experience

1999-	Professor of Astronomy, Harvard University
2001-2002	Visiting Fellow, Yale University *(Sabbatical)*
1996-1999	Associate Professor of Astronomy, Harvard University
1992-1996	Assistant Professor of Astronomy, Harvard University
1995-1997	Head Tutor, Harvard University Astronomy Department
1995-	Research Associate, Smithsonian Astrophysical Observatory
1989-1992	President's Fellow, University of California, Berkeley

Recent Honors and Awards

2004	Sturm Lecturer, Wesleyan University
1998	Bok Prize, Harvard University
1997	Newton Lacy Pierce Prize, American Astronomical Society
1994-1999	National Science Foundation Young Investigator
1994	Pedagogical Innovation Award, Harvard University
1993-1995	Alfred P. Sloan Fellow

Society Memberships

AAS; IAU; URSI Commission J (Radio Astronomy); AAAS; AAUP

External Advisory & Review Committee Work (Past 5 Years)

AAS Publications Board; NSF-Galactic Astronomy Panel Reviews (Chair); National Academy of Science's Committee on Astronomy and Astrophysics; SIRTF Legacy Projects for Galactic Astronomy (Panel Chair); AAS Committee on Astronomy and Public Policy; NRAO Director Search Committee; M4 Satellite Science Advisory Group (Chair); NRAO VLA-VLBA Proposal Reviewer; US Square Kilometer Array Consortium (Harvard Representative); SIRTF Science Center Oversight Committee (2003-)

Relevant Recent Publications:

Arce, H.G. & Goodman, A.A. 1999, *An Extinction Study of the Taurus Dark Cloud Complex*, ApJ, 517, 264.

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Sample Synergistic Activities

AG serves as a member of the SIRTF Science Center Oversight Committee (SSCOC).

AG is P.I. on an NSF Grant to a large group at the CfA developing the "Data Model" for the National Virtual Oberavatory, and Co-I on the $10M NSF NVO grant to the team headed by researchers at Caltech and STScI/Johns Hopkins.

AG and John Huth (Professor of Physics, Harvard) lead a team of nearly 20 faculty requesting the formation of a "Center for Advanced Scientific Computing" at Harvard.

AG maintains an unusually extensive web page, which includes a section called *Information for the General Public*. The links in that section run the gamut from descriptions of star formation to "What do I need to know to become an astrophysicst?" to a hyperlinked table of all of AG's talks and presentations. See http://cfa-www.harvard.edu/~agoodman/.

AG enjoys giving public talks and popularizing science in general. Recent public talks include: *The Multiwavelength Universe* (Hayden Planetarium, New York); *Order, Chaos, and the Space Between Stars* (Boston Museum of Science); *Mapping the Interstellar Medium* (Annual meeting of New England Amateur Astronomers); *A Dynamic View of Star Formation* (Joint meeting of the APS and the American Association of Physics Teachers); *Lifting the Dusty Veil* (CfA Public Observatory Night); *A Recipe for Star and Planet Formation* (Cosmic Origins Series at the University of Michigan); and *A COMPLETE Search for New Suns* (Harvard College Fund Assembly). In March of 2003, AG was one of four scientists on a panel assembled by NASA to speak and answer questions about SIRTF's science at the "Launch-30" SIRTF Press Briefing.

Collaborators within Past 48 Months:

Joao Alves, ESO, Germany
Héctor Arce, Caltech
Javier Ballesteros-Paredes, UNAM (Mexico)
Paola Caselli, Osservatorio Arcetri, Italy
James DiFrancesco, HIA, Canada
Bruce Draine, Princeton University
Jonathan Foster, CfA
Lincoln Greenhill, CfA
Carl Heiles, UC Berkeley
Mark Heyer, FCRAO/UMASS
Doug Johnstone, HIA, Canada
Mika Juvela, Helsinki University Observatory (Finland)
Sungeun Kim, CfA
Helmuth Kristen, Sweden
Kishore Kuchibhotla, MIT
Di Li, CfA
Åke Nordlund, Copenhagen Astronomical Observatory
Paolo Padoan, UCSD
Örnólfur Einar Rögnvaldsson, Nordic Institute for Theoretical Physics (Denmark)
Naomi Ridge, CfA
Erik Rosolowsky, UC Berkeley
Karin Sandstrom, UC Berkeley
Scott Schnee, CfA
Lister Stavely-Smith, ATNF (Australia)
Mario Tafalla, OAS, Spain
Enrique Vazquez-Semadeni, UNAM (Mexico)
Jonathan Williams, University of Hawaii
David Wilner, CfA
Tom Wison, MPIfR, Bonn
Qizhou Zhang, CfA

Graduate Advisor:

Philip Myers, CfA

Students Advised

(*=currently a graduate student at listed institution):

Jonathan Foster*, Harvard
Kishore Kuchibhotla*, Harvard
Scott Schnee*, Harvard
Erik Rosolowsky*, UC Berkeley
Dr. Javier Ballesteros-Paredes, UNAM
Michelle Borkin, Harvard
Dr. Héctor Arce, Caltech
Joseph Barranco*, UC Berkeley
Dr. Sheila Kannappan, DAO
Dr. Subu Mohanty, CfA
Karin Sandstrom*, UC Berkeley
Dr. Matthew (Chip) Sumner,* Caltech

BUDGET JUSTIFICATION

In this proposal we seek funding *only* for the "dynamic" analyses described here, not for the general COMPLETE Survey.

At the moment, we have no United States Government funding for the COMPLETE Survey, other than $32K for a graduate student to participate in COMPLETE's GBT program[1]. While our COMPLETE **observing proposals have had a 100% acceptance rate** (see Table 1), our funding proposals have effectively been bounced back and forth between the NSF and NASA. In 2002, the NSF told us that COMPLETE was too expensive and that reviewers were skeptical of our ability to get the data required, **most of which are now in-hand**. In 2003, an NSF proposal based on COMPLETE data was given "excellent" reviews, except by one reviewer who was skeptical at the time of NASA's ability to successfully launch SIRTF. Now SIRTF is orbiting the Sun and working perfectly (knock-on-wood). When we proposed COMPLETE to NASA's LTSA program—at the suggestion of Tom Soifer, SIRTF Science Center Director—we were told (as we feared would happen) that it was a great idea, but too ground-based for NASA to fund, even if it is in *direct* support of a NASA mission. In those three past proposals[2], we included dozens of letters showing strong community support for COMPLETE, including several from the c2d team members, and from Neal Evans II, the c2d P.I. In this proposal, we have not included these letters, as COMPLETE's value is now known to much of the community. If, however, reviewers or the NSF would like to see such letters, or would like to contact any of the letter-writers directly, we will be happy to facilitate that.

At present, we are in the process of attempting to secure $1M in *private funding* (through the Harvard University Development Office) to be used in establishing a sophisticated archive and retrieval system for the COMPLETE data set. If those efforts succeed, we plan to leverage the NVO efforts here at the CfA by using COMPLETE as a showcase for online access to large surveys that are not part of a NASA "mission." We will also rename the COMPLETE Survey after the donor.

The COMPLETE Survey team (not including graduate students), as of now, is comprised of the following investigators, with the following primary operational responsibilities:

1. Joao **Alves** (European Southern Observatory, Germany) *Extinction mapping lead.*
2. Héctor **Arce** (Caltech, USA) *Outflow finding algortithms.*
3. Paola **Caselli** (Osservatorio di Arcetri, Italy) *High-resolution spectral-line mapping lead.*
4. James **Di Francesco** (Herzberg Institute for Astrophysics, Canada) *Thermal emission mapping, spectral-line mapping.*
5. Alyssa **Goodman** (Harvard-Smithsonian Center for Astrophysics, USA) *P.I.*
6. Mark **Heyer** (Five College Radio Astronomy Observatory/UMASS, USA) *Wide-field spectral-line mapping. Comparisons with numerical simulations.*
7. Doug **Johnstone** (Herzberg Institute for Astrophysics, Canada) *Wide-field thermal-emission mapping lead.*
8. Di **Li** (Harvard-Smithsonian Center for Astrophysics, USA) *HI lead.*

[1] My foreign collaborators are using their respective institutions' "internal" funding for their and their students' COMPLETE efforts, but none of them has any large-scale government funding for COMPLETE either.

[2] All of our funding and observing time proposals are available online at cfa-www.harvard.edu/COMPLETE.

9. Naomi **Ridge** (Harvard-Smithsonian Center for Astrophysics, USA) *Application of the SCF to COMPLETE data; c2d liason and interim data-archive manager.*
10. Mario **Tafalla** (Observatorio Astronómico Nacional, Spain) *High-resolution thermal emission mapping lead.*
11. Thomas **Wison** (Max-Planck-Institut für Radioastronomie, Germany) *Targetted spectral-line followup of COMPLETE high-resolution sourcelist.*

In **Year 1** (FY05[3]) of the budget, we request **1.5 months of Summer Salary** for the P.I., the cost of a **postdoctoral fellow,**[4] and $5.7K toward paying **undergraduate researchers**. Dr. Naomi Ridge, who joined us in September 2003, is currently the only "COMPLETE" postdoc here at the CfA. In calculating this budget, we assume that Dr. Ridge's application for a SIRTF postdoctoral fellowship, to begin in FY05, will be successful. The postdoc funding we request in Year 1 is for an additional postdoc, who would work specifically on the new "dynamical" analysis proposed here[5]. We have had great success with undergraduates as research assistants to date, so we plan to employ one or two (including Harvard student Michelle Borkin, who already works with us), for a total of 360 work hours during FY05.

In addition to salaries, we request the following in Year 1:

> $5500 to be used to **upgrade the memory and storage** on our existing large UNIX workstations. This yearly upgrade is necessary to hold and manipulate the large data cubes (e.g. tens of thousands of spectra) that are utilized by the analyses described in the proposal (e.g. the SCF).
>
> $10,400 in **travel expenses**. The money will fund ~2 inter-continental trips (1 for visits with/by European COMPLETE collaborators and 1 for observing) plus approximately 5 domestic trips (1 for conference attendance, 2 for observing, and 2 for collaboration with US/Canadian COMPLETE collaborators).
>
> $1500 toward **materials and supplies**, to be used for software upgrades and license fees.
>
> $3500 in **publication costs**, to be used for page charges on approximately 35 pp/year at $100/page
>
> **indirect costs ("F&A")**, calculated as 64% of direct costs, excluding equipment over $5K
>
> **salaries and other costs** are increased by 3% each year

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[3] FY05=July 1, 2004 through June 30, 2005.

[4] The fringe benefit rates at Harvard for FY05 are 27% for faculty, 23% for postdocs, and 11.1% for undergraduates, for FY06 rates are 28% for faculty, 24% for postdocs, and 11.1% for undergraduates, and for FY07 rates are 29% for faculty, 25% for postdocs, and 11.1% for undergraduates. Graduate student benefits would not be charged to this grant.

[5] We will advertise the new postdoc position widely, but rest assured that we already have three excellent candidates—Eric Mamajek (stellar proper motion and YSO expert), Subu Mohanty (stellar radial velocity and YSO expert), and Di Li (spectral-line expert)—each of whom is confident this proposal will be funded and would like work on the project we describe here.

In **Year 2** (FY06), the number of personnel involved in this project at the CfA is not expected to change.

In addition to salaries in Year 2, we request the same items as in Year 1, with the addition of small increments to our materials and supplies, travel, and publication cost requests. The overhead rate at Harvard in FY 06 will be 64%.

In **Year 3** (FY07) no postdoc funding is requested. We expect that the postdoctoral fellow will want to stay through this third year, rather than finishing remaining collaborative work long-distance. To make that possible, we will have to seek separate funding for the postdoc for Year 3. Frankly, if we include a third year in this proposal, the total budget we would request from the Galactic Astronomy program would be too far out of line with what we know you can afford. Since Scott Schnee's external graduate student fellowship expires in 2006, and we would like to keep a graduate student involved in this work, we also request 12 months of **graduate student support** in Year 3.

In addition to salaries in Year 3, we request the same items as in Year 2. The total **indirect costs** for Year 3 are calculated at a rate of 64%.