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 03-2 **NSF 03-2**	FOR NSF USE ONLY NSF PROPOSAL NUMBER **0307708**
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) **AST - GALACTIC ASTRONOMY PROGRAM**	

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
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042103580	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE **Harvard University**	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE **Harvard University** **1350 Massachusetts Ave.** **Cambridge, MA. 021383826**
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IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)	☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION	☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS	☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Bubble, Rubble, Roil, Trouble: Analyzing Motions with the COMPLETE Survey of Star-Forming Regions**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 405,937	36 months	07/01/03	

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.6)
- ☐ HISTORIC PLACES (GPG II.C.9)
- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.C.11)
- ☐ VERTEBRATE ANIMALS (GPG II.C.11) IACUC App. Date ________
- ☐ HUMAN SUBJECTS (GPG II.C.11) Exemption Subsection ______ or IRB App. Date ________
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.9) ________
- ☒ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)

PI/PD DEPARTMENT **Harvard College Observatory**	PI/PD POSTAL ADDRESS **Harvard University Astronomy Department** **60 Garden Street--MS 42** **Cambridge, MA 02138** **United States**
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CO-PI/PD				
CO-PI/PD				

Electronic Signature

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 03-2. 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.

Drug Free Work Place Certification

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 A of the Grant Proposal Guide.

Debarment and Suspension Certification

(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 ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix B of the Grant Proposal Guide.

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.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME Paula Sciabarrasi	Electronic Signature	Nov 15 2002 3:11PM

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER
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*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

BUBBLE, RUBBLE, ROIL, TROUBLE: ANALYZING MOTIONS WITH THE COMPLETE SURVEY OF STAR FORMING REGIONS

Alyssa A. Goodman, Harvard University

We will investigate how the systematic gas motions produced as a by-product of star formation effect the productivity and longevity of the molecular clouds where stars form.

The proposal is comprised of three related projects. In Project 1, we will create an "Environmental Impact Statement" assessing the role outflows from young stars upon their ancestral homes. In Project 2, we will follow up on new discoveries made in collaboration with a high school student that show supernova-remnant-like shells actively sculpting molecular clouds. In Project 3, we will use information from a new catalog (compiled by the US Navy's astronomers) to compare stellar and gas motions in molecular clouds. The combined results of the three projects will give an excellent picture of just how, and when, the stars that form in molecular clouds destroy old, and create new, star-forming material.

Each of these three projects will utilize data from both the <u>CO</u>ordinated <u>M</u>olecular <u>P</u>robe <u>L</u>ine <u>E</u>xtinction <u>T</u>hermal <u>E</u>mission (COMPLETE) Survey of Star-Forming Regions and the SIRTF Cores-to-Disks (c2d) Legacy Survey. The PI of the proposed work is also the PI of the COMPLETE Survey, which is presently underway. SIRTF is scheduled to launch in January 2003. The raw and processed data from both surveys are to be released, online, as their quality is validated.

Combining data from surveys as large as COMPLETE and c2d represents an unprecedented opportunity in star-formation research, and the questions we offer for study in this proposal are truly only a tiny sample of what we expect will be done with the data over the coming decades.

COMPLETE is a demonstration project for the NSF-sponsored National Virtual Observatory, which will highlight its resources for the astronomy community, and for the public as well. The internationaly-based COMPLETE team is publicizing the utility of the Survey the world over, and offering many public lectures on its value and results. The COMPLETE web site, at cfa-www.harvard.edu/COMPLETE, offers updates on the project and unrestricted access to new data as it becomes available. Several students (high-school, undergraduate, and graduate) have been, and will be, involved in this work.

When the project is completed, we expect to place fundamentally new constraints on the output of molecular clouds over time, and upon the lifetime of the clouds themselves. These constraints will be of interest to astronomers studying galactic evolution and cosmology, as well as to those studying star formation in the local Milky Way.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

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.

BUBBLE, RUBBLE, ROIL, TROUBLE: ANALYZING MOTIONS WITH THE COMPLETE SURVEY OF STAR FORMING REGIONS

Principal Question: How do the systematic gas motions produced as a by-product of star formation effect the productivity and longevity of molecular clouds?

This proposal describes research designed to exploit the wealth of kinematic data being produced by the molecular spectral-line mapping portion of the **COMPLETE** (COordinated Molecular Probe Line Extinction Thermal Emission) Survey of Star-Forming Regions. The COMPLETE Survey is a large collaborative effort under which three of the five extended (~40 pc^2) star-forming regions to be covered by the SIRTF Legacy **c2D** (Cores-to-Disks) Survey will be mapped in molecular line emission, extinction, and thermal emission from dust.[1] The c2d Survey will produce a full, unbiased, census of the stars in the same regions, giving a wealth of information on the masses, ages, and disk properties of the embedded young sources. A host of questions never before answerable in a statistically meaningful way will be addressable by the combination of the COMPLETE and c2d Surveys, thanks to their unprecedented sensitivity and spatial coverage.

The new work proposed here (see p. 5) includes: 1) evaluating the true role of parsec-scale outflows in the life history of a molecular cloud; 2) estimating the constructive and destructive effects of bubble-producing agents (e.g. SNe) inside molecular clouds; and 3) tracking down all the stars produced in a given star-forming region, and understanding their motions over time.

We begin the proposal with several pages devoted to a description of results from prior NSF support that motivate the current proposal.

Results from Prior NSF Support as Motiviation for the Proposed Project

I have been Principal Investigator on three NSF grants since 1994: a 5-year **Young Investigator Award**; a 3-year Galactic Astronomy Grant called **How the Interstellar Medium Moves**; and a 3-year Information Technology Research Grant entitled **Development of the Data Model for the National Virtual Observatory**.[2] In this section, I focus only on recent work most directly relevant to the new research described in this proposal.[3]

No simple, analytic, model can describe the distribution of gas in a galaxy on scales from 10's of kpc to thousands of A.U. Careful work, utilizing a wide variety of observing and modeling techniques, has shown that at best certain scales can fairly be described as "dominated" by certain physical processes. **Table 1**, on the next page, shows a scale-ordered list of constituents of a neutral interstellar medium. My working hypothesis on the relevance of specific physical processes to each scale/phenomenon is shown in the last column of the table. In essence, I think: gravitationally-driven instabilities dominate the distribution of molecular gas on galactic scales; ram pressure from SNe and outflows "shapes" the outer boundaries of clouds on 100-1 pc scales; magnetohydrodynamic turbulence dominates the "internal" structure of clouds on 100-0.1 pc scales; and that the dissipation of turbulence on 0.1 pc scales leads to the formation of the self-gravitating (e.g. "coherent") cores that ultimately gravitationally collapse (and sometimes fragment) to form individual stars or groups of stars[4]. The projects that formed the basis of this working hypothesis are briefly described below.

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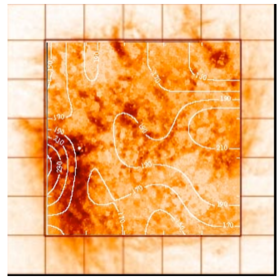
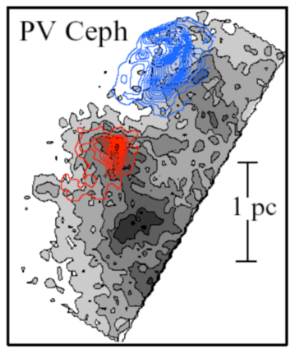
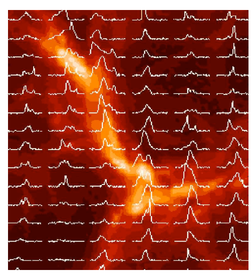
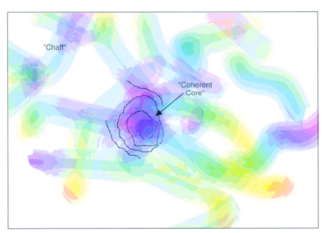
[1] Alyssa Goodman is the P.I. of COMPLETE, and Neal Evans (U. Texas) is the P.I. of c2d. A full list of COMPLETE collaborators is given in the Budget Justification.

[2] I am also one of many co-investigators on the larger ($10M) NSF/ITR NVO grant.

[3] For a fuller picture of recent research accomplishments please see cfa-www.harvard.edu/~agoodman.

[4] While this view may not exactly be a "standard model," I think the community is quickly reaching a consensus its overall outlines. It is similar to the ideas put forward by Bruce Elmegreen in his January 2002 AAS Heineman Prize Lecture (Elmegreen 2002).

Table 1: Dominant Processes in the Neutral ISM

Scale	Phenomenon Recent Work by P.I.		Dominant Physical Structuring Process(es)
~1 to 10's of kpc	**Arrangement of Neutral Gas within a Galaxy** Padoan et al. 2001c; Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2002		"Galactic Dynamics," driven by **Gravity** (i.e. spiral density waves)
~10's to 100's of pc	**Overall Structure of Giant Molecular Clouds, Cloud Complexes** Arce & Goodman 2001 a,b; 2002 a,b		**Ram Pressure** and **Shocks** from Powerful Explosions, Winds and Outflows (e.g. SNe, GRBs, expanding HII regions, pc-scale YSO outflows)
~tenths to 10's of pc	**Internal Structure of Molecular Clouds** Arce & Goodman 1999a,b; Rosolowsky et al. 1999; Padoan et al. 2001b; Padoan et al. 2002		Compressible Magnetohydrodynamic **Turbulence**
1000's of A.U. to tenths of pc	**Internal Structure of Star-forming "Cores"** Barranco & Goodman 1998; Goodman et al. 1998; Schnee et al. 2003		**Hydrostatic Equilibrium, Gravitational Collapse**

The Spectral Correlation Function

In 1998, I was awarded an NSF Galactic Astronomy grant to study "How the Interstellar Medium Moves," using a new algorithm I had developed, called the "Spectral Correlation Function" (SCF). This algorithm measures how the properties of spectra vary as a function of position and/or scale, and has now been used very successfully in a variety of applications, both by our group and several others.

Applying SCF diagnostics to both observed and simulated spectral-line maps of interstellar clouds, we have been able to determine which physical inputs to simulations are most important for "matching" various observed cloud properties (Rosolowsky et al. 1999; Padoan, Rosolowsky & Goodman 2001). The 3rd figure down in Table 1 shows a small grid of ^{13}CO spectra synthesized by applying a Monte Carlo radiative-transfer code to the output of MHD simulations, overlaid on a ^{13}CO column density map from the same simulation. By comparing this kind of synthetic spectral line map to observed maps, Padoan, Goodman & Juvela (2002) show, somewhat surprisingly, that *MHD models, especially those with relatively weak magnetic fields, can do a very good job of approximating the structure of molecular clouds on ~10-pc scales, without including self-gravity*. In Ballesteros-Paredes et al. 2002, we show that even the best existing simulations of the atomic ISM are very inadequate when the effects of thermal pressure are not taken into account correctly. In molecular clouds, the temperatures are very low, and the thermal line width is typically a tiny fraction of the total observed width. So, it is not surprising that inaccurate modeling of heating, cooling, and thermal broadening does not effect synthetic molecular-line maps much at all.

By applying the SCF to an unprecedentedly large and sensitive H I map of the LMC (Kim et al. 1998; Kim, Staveley-Smith, & Sault 2001), we mapped out the thickness of this nearly-face-on galaxy, by finding the spatial scale at which the spectral correlation becomes inconsistent with three-dimensional turbulence (Padoan et al. 2001c).[5] The top inset figure in Table 1 shows our derived contour map of galactic thickness superimposed on Kim et al.'s HI map of the LMC. Note the "puffing out" of the LMC evident near the 30 Doradus region (lower left of the figure).

The impact[6] of the SCF has now reached beyond astrophysics, to fire fighting and air safety. A graduate student in Wyoming studying ways to improve the fighting of forest fires through spectral imaging discovered the SCF through its web site [7], and was able to download the IDL code and start using it on "fire pollutant" measurements right away. In addition, I am working, in collaboration with the Harvard Development Office, with commercial firms interested in investigating the real-time application of the SCF using Doppler radar and/or lidar installed in the nose cones of large jets. The hope is that the SCF could instantly identify areas showing abrupt spectral changes, indicative of wind shear, in the (coarsely-resolved) spectra measurable with futuristic radar systems.

The Effects of Giant Outflows from Young Stars on the ISM

As Table 1, our SCF work, and the work of many others show, turbulence plays a large role in shaping structures smaller than GMCs but larger than star-forming cores in the neutral ISM. Yet turbulence in these regions dissipates in roughly a free-fall time without being driven (Mac Low 1999; Padoan & Nordlund 1999; Stone, Ostriker, & Gammie 1998). So, depending on how fast stars form, maintenance of a turbulent state may require driving. Outflows from young stellar objects (YSOs) have long been suspected to be a player in this driving (e.g. Armstrong & Winnewisser 1989), but often seemed to fall just a bit short of "energetic significance." In the late 1990's, however, when "giant" (many-pc scale) Herbig-Haro flows were shown to be common (Reipurth, Bally, & Devine 1997), it seemed a good time to reconsider the impact of YSO outflows on molecular clouds.

In the articles resulting from Dr. Héctor Arce's thesis on "The Impact of Giant Stellar Outflows on Molecular Clouds," we offer the following conclusions:

Within the large plane-of-the-sky region covered by a pc-scale flow, flow kinetic energy densities range from comparable to the average in the surroundings to more than enough to completely destroy and/or reshape the host "cloud" (Arce & Goodman 2001a; Arce & Goodman 2002b).

Some features of molecular clouds are *entirely* due to the action of the outflow. For example, *all* of the molecular gas due north of PV Ceph (see outflow figure in Table 1) is at blue-shifted velocities: there is no "ambient" cloud (grey shading in the figure) there—the cloud *is* the outflow. (Arce & Goodman 2002b)

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[5] The (tiny) figure at the top of Table 1 illustrates our map of LMC thickness determined in this way.

[6] Following NSF guidelines, we have interleaved information about the broader impact or our work with information on its scientific impact. To aid reviewers, we have highlighted this information in yellow.

[7] For this site, and all others related to specific research projects, reviewers can find the links at http://cfa-www.harvard.edu/~agoodman/research.html. My entire web site is maintained by Harvard Astronomy undergraduate Michelle Borkin, who first came to work with me when she was a Boston-area high-school student.

Flows are highly variable on many timescales simultaneously ("episodic," Arce & Goodman 2001b; Arce & Goodman 2002a), making estimation of the full impact of an individual flow over its lifetime extraordinarily difficult. The COMPLETE census of outflowing gas (see p. 8) combined with statistical estimates of flow variability will make this problem tractable.

Analysis of the spatial positions of shocked-gas ("HH") knots in the flow from PV Ceph, along with a variety of other evidence based on molecular-line observations, indicate that the YSO PV Ceph is moving at ~10 km s^{-1} with respect to its surroundings (Goodman & Arce 2002). Given the typical velocity dispersion in the gas out of which PV Ceph formed (<2 km s^{-1}), a 10 km s^{-1} velocity is almost certainly the result of one or more gravitational interactions between PV Ceph and (former) companions. This new result raises a host of questions concerning the provenance astronomers assign to young stars, and motivates the research described on p. 14.

Coherent Dense Cores

Since stars are spherical, and gravity is a radial force, we *know* that the chaotic turbulent nature of the ISM must fundamentally change at some scale larger than a star and smaller than the smallest bit of molecular gas we would still call "turbulent." We believe that this "transition to coherence" occurs at a scale where the (self-) gravitional energy of a density fluctuation formed by a chance compression (e.g. Padoan et al. 2001b) in a turbulent flow is enough to compete with magnetic and turbulent pressures striving to stop this fluctuation from collapsing. Observationally, we have found clear evidence for this transition at a scale of about ~0.1 pc, by studying the behavior of velocity dispersion on scale within very deep spectral-line maps of individual star-forming cores in non-cluster-forming cores (Barranco & Goodman 1998; Goodman et al. 1998).[8]

Extinction Structure in Dark Cloud Regions

In 1999, Héctor Arce and I published a comprehensive paper entitled "An Extinction Study of the Taurus Dark Cloud Complex" (Arce & Goodman 1999a). In that paper, we created four different kinds of extinction profiles along strips through the Taurus clouds, based on: 1) our own optical spectroscopy and photometry; 2) star-counting, using our own photometry; 3) average color excess[9]; and 4) thermal emission from dust as mapped by IRAS. We were very surprised to learn how well method #1 agreed with the others, as we had anticipated at least a few wild deviations of the "pencil beam" extinction measurements from the smoother measurements offered by the other techniques. We also showed that the other three extinction-mapping methods agreed to within ~5%, when properly calibrated. In a short *Letter* (Arce & Goodman 1999b), Héctor and I showed that our extinction profiles for Taurus showed 50% discrepancies in regions with A_V>0.5 mag when compared with the COBE/IRAS-based all sky extinction maps of cosmologists Schlegel, Finkbeiner, and Davis (1998; "SFD"). In the *Letter, we* identified the statistical flaw in SFD's analysis that led to this discrepancy, and the SFD models have since been improved, in part to reflect our findings (Finkbeiner, Davis, & Schlegel 1999).

The Role of Magnetic Fields in Molecular Clouds

In the early 1990's, my colleagues and I showed that mapping the polarization of background was *not* a valid way to reliably map the magnetic field in dark clouds, despite its prior popularity (including with us!) in that regard (Goodman et al. 1992, 1995). Our results implied that polarization mapping would only be reliable as a magnetic field probe in "low density" regimes. In 1998, we quantified the boundary between "low" and "high" extinction regions in this regard, showing that the percentage polarization begins fail to

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[8] The bottom-most figure in Table 1 shows a highly schematized version of the formation of a coherent core.

[9] The average color-excess technique we used is based on the work of COMPLETE collaborator João Alves, who helped develop the NICE (Lada, Alves, & Lada 1999; Lada et al.) and NICER (NICE Revisited, Lombardi & Alves 2001) extinction mapping methods that will be applied to the COMPLETE data.

rise with extinction *only* when the local extinction exceeds A_V~1.4 mag (Arce et al. 1998). This result agrees with theoretical indications that the grain alignment processes responsible the observed polarization also fail at this threshold (e.g. Lazarian, Goodman, & Myers 1997).

More recently, the amount of polarization of thermal emission from dust has, similarly, been shown to rise more slowly than expected at density peaks within molecular clouds (e.g. Henning et al. 2001; Matthews & Wilson 2002; Weintraub, Goodman, & Akeson 2000 and references therein). Using the same simulations employed in our SCF analyses, we have shown that geometric effects *cannot* explain the observed "polarization holes" and that a drop in grain alignment efficiency must once again be responsible (Padoan et al. 2001a).

Given my intimate knowledge of just how deceiving aligned-dust polarimetry can be, and how difficult Zeeman measurements are (Crutcher et al. 1993; Goodman et al. 1989; Troland et al. 1996) in molecular clouds, I have decided, for now, to confine my evaluation of the magnetic field's role in star forming regions to less direct, but perhaps more reliable probes[10]. For example, in applying the SCF to COMPLETE data, varying the field energy in comparison simulations will offer critical tests of the field's role.

End of "Results from Prior NSF Support"

Introduction to the Proposed Research

The **COMPLETE** (COordinated Molecular Probe Line Extinction Thermal Emission) **Survey of Star-Forming Regions**, in conjunction with the **c2d** (Cores-to-Disks) SIRTF Legacy Survey, will offer the opportunity to address some of the most important open questions about the star formation process in galaxies, such as:

How much of an effect do parsec-scale outflows from young stars have on the lifetime and stellar output of a molecular cloud?

Are molecular clouds created by giant explosions in the interstellar medium, destroyed by them, or both?

What is the star-formation efficiency of molecular gas, and (how) does it change over time?

What is the star-forming lifetime of a molecular cloud, and what becomes of its progeny?

Below, after a quick introduction to COMPLETE, we describe our plans to: 1) write an **Environmental Impact Statement on Outflows** (p. 9); 2) evaluate the importance of **expanding shells** in determining the structure of molecular clouds (p. 11); and 3) infer the **spatial and velocity distribution of stars** formed in a given molecular cloud, as a function of time (p. 14).

Origin and Status of The COMPLETE Survey

COMPLETE was conceived at the Summer 2001 Santa Cruz Star Formation workshop, as the result of discussions amongst Alyssa Goodman, João Alves, Paola Caselli, James di Francesco and Doug Johnstone. The discussions began, early in the meeting, with our lamenting what a shame it was that no two groups ever seem to choose to observe the same large region(s) with their latest-and-greatest observational technique. While molecular lines gave kinematics, extinction-mapping charted column density, and sub-mm maps gave wonderful estimates of dust temperature and column density, the *lack of coordination* amongst groups meant no one could ever intercompare results of these different kinds measurements over large swaths of sky.

[10] The obscure but useful "Chandrasekhar-Fermi" method for estimating field strength based on polarimetric and velocity dispersion has also given good results when used in conjunction with correction factors based on applying the same technique to synthesized polarization maps (Ostriker, Stone, & Gammie 2001; Sandstrom & Goodman 2002).

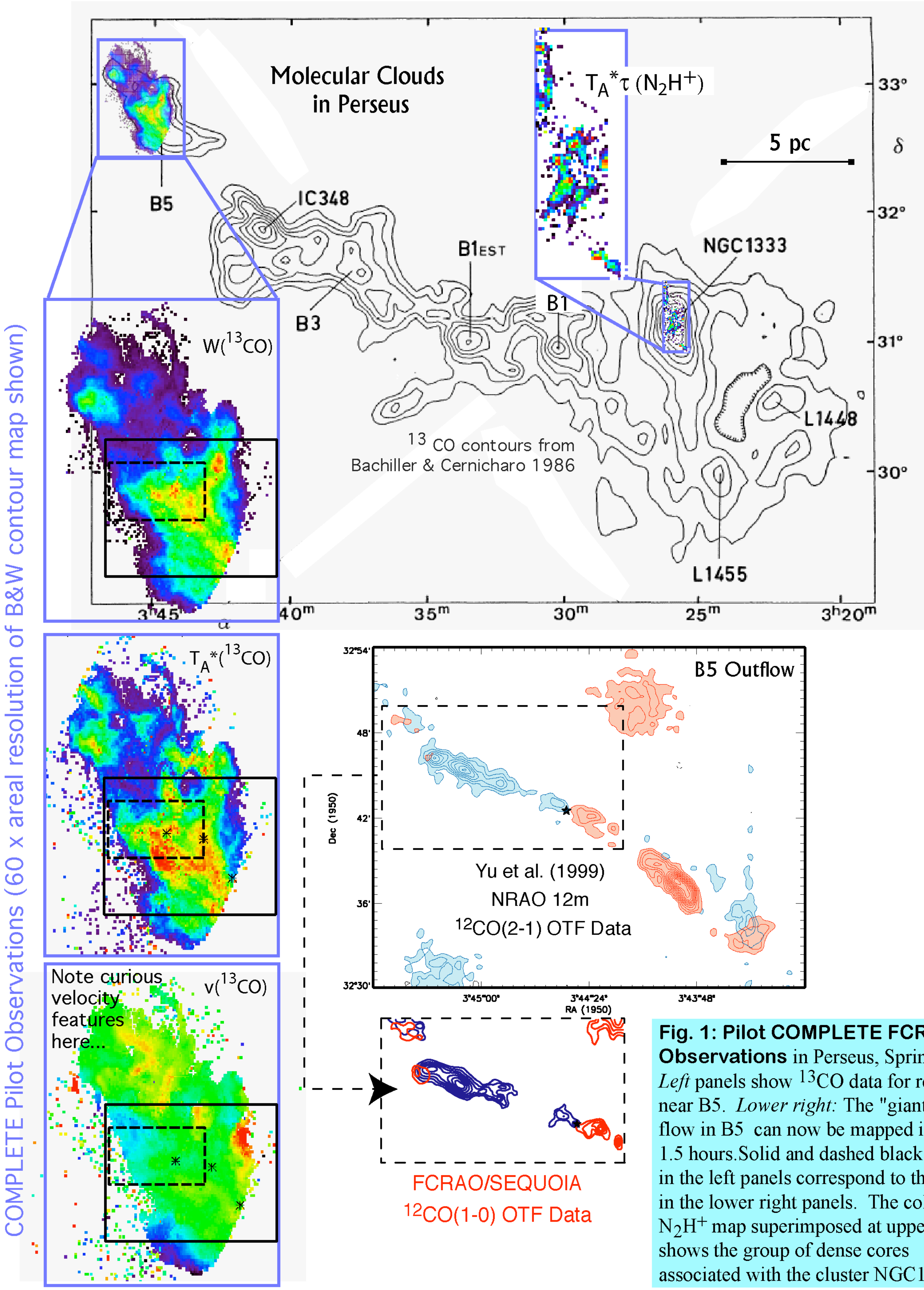

Fig. 1: Pilot COMPLETE FCRAO Observations in Perseus, Spring '02. *Left* panels show ^{13}CO data for region near B5. *Lower right:* The "giant" HH flow in B5 can now be mapped in just 1.5 hours.Solid and dashed black boxes in the left panels correspond to those in the lower right panels. The color N_2H^+ map superimposed at upper right shows the group of dense cores associated with the cluster NGC1333.

In small regions of the sky, molecular line/extinction/thermal emission intercomparisons had given fabulous results. At the Santa Cruz meeting, João Alves showed that he and his collaborators had found the Bok Globule B68 to be a *near-perfect critical Bonnor-Ebert sphere*[11] according to both extinction and thermal-continuum mapping, and that B68 showed extreme *depletion* of carbon-bearing molecules onto dust grains in its cold, dense, core (Alves, Lada, & Lada 2001; Bergin et al. 2002).

While the meeting was abuzz with the B68 results, the five of us kept thinking and talking. What if we could make maps like what João had made in B68 not for a little Bok globule, but for a *whole molecular cloud complex*? Then, finally, we could do the kind of detailed analysis Alves et al. had done for B68, and much more, on the scale of whole star-forming regions. No more guessing about how good a tracer of density this or that molecular probe was. No more wondering just how many outflows might be inside a whole star-forming region. No more guessing about the relationships between gas and dust temperature.

No one had ever attempted this kind of obviously useful large-scale molecular-line, extinction, and thermal emission mapping because it would take too long. Now, though, thanks to focal-plane arrays, clever mapping strategies and better receivers, the total time to map a 10-pc cloud in ^{13}CO with 40-arcsec resolution is of order 100 hours—down from more than 10,000 hours twenty years ago. And similar improvements have been made in the near-IR for extinction mapping and in the sub-mm for dust continuum mapping. The five of us chatting in Santa Cruz, and every colleague we talked with, agreed how wonderful this kind of survey would be — *for so many people's research* — especially if it could cover the same large (>10 pc) regions as the recently-approved SIRTF Legacy c2d project. One acronym later, "COMPLETE" was born.

Today, the COMPLETE team has ten members, as listed in the Budget Justification. The observations for the full COMPLETE Survey consist (and will consist) of: molecular-line mapping at the FCRAO, IRAM 30-m, and BIMA telescopes; extinction-mapping using 2MASS, SIRTF Legacy, and 8-m-class telescope data; and thermal emission mapping from SIRTF, the HHT, and SCUBA on the JCMT[12]. Phase I of COMPLETE focuses on the large-scale ~arcmin-resolution mapping of three ~40 pc^2 regions, and it is now underway (see Figure 1). Phase II, which zooms in with higher resolution on the highest-extinction portions of the clouds under study, is currently at the observing-proposal stage, and should begin in 2003. This science proposed here requires only data from Phase I.

The target list for COMPLETE consists of the three most northerly cloud complexes included in the SIRTF c2d project: Perseus; ρ-Ophichus and Serpens. Each of these is being *fully* mapped (within the ~40 pc^2 SIRTF observing boundaries) in ^{12}CO and ^{13}CO at FCRAO[13]. Every portion of the cloud above A_V~6 mag is also being mapped from FCRAO in N_2H^+ and CS (see Figure 1). The same high-extinction regions will be fully mapped at 850 μm, requiring >200 hours of SCUBA time. 2MASS, which is an all-sky survey, allows us to map *any* size region in extinction, and we have shown that NICER (Near-infrared Color Excess Method Revisted, see Lombardi & Alves 2001) can provide 2MASS-based extinction maps with ~3 arcmin resolution, and will provide SIRTF-based extinction maps with sub-arcmin resolution.

As of November 2002: COMPLETE is a Key Project at the Five College Radio Astronomy Observatory and we are awaiting approval as a Canadian "Long Term" (Key) Project on SCUBA at the JCMT. In

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[11] A "Bonnor-Ebert" sphere is a configuration akin to an isothermal sphere bounded by a constant pressure. This configuration has often been proposed as a more realistic initial state to consider in star-formation collapse calculations than a "singular isothermal sphere."

[12] The c2d Survey will also produce extended dust-continuum maps, but due to the extraordinary (over-) sensitivity of the long wavelength SIRTF detectors, most of those maps will be too saturated to be useful in mapping out cold dense material.

[13] The ^{13}CO isotope of CO trace gas above an A_V >1 mag threshold, which typically corresponds to a volume density ~10^3 cm^{-3}, and is only optically thick at A_V>10 mag. The more common isotope of CO, ^{12}CO, is optically-thick in most star-forming regions, and is useful there principally as a probe of outflowing gas, whose velocity is far-enough removed from the line core to make it ~optically thin.

addition, the c2d SIRTF Legacy Survey[14] is relying on COMPLETE to provide all of its large-scale ancillary data.

By 2004, COMPLETE will provide the first high-kinematic-resolution sky survey of ~40 pc^2 dense Galactic molecular clouds within 0.5 kpc of the Sun[15]. Figure 1 shows just a subset of the pilot COMPLETE observations carried out in April 2002. These observations demonstrated, both to our team and to the FCRAO TAC which awarded us hundreds of hours of additional time, that we can easily detect outflows in hours that took days or weeks to map just a few years ago, and that our entire plan is feasible. The observations also turned up unexpected phenomena, like the extended regions of "aberrant" ^{13}CO velocity evident lower left panel. These velocity features are as yet unexplained—they are not correlated with any known outflow.

All the data from both the COMPLETE and c2d Surveys will be made public, via the web, immediately upon validation[16]. We expect at least 100 papers to be written by members of the astronomy community using the COMPLETE database, in just the first few years following its full release. The COMPLETE Survey is a demonstration project for the CfA's NSF-sponsored NVO efforts, and as such will be widely publicized, in both the astronomy and public communities[17]. We are currently developing a set of materials aimed at presenting COMPLETE's science to the public. My first two uses of these public-audience materials will be at an upcoming CfA public lecture (December 2002) and at the "Launch-30" NASA Press Conference for SIRTF (January 2003), where I have been asked to speak on behalf of the U.S. star and planet formation community.

The costs associated with acquiring, organizing, and archiving the COMPLETE data are expected to be covered largely by NASA's LTSA program[18]. The present proposal seeks funds to be used in the kinematic analyses of the COMPLETE data described below.

Planned Analysis

The COMPLETE team is organized with various members assigned to "lead" specific efforts, even though many team members will participate in several intertwined projects.[19] In addition to serving as P.I. for the whole project, it is my role in COMPLETE to coordinate the acquisition and analysis of the **large-scale molecular line data**. This proposal *only* requests funding for three near-term projects stemming from the analysis of kinematic information provided by COMPLETE molecular line data.

Deriving Key Physical Quantities

In all three of the projects described below, we will need to extract basic physical parameters, such as mass density, dust and gas temperature, and gas velocity, from an optimized combination of COMPLETE, c2d, and existing data. The general idea is to use the extinction measurements, based at first on 2MASS data and later on SIRTF c2d data as the best measure of mass density. Far-infrared and sub-mm dust emission

[14] The SIRTF Launch is now scheduled for January 2003, and Legacy observations are planned to begin within the first six months.

[15] Our COMPLETE funding proposal to NASA gives the details of all of the Survey's observations and their usage, and gives a timeline for the Survey's completion, is available online to reviewers at http://cfa-www.harvard.edu/COMPLETE/. The full c2d proposal is online at http://peggysue.as.utexas.edu/SIRTF/.

[16] Many COMPLETE observations are already online, at http://cfa-www.harvard.edu/COMPLETE.

[17] Several COMPLETE papers, as well as giveaways emblazoned with the COMPLETE logo and URL, will be presented at the 2003 January AAS.

[18] See Budget Justification for more information.

[19] The first (semi-annual) COMPLETE Workshop was held in Arcetri in June 2002. Each workshop includes: status and science reports and discussions; paper and proposal planning; and a public session where the latest COMPLETE results are presented at the host institution.

measurements (e.g. IRAS, unsaturated SIRTF, and SCUBA data) will be fitted with emissivity-weighted blackbodies to derive dust temperature and emissivity, constraining the fits so that the total dust column density implied matches the one derived from extinction measurements. Molecular-line data will be used in several ways, principally to determine the motions of gas whose mass distribution is mapped out by the extinction and thermal emission measurements. Also, we will find a global correlation between ^{13}CO integrated intensity and sub-mm flux that we can use to approximate missing sub-mm fluxes in dust spectral-energy distributions. This procedure will allow us to use the temperature of the (cold) molecular gas traced best by ^{13}CO to estimate the (otherwise missing) flux from undetected cold dust.

Project 1: COMPLETE Outflow Census and Environmental Impact Statement

What *exactly* outflows from young stars do to molecular clouds is still unclear.

We have tantalizing hints from detailed studies of individual sources (e.g. Lada & Fich 1996; Yu, Billawala, & Bally 1999; Arce & Goodman 2001, 2002) telling us that at least some flows are quite capable of significantly restructuring their parent cloud. In fact, some outflows possess as much as an order of magnitude *more* energy than is needed to completely *destroy* their ~1 pc-scale host "cloud." Trouble is, this ~1 pc-scale host is nearly always itself part of a much larger cloud complex, which in turn often contains ~tens of active flows (see Figure 2[20] & Bally et al. 1999). The "host" cloud in a study of any given outflow is defined by a somewhat arbitrary boundary that encloses the "dense" material (usually ~several x 10^3 cm^{-3}) "associated" with the YSO launching the flow (see boxed-in region in Figure 2a). So, in order to study the cumulative effect of multiple outflows on a parent cloud, it is necessary to map *all* of the molecular gas in the cloud, and to understand the time history of star formation in the cloud (see Project 3, p. 14).

COMPLETE will give maps of *every* outflow in three large star-forming molecular clouds, and c2d, will give the positional and age distribution of the young stars in the same clouds. We plan to combine these data sets, using an algorithm for the spatial and temporal distribution of outflow kinetic energy input based on Figure 2 and described below, to issue the best "environmental impact statement" (EIS) on outflows to date. This kind of EIS has been issued once before, in 1999 by John Bally and his colleagues, in their pioneering study of the outflows in a 10-pc-wide swath of the Circinus molecular cloud[21]. Their paper concludes that:

> *The Circinus cloud appears to have been severely modified by extensive star formation over the past few million years. The formation of dozens of stars has shredded and churned the cloud, producing dozens of outflow cavities surrounded by dense filaments of compressed gas that may be responsible for the "Swiss Cheese" appearance of the cloud. Even with low efficiency, star formation is capable of producing the observed chaotic motion and structure in the cloud.*

So, the question to answer is: "just how common is the Circinus case?" Or, put more physically, "which is more important in determining the structure and ultimate fate of molecular gas in star-forming regions, turbulence or outflows?" My working hypothesis on this question is that outflows effect a cloud more and more over time, and that the higher the density of the region before star formation commences, the more resistant it is to being ripped apart by flows. But, I certainly do not *know* this to be true—our environmental impact statement will rely on the following algorithm:

1. For each cloud, create a census list of all outflows currently detectable using position-velocity information from the ^{12}CO COMPLETE survey data cubes. Maps of the SCF will be used to "automatically" detect outflow regions, but human intervention will be needed in creating the final outflow maps and list.

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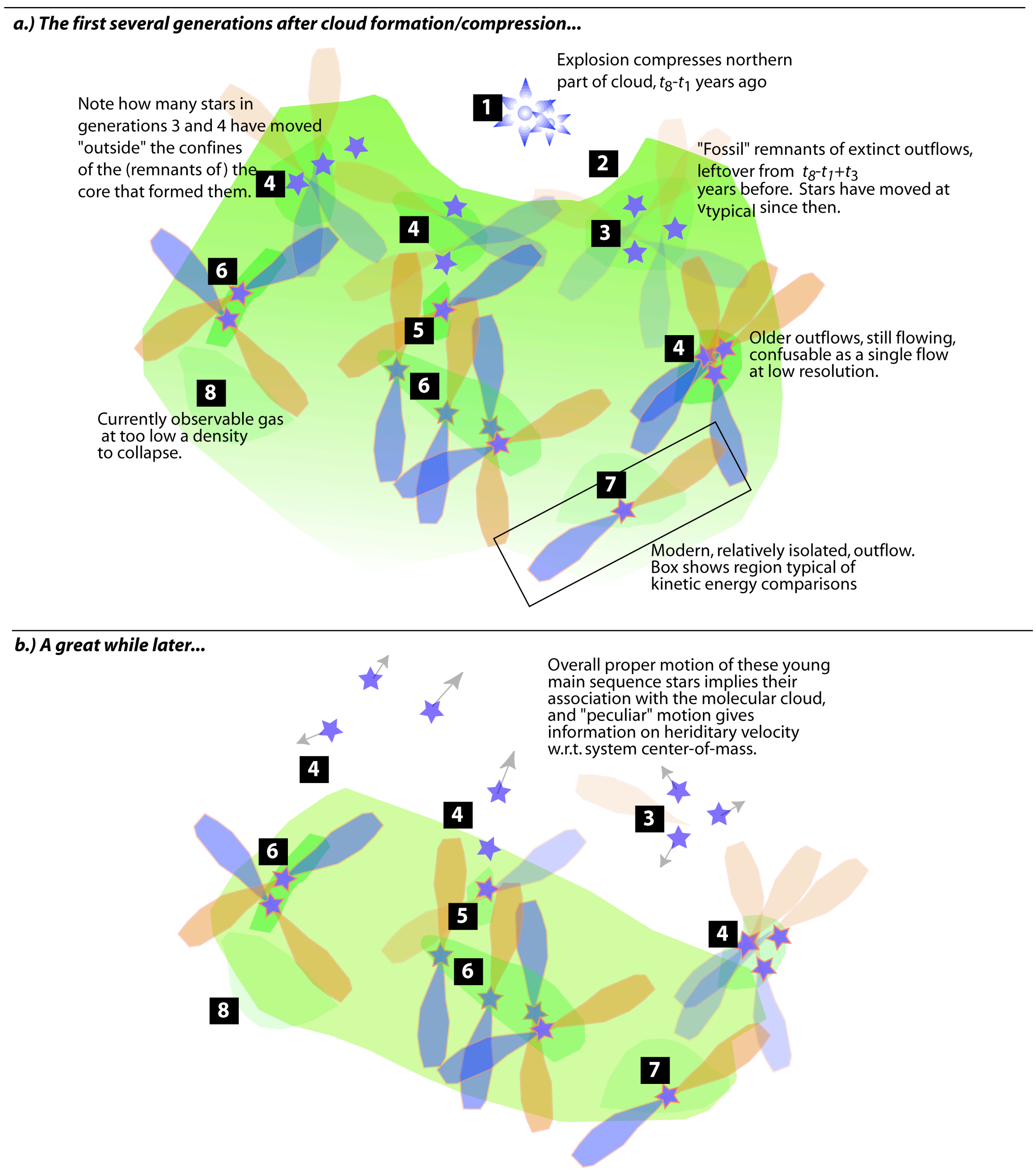
[20] Figure 2 is a *schematic* diagram. The filamentary/holey/stringy-looking substructure created by turbulence and/or outflows within the regions shaded green is not shown, for the sake of clarity.

[21] The Bally et al. (1999) paper is distinguished from prior global estimates of outflows' influence (e.g. Margulis, Lada & Snell 1988) by its use of detailed outflow mapping, rather than spatially-averaged estimates of "high" vs. "low" (e.g. outflowing vs. ambient) velocity gas.

Figure 2: Schematic Diagram of a Molecular Cloud



2. For each flow, estimate its: age, based on a dynamical age corrected for deceleration;[22] and the variability in its energy output as a function of time based on position-velocity and mass-velocity relations.[23]

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[22] In our work on the rapid motion of PV Ceph (Goodman & Arce 2002), we developed a model for the deceleration of HH knots that predicts the true age of an outflow as a function of the dynamical age implied by its current terminal velocity. For reference, for a pc-scale flow, the true age is ~10 times the age implied by the straightforward (age=size/velocity) dynamical age.

[23] In Arce & Goodman 2001, we show that the jags in position-velocity diagrams for individual flows and the steep slope of mass-velocity relations can be consistently explained in a model where outflows are

3. Using the c2d and prior point-source surveys, identify the positions and estimate the ages of all embedded YSOs in the target regions.
4. Associate the point sources with observed flows, and search for missing flows in cases where source age implies one should exist. This search will provide the "completeness" limit for the outflow search done in Step 1.
5. Using the procedures described on p. 8 to map out mass and velocity, and then create maps of the momentum deposition and kinetic energy distributions in the target clouds.
6. Create a time-resolved Monte Carlo code with inputs based on results of Steps1-5 for the: number of stars and outflows formed; outflow energy output; typical conditions (e.g. density, velocity dispersion) encountered in the host cloud; and size of outflow, all as functions of time. In this code, the total mass of the parent cloud and the distribution of the duration of outflows will be adjustable input parameters.
7. Create plots of the following as functions of time: 1) filling factor of gas of various velocities (e.g. outflow or ambient gas fraction vs. time); and 2) kinetic energy divided by total gravitational potential energy (which indicates how "bound" a cloud is), for a variety of scales, ranging from the size of a single flow up to the size of the whole cloud.
8. Create simulated cloud maps (not full MHD simulations[24]) as functions of time, using the outputs of Step 6, which will schematically show the evolution spatial distribution of density and kinetic energy within the cloud.

The series of papers based on this work will form a statistically-based EIS quantifying the impact of outflows on the time evolution of molecular clouds, and a large portion of graduate student Scott Schnee's thesis.

Using the results of Steps 6, 7 and 8 in concert along with Project 3's estimate of how long any cloud has been producing stars (see p. 14), we will also have enough information to offer an actuarial estimate of the productivity and longevity of molecular clouds like the ones we will observe.

Project 2: Study of Large-Scale "Bubbles" in Molecular Clouds

In preparation for proposng COMPLETE as a Canadian Long-Term Project at the JCMT, we created new IRAS-based maps of Serpens, Perseus and Ophichus. This work was carried out in large part by Jason Li, a brilliant high-school student from Great Neck, New York, in Summer 2002. By carefully recalibrating the IRAS 60 and 100 μm flux maps in the ISSA catalog so as to have their "zero-points" best represent zero flux, we were able to construct extraordinarily high dynamic-range color-temperature and dust column density maps (for methodology see Arce & Goodman 1999a; Wood, Myers, & Daugherty 1994).[25]

One IRAS map we made astonished us and another just surprised us. Figure 3 shows the astonishing map. The dust color-temperature map of Ophiuchus shows a previously-undiscovered,[26] 2-pc diameter, nearly circular ring of ~37 K emission in a sea of 30 K emission, just North of the famous embedded cluster of

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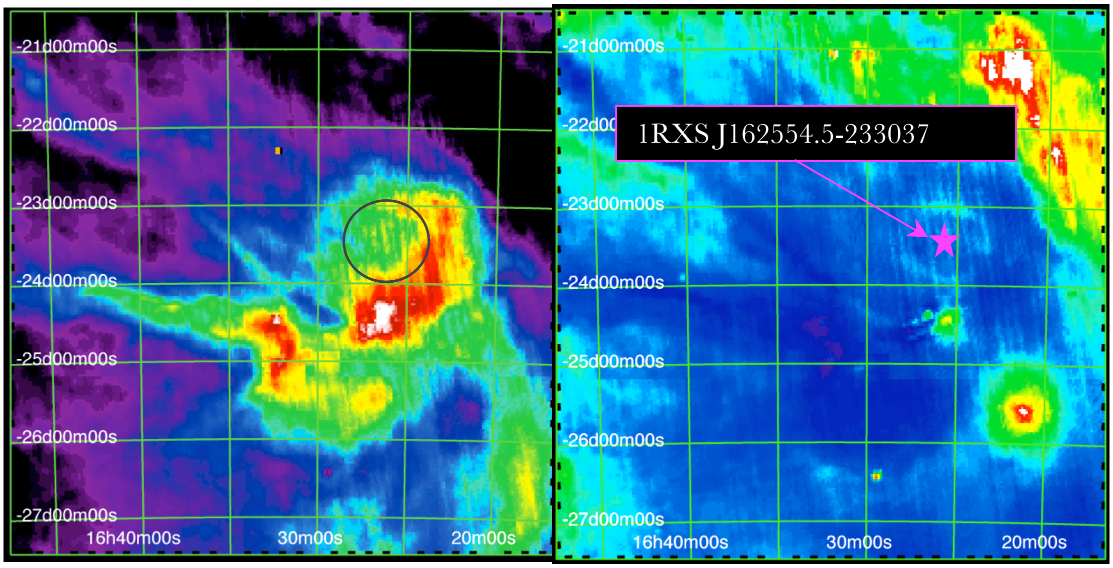
episodic. More episodic outflows show steeper mass-velocity relations, and will be modeled in the proposed work as such.

[24] Full MHD simulations using input parameters derived from Project 1 will in fact be done, and those simulations will be compared with COMPLETE data via SCF analysis. MHD simulation experts Paolo Padoan, Eve Ostriker, and Mordecai MacLow have all expressed interest in running realistic "outflow-driven" simulations. While we are likely to collaborate in this work, no funding for it is requested here.

[25] These new maps have already been made available to the public as FITS and JPEG images through the COMPLETE web site at http://www-cfa.harvard.edu/COMPLETE/iras/. Jason Li will be using this research as his entry in several high-school science and scholarship competitions.

[26] All of our attempts to find previous mention of this ring in the literature or knowledge of its existence among our expert colleagues have failed, so we believe that Jason Li's work actually uncovered this feature for the first time.

Figure 3: Column Density *(left)* **and Color Temperature** *(right)* **Maps of Ophiuchus**



young stars near ρ-Oph. (The cluster is apparent as the bright white blob SW of center in the column density map.) We later determined that the X-ray source 1RXSJ162554.5-233037 lies at the circle's center, and that the elevated-temperature circle fits neatly inside a crook of dust emission extending North from the ρ-Oph cloud (see Figure 3). We do not yet know much about the X-ray source, other than: its flux at two ROSAT bands; that it is part of a cluster; and that no papers appear in the literature about it.

According to the formalism set out in Mike Shull's "Signature of a Buried Supernova" paper of 1980, we calculate that a 0.5 x 10^{51} erg supernova ejecting a mass of 1 solar mass into a medium, like the dense parts of Ophiuchus, with a density of 10^5 cm^{-3} would reach the size apparent in Figure 3 (~2 pc at the 160 pc distance of Ophiuchus) in about 200,000 years. At that time, the temperature of the shell would be 38 K—eerily like the color temperature we observe. The velocity of this shell at 200,000 years would be only 1.7 km s-1, which is only slightly larger than the ^{13}CO line widths in this region, and thus nearly undetectable as an expansion—unless one were explicitly looking for such a signature. Ophiuchus contains some ~1 Myr old stars (Wilking et al. 2001), so we do *not* think that this hypothetical supernova effected the formation of the complex—but we do strongly suspect that the Ophiuchus molecular cloud complex has at least been struck by at least one supernova—or event of equivalent energy—since it began forming stars.[27]

The new IRAS map that only surprised us is shown in Figure 4. Examining the black-and-white ^{13}CO map in Figure 1, one sees that the *cold* molecular gas in Perseus forms a chain of blobs along a NE-SW line. Knowing that, we were very surprised to see Jason Li's IRAS map of Perseus (Figure 4)—which is so clearly dominated by a ring-like geometry. (Note the well-known sub-regions labeled in both Figures 1 and 4 to facilitate comparison.) This lack of correspondence is explicable when one realizes that if comparable amounts of warm (~30 K) and cold (~10 K) dust are present along a line of sight, the warmer dust will dominate the emission geometry observed in the far-IR. So, what Figure 4 tells us is that the warm material in Perseus is not arranged in the same way as the cold material.

Unlike the case in Ophiuchus, the ring in Perseus is much larger and shows up only in the column density, and not in the temperature map. Thus, if this ring was caused by a supernova, the "shell" temperature would need to equal the background temperature at present. Using Shull's equations again, we find that a 2 x 10^{51} supernova ejecting 1 solar mass of material into an ambient medium with average density10^4 cm^{-3}

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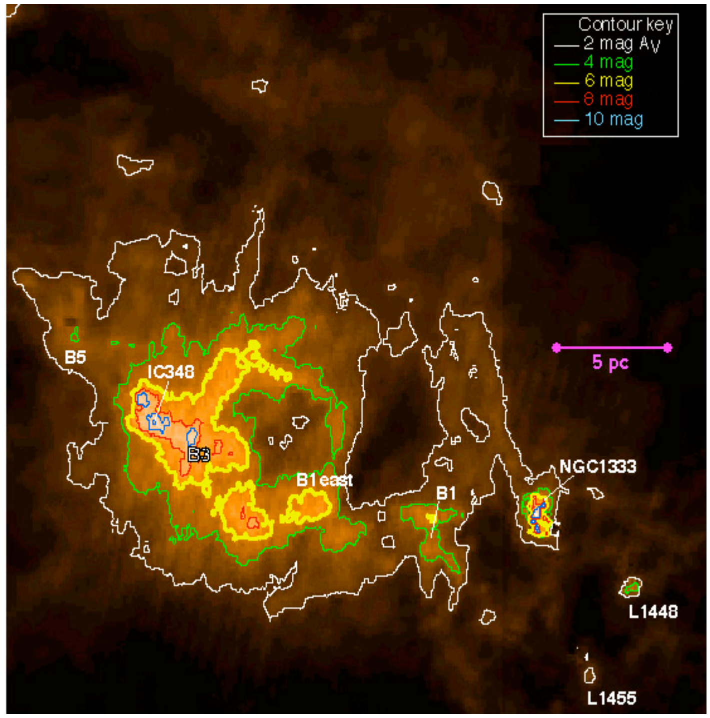
[27] On the longer time scale, and larger spatial scale, de Geus and colleagues argued very convincingly that the bubbly and filamentary nature of the entire Sco-Cen-Oph region of the ISM can be explained as due to the effects of stellar associations and their winds upon each other (de Geus 1992; de Geus, Bronfman, & Thaddeus 1990; de Geus & Burton 1991; de Geus, de Zeeuw, & Lub 1989).

Figure 4: IRAS-based "Extinction"Map of Perseus



will give a 5 pc radius remnant in 1 Myr, whose temperature is 30 K and expansion velocity is 1.5 km s^{-1}. This low temperature is equal to the background (ambient) temperature in our Perseus map, and so a SN shell should not be observable in the temperature map. A velocity of 1.5 km s^{-1} is comparable to the line width of tracers observed on 10-pc scales in Perseus (e.g. ^{13}CO), and would thus be undetectable as expansion without optimized modeling.

After an extensive literature search, we found that the Perseus ring, called G159.6-18.5, was first glimpsed in a lower-quality release of the IRAS data by Pauls & Schwartz, who only published their findings in a conference proceedings (Pauls & Schwartz 1989). Since then, only one paper has been devoted to G159.6-18.5 (Andersson et al. 2000). In that paper, ^{12}CO mapping gives no obvious evidence for shell expansion, although enhanced line width is found at the shell boundary[28]. Andersson et al. argue that the non-thermal radio continuum they find emanating from the shell is not inconsistent with non-thermal emission one might expect from a SNR, but that it is more consistent with simply an expanding H II region, emanating from HD 278942, an O9.5-B0 V star at the shell's center.

So, we are left wondering about the causes—but more interestingly—the effects of the large bubbles we see in both Ophiuchus and Perseus.

Both supernovae and H II regions have been proposed as both *constructive* and *destructive* forces in molecular clouds. In the *constructive* sense, the powerful winds and shocks driven into the ISM by can compress certain pieces of interstellar gas enough so as to make their densest parts more susceptible to collapsing under their own weight into stars. In the *destructive* sense, because stars that produce H II regions and SNe are short-lived, both phenomena are likely to wreak havoc upon their ancestral home. In addition, H II regions and SNe have each been proposed, by numerous authors, as potential drivers of turbulence in the interstellar medium.

At least initially, we are more interested in evaluating the effects than determining the cause of the shells evident in our IRAS maps. So, we plan to address the following issues with our COMPLETE data:

i.) Kinematics. Can any systematic effect of the shell upon the molecular gas be found? (e.g. What are the implications of any enhanced line width found, and how much energy input does it imply? Does a map of the SCF show any features associated with rings? Can a smoothing or fitting algorithm show expansion in the molecular gas, at any resolution?)

ii.) Density Structure. Early 2MASS analysis shows that the overall dust column density in Perseus is structured more like the ^{13}CO than the IRAS emission (Carpenter 2000). We will use the procedure for combining extinction, thermal emissionand molecular line data described on p. 8 to map out column density, bolometric temperature, and dust emissivity in the shells in as unbiased a way as possible.

[28] The line width of ^{12}CO in Perseus is typically much larger than ^{13}CO, and larger than the expected expansion velocity.

iii.) Kinetic Energy and Momentum. Using the mass information derived in **ii.)**, and the velocity information derived in **i.)**, we will map out the kinetic energy and momentum deposition, at present, due to the presence of shells in these clouds.

The results from this shell work (Project 2) will be analogous to the analyses of outflows' impact on clouds done prior to the more general EIS we offer in Project 1, in that they will *not* represent a statistical sample of interactions, or have much to say about the time history of interactions. That kind of analysis of bubble interactions would require a galactic-scale, Hubble-time baseline evaluation. We anticipate, instead, that the results we obtain in Project 2 will be best evaluated alongside numerical MHD models (e.g. Kim et al. 2001), with tools like the SCF. Constraining those models with observations should be an excellent way to predict the long-term effects of SNe and/or H II regions on molecular clouds' origin, structure and fate.

Project 3: Comparison of Stellar Velocities with Gas Velocities

Learning that the young star PV Ceph is moving at ~10 km s^{-1} (Goodman & Arce 2002) leads one to question the oft-made assumption that most young stars still live near their birthplace. In 1 million years, an object moving at just 2 km s^{-1} will move 2 pc from its place of origin. The typical random velocity dispersion on 2 pc scales in molecular gas is ~2 km s^{-1}, so it is likely that stars born in the past Myr within a 2 pc-radius circle on the sky may have come from *anywhere* within that area.

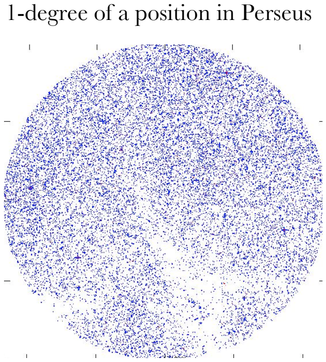
This kind of scrambling has dramatic effects on calculations of the so-called "star formation efficiency" (=(total mass of stars formed)/(mass of gas from which they formed)). If one counts up stars within only the same area where one currently finds gas, one will clearly miss stars that have left that area since their birth (see Figure 2, lower panel & labeling). The faster the stars move, and/or the smaller the area over which one calculates efficiency, the greater the danger of making an error.

In the past, proper motion studies have primarily been used to associate stars with each other as "moving groups" or as having a common origin (e.g. Teixeira et al. 2000), but have only less often been compared with gas velocity distribution (e.g. de Geus et al. 1989; de Geus and Burton 1991; de Geus 1992).

The combination of the kinematic information on gas motions provided by COMPLETE with proper motion lists derived from the new USNO-B catalog should provide us with the best chance ever of tracking down the progeny of particular molecular clouds. USNO-B is an all-sky catalog that presents positions, proper motions, magnitudes in various optical passbands, and star/galaxy estimators for 1,042,618,261 objects (Monet & al. 2002). By combining proper motion and color information from USNO-B with other recent surveys' proper motion and distance measures (e.g. Hipparcos, Tycho-2) we will compile lists of all stars within the volumes around our Perseus, Ophiuchus and Serpens survey areas.

About 1% of the billion stars in the USNO-B catalog have proper motions measured with milliarcsecond (mas) accuracy. For reference, 2 km s^{-1} at 200 pc gives a proper motion of 2 mas yr^{-1}. In the 1 degree radius circle in Perseus shown in Figure 5, there are 28,000 stars in the USNO-B catalog. The good news is that the most accurately measured proper motions (e.g. as in Hipparcos) are nearly all for stars closer than 0.5 kpc to the Sun. As a result, at least 10% (28) of the 280 (=1% of 28,000) stars within the 1 degree circle should lie within 50 pc of Perseus' distance (~300 pc). The whole Perseus molecular cloud complex covers just over five times the area shown in Figure 5, implying that we can expect a total of roughly150 USNO-B stars to *both* be projected on top of the Perseus complex and to have distances within 50 pc of 300 pc. In fact, ±50 pc (=10 km s^{-1} for 5 Myr) is the very outer limit of what is reasonable to search along the line of sight, but this line-of-sight optimism is countered by plane-of-the-sky pessimism when we neglect motion of stars out of the Perseus molecular cloud's current projected boundary (see Figure 2). So, 150 stars with known distances and proper motions is probably a fair estimate of the sample USNO-B could give in Perseus.

Figure 5: USNO-B stars within 1-degree of a position in Perseus



Once we have identified stars potentially associated in space with a particular cloud complex, the next task will be to estimate the age of each star. At our disposal, we will have optical colors, near-IR colors from

2MASS, and far-IR colors from IRAS. Using that color information, we should be able to at least separate "old" (e.g. >>1 Myr) stars from "young" (~1 Myr) ones. We do not know what fraction of these stars will be young—this is one of the questions our analysis will answer. In answering, we will need to carefully account for the biases introduced by extinction, and by the fact that it will be easiest to detect older stars.

Our next step will be to compare the position-velocity distributions of stars of various age categories with each other, and then, finally, with the position-velocity distribution of the molecular gas as determined by the COMPLETE Survey. One goal of this analysis will be to see if we can find the largest spatial scale where the velocity dispersion of the oldest associated stars matches the velocity dispersion of the gas averaged over the entire (present-day) molecular cloud. If we can find it, *this scale will tell us how "dispersed" the population formed by one molecular cloud becomes over time.* Another goal will be to identify any rapidly-moving stars that seem to be associated with the cloud, and then try to understand the physical origins of their motion. Since no one has ever had the opportunity to compare stellar proper motions and molecular gas motions on such a large scale before we are also excited about the serendipitous discoveries we are almost certain will come from this work. Project 3 may be the riskiest we propose, but if it succeeds in telling us what becomes of a particular molecular cloud's progeny, its results may well be the most important.

Summary: Bubble, Rubble, Roil, Trouble

Bubble: Supernovae, H II regions, and stellar winds all blow bubbles into the ISM. We seek to quantify how much of a role those bubbles play in sculpting molecular clouds, in comparison with outflows from young stars and turbulence.

Rubble: The same bubbles that can compress and sculpt molecular clouds can also turn them to rubble, leaving them incapable of further self-gravitational collapse once too much star formation has taken place. Our outflow census and bubble study will tell us how destructive these influences are over time, and combining those results with our proper motion investigation will allow us to estimate how long clouds live before their own children turned their homes to rubble.

Roil: To roil is to churn up solid into a mixture. The mass-calibration of all of our molecular line observations in COMPLETE depend on "roiling" in the ISM. COMPLETE's unique combination of extinction, thermal emission, and molecular-line mapping of the same regions will allow us to use roiled dust to map out an accurate mass distribution while using molecular lines probes to measure velocity.

Trouble: None at all, we're happy to do it.

Timetable

The three projects described here will proceed concurrently. **SIRTF** is scheduled to launch in January 2003, and the Legacy data should begin to become available in **2004**. **2MASS** extinction maps of all COMPLETE targets will be ready at the end of **2003**. The COMPLETE **postdoctoral fellowship** (for which partial funding is requested here) has been advertised and "the postdoc" will begin work in **Fall 2003**.

Project 1 forms the bulk of Scott Schnee's **Ph.D. Thesis**. Scott is in charge of acquiring the FCRAO data for COMPLETE, and he plans to have half of the COMPLETE Survey area observed by May 2003, and the full survey finished by May 2004. Scott plans to finish his thesis, and thus Project 1, in the **2005/6** academic year. The postdoc and NVO staff will assist in the archiving of the FCRAO (and other) COMPLETE data as it is acquired.

Project 2 The PI will begin work on this project in Summer 2003, and be joined in her efforts by the postdoc in Fall 2003. An initial "morphological" paper will be submitted in Fall 2003, with more comprehensive work to follow in **2004/5**.

Project 3 will form the "Research Exam" (~**Master's Thesis**) of a graduate student (most likely 1st year Ryan Hickox) at Harvard. The work will commence in 2003, and conclude in **2005.**

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Biographical Sketch for Alyssa A. Goodman

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

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)

Smithsonian Astrophysical Observatory Time Allocation Committee; NSF Caltech Submillimeter Observatory Review; M4 Satellite Science Advisory Group (Chair); NRAO VLA-VLBA Proposal Reviewer; US Square Kilometer Array Consortium (Harvard Representative); 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

Relevant Recent Publications:

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

Arce, H.G. & Goodman, A.A. 2001, *The Mass-Velocity and Position-Velocity Relations in Episodic Outflows*, ApJ, 551, L171.

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Padoan, P., Juvela, M., Goodman, A.A. & Nordlund, A. 2001, *The Turbulent Shock Origin of Proto-Stellar Core*s, ApJ, 553, 227.

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Sample Synergistic Activities

AG is P.I. on an NSF Grant to a large group at the CfA developing the "Data Model" for the National Virtual Obervatory, 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* at the Rose Center's Hayden Planetarium in New York; *Order, Chaos, and the Space Between Stars* at the Boston Museum of Science; *Mapping the Interstellar Medium* at the annual meeting of New England Amateur Astronomers; and *A Dynamic View of Star Formation* at the recent joint meeting of APS and the American Association of Physics Teachers. This coming January (2003), at NASA's request, AG will be one of four scientists on a panel to speak and answer questions about SIRTF's science at the "Launch-30" SIRTF Press Conference.

Collaborators within Past 48 Months:

Rachel Akeson, Caltech/IPAC
Héctor Arce, Caltech
Javier Ballesteros-Paredes, UNAM (Mexico)
Joseph Barranco, UC Berkeley
Pierre Bastien, U. Montreal (Canada)
Bruce Draine, Princeton University
Lincoln Greenhill, CfA
Carl Heiles, UC Berkeley
Mark Heyer, FCRAO/UMASS
Mika Juvela, Helsinki University Observatory (Finland)
Alexander Lazarian, University of Wisconsin at Madison
Sheila Kannappan, DAO
Scott Kenyon, CfA
Sungeun Kim, CfA
Helmuth Kristen, Sweden
Kishore Kuchibhotla, MIT
Nadine Manset, U. Montreal (Canada)
Philip Myers, CfA
Åke Nordlund, Copenhagen Astronomical Observatory
Paolo Padoan, CfA
Marc Pound, University of Maryland
Örnólfur Einar Rögnvaldsson, Nordic Institute for Theoretical Physics (Denmark)
Erik Rosolowsky, UC Berkeley
Karin Sandstrom, Harvard University
Scott Schnee, CfA
Lister Stavely-Smith, ATNF (Australia)
Enrique Vazquez-Semadeni, UNAM (Mexico)
David Weintraub, Vanderbilt University
Jonathan Williams, University of Hawaii
David Wilner, CfA
Qizhou Zhang, CfA

Graduate Advisor:

Philip Myers, CfA

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

Kishore Kuchibhotla, MIT
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

Budget Justification

The principal costs of the COMPLETE Survey and its analysis are for personnel—many researchers are needed to even skim the cream off the database that will be created, and programmers' services are needed to assure the data's proper public dissemination and archiving.

The COMPLETE Survey team, as of now, is comprised of the following people, at the following institutions:

1. Joao **Alves** (European Southern Observatory, Germany)
2. Paola **Caselli** (Osservatorio di Arcetri, Italy)
3. James **di Francesco** (Herzberg Institute for Astrophysics, Canada)
4. Alyssa **Goodman** (Harvard-Smithsonian Center for Astrophysics, USA)
5. Mark **Heyer** (Five College Radio Astronomy Observatory/UMASS, USA)
6. Doug **Johnstone** (Herzberg Institute for Astrophysics, Canada)
7. Mario **Tafalla** (Observatorio Astronómico Nacional, Spain)
8. Thomas **Wison** (Max-Planck-Institut für Radioastronomie, Germany)
9. Héctor **Arce** (Caltech, USA)
10. Scott **Schnee** (Harvard-Smithsonian Center for Astrophysics, USA)

While Alyssa Goodman is the P.I. of the COMPLETE Survey, others on the team have taken responsibility for several aspects of the data acquisition, analysis, and interpretation not covered under the present proposal. Joao **Alves** is heading the **extinction mapping** efforts, and can involve and fund students in Germany to work on COMPLETE data with him. Doug **Johnstone** is heading the **thermal-emission mapping** projects, and has already involved several Canadian students in the project. Paola **Caselli** and Mario **Tafalla** will spearhead the **higher-resolution spectral-line mapping** efforts (at the IRAM 30-m), and will secure European funding for most of those efforts.

In this proposal we seek funding *only* for the kinematic analyses described here. We have asked (and hope) for additional funding from the NASA LTSA program, which we plan to use for data dissemination and analysis beyond what is described here. In addition, we have (very) limited funding available for data archiving and dissemination through the P.I.'s NSF NVO grants.

In **Year 1** (FY04[1]) of the budget, we request **1.5 months of Summer Salary** for the P.I., the cost of **half a postdoctoral fellow,**[2] the full cost of a **second-year Harvard graduate student**, and $2K toward paying **undergraduate researchers**. We expect to use NASA LTSA or the P.I.'s startup funds to cover the other half of the postdoc's salary. The full COMPLETE research effort at the CfA in that year will be a full-time postdoc, senior graduate student Scott Schnee[3], a junior graduate student (to be hired on this grant), two undergraduate students, and the P.I. In addition the NASA SIRTF c2d project will fund a postdoctoral fellow

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[1] FY04=July 1, 2003 through June 30, 2004.

[2] The fringe benefit rate at Harvard for FY04 is 19.3% for faculty and 18% for postdocs. Student benefits would not be charged to this grant.

[3] Scott Schnee has an outside fellowship that should cover his stipend through his graduation in 2005/6.

at CfA that year, with whom we will coordinate effort, but who will *not* work directly on COMPLETE data. We are trying our best to put together adequate funding for a proper treatment of the COMPLETE and SIRTF c2d data at the CfA—a very big job—by using every NASA and NSF funding source we can think of.

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

> $5100 to be used to **upgrade the memory and storage** on our (2) existing large UNIX workstations. This upgrade is necessary to hold and manipulate the large data cubes (e.g. tens of thousands of spectra) that will be utilized by the analyses described in the proposal (e.g. the SCF).
>
> $8000 in **travel expenses**, divided equally between foreign and US/Canadian travel. The money will fund ~2.5 inter-continental trips (1.5 for visits with/by European COMPLETE collaborators and 1 for observing) plus approximately 4 domestic trips (1 for conference attendance, 2 for observing, and 1 for collaboration with US/Canadian COMPLETE collaborators).
>
> We request an additional $3K to support "**Participant**" travel. We plan to continue to host at least one COMPLETE workshop per year, and this $3K will be used to defer the travel expenses of a small number of invited participants.
>
> $1200 toward **materials and supplies**, to be used for software upgrades and licensce fees.
>
> $3000 in **publication costs**, to be used for page charges on approximately 30 pp/year at $100/page
>
> **indirect costs ("F&A")**, calculated as 63% of direct costs, excluding equipment over $5K and Participant Costs

In **Year 2** (FY05), the number of personnel involved in this project at the CfA is not expected to change. The only notable change to the salary portion of the budget is that a **3rd-year graduate student** at Harvard costs an advisor significantly more than a 2nd-year graduate student.

In addition to salaries in Year 2, we request the same items as in Year 1, with the exception of the $5100 for the computer upgrade. The overhead rate at Harvard in FY 05 will be 64%.

In **Year 3** no postdoc funding is requested. We expect the data-coordination job, which will be the only "service" aspect of the postdoc's position at CfA[4], to be mostly complete by 2005-6.

In addition to salaries in Year 3, we request the same items as in Year 2, with the exception that we increase (to $3,900) our **materials and supplies** request, anticipating that approximately $2,700 will be spent on a laptop computer. The laptop will be used by group members while traveling and giving presentations. The total **indirect costs** for Year 3 are calculated at a rate of 64%.

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[4] The COMPLETE postdoctoral fellowship has already been advertised, with a deadline of November 30, 2002. At this time (in early November), we already have several excellent applicants, who are happy to help organize the COMPLETE database, in exchange for being among the first to reap its rewards.