THE COMPLETE SURVEY OF STAR-FORMING REGIONS

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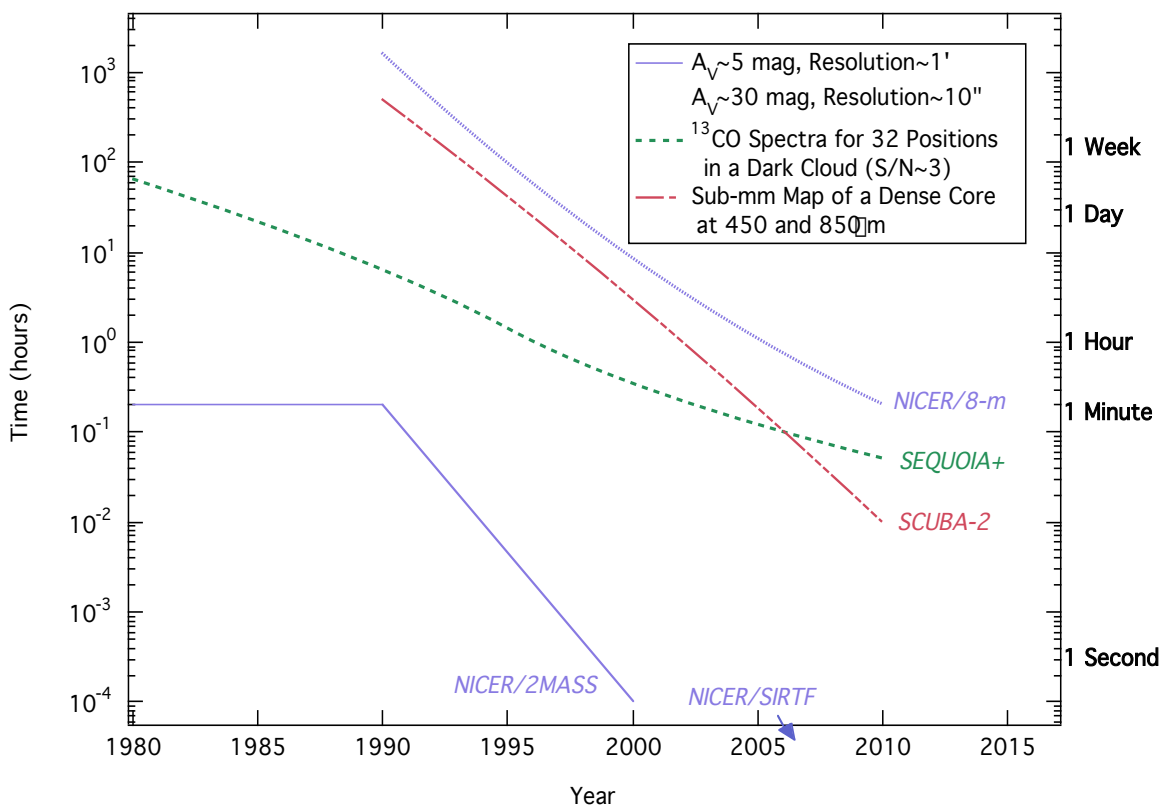

Figure 1: **Dramatic improvements in sensitivity** that make a COMPLETE Survey feasible. (Labels for sample instruments are shown near "2010" for graphical clarity, but these instruments will each be ready between now and ~2006. Note that "SEQUOIA+ refers to a SEQUOIA-like array on the Large Millimeter Telescope, scheduled to begin operations in ~2005.) Details of the observing modes summarized in this figure are discussed in the Project Plan section, beginning on p. 15.

SUMMARY OF PERSONNEL AND WORK EFFORTS

The P.I. and Senior Collaborators in the table below are those listed on the Cover Page of this proposal. As the proposal explains, the Senior Collaborators' participation in COMPLETE is vital to its success. The only reason these researchers are not listed as Co-I's is that their work on COMPLETE will not require any NASA funding. The ongoing and planned participation of undergraduate students and programmers at the Harvard-Smithsonian Center for Astrophysics (CfA) are also listed here.

PERSON	LEVEL OF EFFORT	SALARY SUPPORT REQUESTED
Alyssa **Goodman** Harvard College Observatory	P.I.	2 months
João **Alves** ESO Garching,, Germany	Senior Collaborator, 2 months/year	None
Hector **Arce** Caltech	Senior Collaborator, 2 months/year	None
Paola **Caselli** Osservatorio Arcetri, Italy	Senior Collaborator, 1 month/year	None
James **Di Francesco** HIA, Victoria, Canada	Senior Collaborator, 1.5 months/year	None
Doug **Johnstone** HIA, Victoria, Canada	Senior Collaborator, 2 months/year	None
Scott **Schnee** Harvard University	Graduate Student, 12 months/year	2 years
Mario **Tafalla** OAN, Spain	Senior Collaborator, 1.5 months/year	None
Thomas L. **Wilson** MPI, Bonn, Germany	Senior Collaborator, 0.5 months/year	None
Postdoctoral **Fellow** Harvard College Observatory	Postdoc, 12 months/year	3 years
Undergraduate **Students**	Website administration, archival research (1.5 months/year/student)	<250 hours/year per student
NVO **Programmers** CfA	3 person-months/year	None

THE COMPLETE SURVEY OF STAR-FORMING REGIONS

ABSTRACT

The COMPLETE Survey will produce an unbiased database that will serve the star-formation research community for many years to come. COMPLETE is comprised of COordinated Molecular Probe Line Extinction and Thermal Emission observations of a small set of large star-forming regions scheduled to be extensively observed by SIRTF. What is unique about COMPLETE is its coordinated approach. Prior observations of the types proposed here abound, but they only rarely fully-sample any region, and *no survey has ever* covered a single (~10 pc) region fully with molecular line, extinction, and dust emission observations. The lack of an unbiased survey like COMPLETE has left star formation theories without statistical constraints on the temporal and spatial frequency of: inward motions, outflow motions, star-formation; cloud disruption; core formation and several other key parameters. All of the COMPLETE data will be made publicly available on the Internet within one year of its acquisition, and we expect the statistical constraints offered by the COMPLETE Survey to be of great interest to the Milky Way, nearby-galaxy, and high-redshift star formation communities.

HISTORY & MOTIVATION

A CENTURY OBSERVING STAR-FORMING REGIONS

The COMPLETE Survey proposed here is inspired by the tremendous new insights surveys of star-forming regions have offered in the past. In this section, we give a brief history of past observations and their implications, underlining the most important surveys of the past century.[1]

1901-1963

In 1919, commenting on the blackness of the "dark nebulae" in his catalog, E.E. Barnard wrote that he had "proven" them to be "obscuring masses of matter in space" (Barnard 1919). Barnard pioneered the technique known as "star-counting," where one compares an expected to an observed density of stars on the sky and attributes any dearth to intervening interstellar dust. By associating the presence of this dust with gas seen to absorb background starlight and to produce emission line nebulae near hot young stars, many researchers during the first half of the twentieth century correctly concluded that large clouds of interstellar material somehow collapsed, either in whole or in part, to form new generations of stars.

Prior to the advent of radio-frequency molecular-line spectroscopy (c. 1964, see below), optical star-counting and spectroscopic observations were all theorists had to go on. Since the velocity resolution of optical spectroscopy is coarse in comparison with typical (non-violent) interstellar velocity dispersions, nothing was known about outflow, inflow, or turbulent motions in star-forming regions. As a result, most early "cloud-scale" (~10 pc) star-formation theories revolved around thermo-gravitational instabilities. Essentially none of those theories proved viable in the light of kinematic information that radio astronomy offered later.

1964-1989

In 1964, radio-frequency emission from OH was discovered to be coming from the interstellar medium (Barrett, Meeks & Weinreb 1964), and CO was detected six years later (Wilson, Jefferts & Penzias 1970). The detection of these two molecules, and more than 100 others since, revolutionized the study of star formation. It rapidly became obvious that stars formed from giant clouds of molecular hydrogen in our Galaxy, and that the motions in those clouds were highly supersonic. Many workers scrambled to explain the observed supersonic motions, often hypothesizing large-scale collapse. When the first large-scale CO surveys[2] began to reveal the huge reservoir of molecular gas available for star formation in the Milky Way, claims of collapse were scaled back, for fear of too high a star formation rate (see Zuckerman & Palmer 1974). Careful analysis of the kinematic information provided by molecular probe lines led Richard Larson

[1] We focus here on observations related to the study of star formation in "dark clouds," on scales > 0.1 pc.

[2] For the most recent CO survey, and a summary of prior surveys, see Dame, T.M., Hartmann, D. & Thaddeus, P. 2001, *The Milky Way in Molecular Clouds: A New Complete CO Survey*, ApJ, 547, 792..

to correctly conclude that the origin of the supersonic motions was likely to be turbulent (Larson 1981).

In 1980, Snell, Loren & Plambeck published a study of L1551 in CO, which showed a bipolar outflow in the molecular gas around the embedded young star IRS 5. The molecular outflow's spatial coincidence with several optically-detected Herbig-Haro knots of shocked emission bolstered the idea that the HH knots were part of a highly-collimated fast wind from the young star (Canto & Rodriguez 1980). Since 1980, numerous surveys for outflowing gas (e.g. Fukui et al. 1993) have been conducted, and they have shown that the outflow phase of star formation is common and long-lived.

In 1983, NASA's Infrared Astronomy Satellite flew, and its infrared survey of the Galaxy provided tremendous gifts to all astronomers. The star-formation community suddenly had *both* a complete census of young embedded sources (Beichman et al. 1986) and maps of the whole sky in thermal dust emission. Comparisons of the thermal dust emission with molecular-line emission from molecular clouds showed that velocity-integrated ^{13}CO J=1-O emission provided the best match to the 100-μm IRAS maps, with each tracing regions where the visual extinction was greater than about 1 or 2 magnitudes.[3] The wealth of velocity information in the molecular line data began to be combined with structural information provided by IRAS and star-counting probes of the clouds' density structure (e.g. de Vries, Heithausen & Thaddeus 1987).

In the same year as the IRAS Survey, Myers and Benson published their landmark NH_3 survey of dense cores (Myers & Benson 1983). Myers, Benson, and colleagues (including the PI and several of the Senior Collaborators) have gone on to quantify the properties of these cores, and to show that they are the sites of star formation in molecular clouds. To create the sourcelist for the Myers & Benson survey, Priscilla Benson scoured the Palomar Sky Survey for regions where A_V might be more than five magnitudes. However, the Palomar plates are not deep enough to tell with certainty by visual inspection where the A_V is that high, and radiotelescopes were not efficient enough to observe a "full sample" of these high extinction regions, even if they could have all been found.

1990-2002

By 1990, near-infrared cameras had developed to the point where a 64 x 64 array could image a star-forming region to a completeness limit of about 12th magnitude at 2.2 μm in under an hour. In 1991, Elizabeth Lada and colleagues exploited the new cameras *and* improvements in radio (mm-wave) detectors, to complete the first fully-sampled survey of a ~10-pc scale star-forming region in *both* near infrared emission and molecular lines. The combination of fully-sampled molecular line (CS) maps and 2 μm images allowed for the very first statistically-significant comparison of gas properties (Lada, E.A., Bally & Stark 1991a) with those of an embedded stellar population (Lada, E.A. et al. 1991b). Lada et al. created one of the first plots of a "clump mass spectrum" from their CS maps, and compared it with the "stellar mass spectrum" (or IMF) from their near-IR point-source catalog. The slopes of these two functions were very different, and this result is still the subject of intensive study today (see below). In addition, the near-IR/molecular-line map comparisons showed that most stars form in clusters, and that the clusters are embedded in the most massive molecular clumps. Lada et al.'s surveys and results stand as a benchmark in our field, with few as complete to have followed.

During the 1990's the speed with which large regions could be mapped in mm-wave spectral-lines increased dramatically due to: 1) improvements in detector technology; 2) the development of focal-plane arrays; and 3) a new observing technique known as "on-the-fly" mapping. By the end of the decade, it became possible to map ~10-pc scale regions fully in ^{13}CO in just days (rather than months) of observing time (see Figure 1). Extracting quantitative information from the wealth of large molecular-line surveys created proved challenging (see Padoan & Goodman 2001 and references therein). One popular statistic was the "clump mass spectrum," which continued to show a shallower power-law slope than the IMF (e.g. Williams, de Geus & Blitz 1994). In 1999, P.I. **Alyssa Goodman** and collaborators published a technique for analyzing large spectral-line maps, called the "Spectral Correlation Function" [SCF], which allows the

[3] Figure 4 shows a 1986-vintage ^{13}CO map in black-and-white contours (Bachiller & Cernicharo 1986). In the same amount of integration time used for this 1986 map, the FCRAO/SEQUOIA ^{13}CO observations in COMPLETE (see below, and Figure 4), will have 60 times the areal resolution and 4 times the velocity resolution of the 1986 map, and will be made in two lines (12CO and 13CO) simultaneously.

maps to be quantitatively compared with each other, and with numerical simulations. As of 1999, according to the SCF, no numerical simulation was able to create a highly realistic rendition of a star-forming region, but some simulations were shown to be "better" than others (Rosolowsky et al. 1999, *reprint attached*).

Molecular-line observers were inspired to renew their search for outflows on still larger scales, since Reipurth, Bally and Devine had shown that HH flows from young stars often extend for several pc on the sky, criss-crossing star-forming regions with long jets (Reipurth, Bally & Devine 1997). These searches (e.g. Yu, Billawala & Bally 1999, Arce & Goodman 2001b, 2002) showed the outflowing gas from young stars to have much greater mass, momentum, and energy—and a greater impact on cloud structure and evolution--than previously suspected (Bally et al. 1999; Arce 2001; Arce & Goodman 2002, *reprint attached*).

On smaller scales, molecular-line observers surveyed several "dense cores" with higher sensitivity and spectral resolution than in the past. The two prime results of these efforts were: 1) evidence for "inflow" (a.k.a. infall) in many sources[4] (e.g. Mardones et al. 1997) ; and 2) evidence for depletion of many (allegedly) high-density-tracing molecular species (e.g. Caselli et al. 1999; Tafalla et al. 2002, *reprint attached*). Senior Collaborators **Paola Caselli**. **Mario Tafalla** and **James Di Francesco** were instrumental in obtaining these results.

Some of the most dramatic advances of this decade stemmed from the completion of mm and sub-mm bolometer arrays that allowed for the creation of extended maps of the thermal emission from dust in star-forming regions. The 19-channel bolometer operating at 1.3-mm at the IRAM 30-m telescope was used by Motte, Andre & Neri (1998) to create the first "clump mass spectrum" showing a slope *similar to the IMF*.[5] The Submillimeter Common User Bolometer Array (SCBUA[6]) at the JCMT was used by Senior Collaborator **Doug Johnstone** and his collaborators to fully map several extended star-forming regions in 850 μm emission (see Figure 2). Johnstone and colleagues also found an IMF-like slope for the clumps identified in their continuum survey (e.g. Johnstone et al. 2000b, *reprint attached*). Current thinking is that the emission mapped at 1.3 mm or 850 μm shows *only* the dust associated with the densest gas in the regions observed, and that this gas' mass distribution is similar to that of the stars that ultimately form there. Thus, a good hypothesis now is that the *clump mass spectrum steepens (and ultimately matches the IMF slope) at higher density within a star-forming region.* COMPLETE will allow for by far the best tests ever of this idea.

Finally, the 1990's was a boom time for extinction mapping. Charles Lada and collaborators re-invigorated the field of "optical" extinction-determination, by inventing the Near-Infrared Color-Excess (NICE) Method (Lada et al. 1994). In brief, the method assumes that most stars have similar color excesses in the near-infrared, uses large near-infrared surveys of molecular clouds to measure an average color excess within a box, and assigns the difference between the expected and observed color to extinction. Senior Collaborator **João Alves** used the NICE method in his Ph.D. thesis with Charles Lada to find density structures in dark clouds that are inexplicable by existing theory (Alves et al. 1998, Alves, Lada & Lada 1999). On smaller scales, Alves and colleagues have used the NICE method to analyze the structure of a pre-stellar core and have found it to have the density profile of a perfect critical Bonnor-Ebert[7] sphere density profile (see Figure 3 and Alves, Lada & Lada 2001, *reprint attached*). SCUBA and CSO observations of dust *emission* in similar sources have also shown Bonnor-Ebert-like density profiles in cores (Johnstone et al. 2000b--*reprint attached*, Evans et al. 2001, Johnstone et al. 2001).

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[4] The evidence for "inflow" comes from the presence of redshifted self-absorption features in high-opacity molecular-line tracers at the center velocity of low-opacity tracers that show no self-absorption. An example of such spectra is given in Table 1. The important point to remember about most of the "inflow" found thus far is that it is too rapid and extended to be associated with gravitational "infall."

[5] Motte et al.'s target was the relatively nearby (160 pc) Ophiuchus star-forming region. Testi & Sargent (1998) found similar results in the more distant (310 pc) Serpens cloud, using the OVRO interferometer at 3-mm.

[6] Prior to SCUBA, extensive sub-mm "mapping" of molecular clouds was almost never undertaken.

[7] As a reminder, a "Bonnor-Ebert" sphere is a self-gravitating isothermal sphere bounded by a fixed external pressure (Ebert, 1955, Bonnor, W.B. 1956)

The picture starting to emerge from the column-density mapping is that the turbulent density and pressure structures on a given scale are critical in determining the density and pressure structure on the next smallest scale. Again, COMPLETE will allow for excellent tests of this idea in the near future.

2002-2007: WHY A COMPLETE SURVEY IS NOW POSSIBLE

Over the next five years, a series of events will conspire to make a "COMPLETE" Survey possible.

1. The entire **NASA 2 Micron All Sky Survey** (2MASS) survey will be released. Lombardi & Alves (2001) have already shown, using early 2MASS data, that an improved version of the NICE method (**NICER**) can produce extinction maps of nearly any molecular cloud region with ~arcminute resolution[8] to a depth of about 5 magnitudes A_V (see Figure 2, below.).
2. The **NASA SIRTF Legacy project**, "From Molecular Cores to Planet-forming Disks" (Neal Evans, PI), will spend hundreds of hours of SIRTF time (in ~2003) mapping out five molecular cloud complexes in far-infrared emission and take a full (near-IR) census of embedded sources in those complexes. Infrared spectroscopy will also be done for a large sample of the (new and known) embedded sources in the target regions. (*The COMPLETE Survey is explicitly intended as a contextual complement to the SIRTF Legacy Project*. The three regions selected for COMPLETE are a subset of the five Legacy targets.)
3. The **32-element SEQUOIA** array is, as of 2002, complete and ready-to-use on the FCRAO 14-m telescope. Our "pilot" FCRAO SEQUOIA observations, shown in Figure 4, demonstrate that SEQUOIA lives up to the expectations shown in Figure 1.
4. The **19-element bolometer** formerly used at the IRAM 30-m has been re-outfitted to work at 850 μm at the **Submillimeter Telescope** on Mt. Graham Arizona. The COMPLETE collaboration has entered into an agreement with Arizona to use the SMT to map out large sections of molecular clouds in 850μm emission, if the SMT is deemed more effective than SCUBA for the COMPLETE Survey (see p. 9).
5. Several **8-m-class telescopes** have been or are about to be outfitted with **near-IR cameras**. It will be possible to use these cameras, with techniques like NICER, to make exquisite high-resolution (~10") deep (>30 mag A_V) column density maps of embedded cores in molecular clouds, like the one shown for B68 in Figure 3.
6. The IRAM 30-m telescope has two new instruments, **HERA** a 9-element 1.3-mm heterodyne receiver array, and **MAMBO**117, a 117-element 1.3-mm bolometer array. Both of those instruments will speed mapping of star-forming regions at ~10" resolution by at least an order-of-magnitude over 1990's rates.
7. The SCUBA array at the JCMT is slated to be replaced with the **SCUBA-2** array, which, in addition to being bigger and faster than SCUBA, will subdivide the sub-mm passband in order to do narrow band photometry—allowing for much better dust temperature determinations than previously possible.
8. The **National Virtual Observatory** is becoming a reality. The P.I. of COMPLETE is also the P.I. on an NSF NVO grant to Harvard, and a Co-I on the $10M U.S.-wide NVO project. Please see p. 20. for more information on the NVO-COMPLETE connection. The reality of NVO means that huge, diverse, data sets like the one to be generated by COMPLETE can be stored and accessed on-line by experts and non-experts alike.

As explained in Table 1, and in the Project Plan below, *COMPLETE's top priority will be to fully sample three SIRTF Legacy regions at ~arcmin resolution* using developments 1-4, and 8, above. Much use will also be made of (higher-resolution) developments 5-7, but "completion" will not be promised at those scales.

THEORY OF STAR-FORMING REGIONS

The theory of star formation in 2002 comes in two forms. First, there are analytic theories, most of which treat only the formation of a single star, in a relatively quiescent, symmetric (e.g. spherical, toroidal), blob of gas. The second kind of "theory" is numerical, and treats star formation as the end product of a very turbulent process that, with the help of gravity, can convert a large cloud of gas into many stars.

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[8] Laurent Cambrésy and his colleagues at IPAC have recently developed a technique for mapping extinction using 2MASS data that they claim competes favorably with NICER (Cambrésy et al. 2002). We discuss the comparison of these techniques further on p. 9.

Analytic or "Smooth" Star Formation

Much of the theoretical work in this area stems from a picture of star formation that evolved from Frank Shu's calculations of the inside-out collapse of a singular isothermal sphere (Shu 1977).[9] Since 1977, a variety of important "complications" have been added to the "smooth" theory, motivated in large part by the observational findings about outflows (Snell et al. 1980) and energetically-significant magnetic fields (Myers & Goodman 1988a), and by results that show that the vast majority of stars form in binaries or higher-order multiple systems (White & Ghez 2001). The current "smooth" theory of star formation includes a magneto-centrifugal wind responsible for driving outflows (see Shu et al. 1994 and citations thereof) that interacts with a disk-like geometry around forming stars (e.g. Li & Shu 1996). At present, no self-consistent analytic theory is very good at forming binaries—and all are very bad at explaining clusters.

In our opinion, smooth models do apply to the real star formation going on in the ISM, but within self-gravitating blobs of gas that are relatively cut off from their more turbulent surroundings. In regions without large clusters (e.g. the filamentary parts of dark clouds), we have found such "cut-off" regions observationally, and call them "coherent cores" (Goodman et al. 1998). Barnard 68, featured in Figure 2, is a good example of such a core. In cluster-forming dense regions, Myers has studied the existence of similarly "quiescent" pre-stellar condensations, and calls them "kernels" (Myers 1998). Both we and Myers and his colleagues hypothesize that the "islands of calm in a turbulent sea" represented by coherent cores and kernels are created in magnetized turbulent flows when an overdense region is created either randomly or due to the dissipation of magnetic fields. In our picture, these overdense, self-gravitating, regions evolve into Bonnor-Ebert-like condensations (like the ones found in the NICE analysis of B68 and the SCUBA observations of cores), where the "external pressure" on the condensation is the turbulence in the ambient medium. (A related idea has cores created in colliding streams within a turbulent flow, see below.) Tests this picture will be one of the P.I.'s highest priorities when analyzing the COMPLETE data.

Numerical or "Turbulent" Star Formation

On scales larger than coherent cores or kernels (roughly, >0.1 pc), no satisfactory analytic physical theory of the origin and evolution of the structures in star forming gas has yet been made. Instead, most of the "theoretical" insights into the physics of gas on ~0.1 to 100 pc scales has come from numerical simulations of the ISM.

Over the past five years, with the advent of computers fast enough to simulate a dynamic range greater than one order of magnitude in density, several groups including one that includes the P.I. as a collaborator, have embarked on numerical simulations of the star-forming ISM. The P.I.'s 1998-2002 NSF grant was largely devoted to testing the validity of these simulations with the Spectral Correlation Function. As of today, the SCF analysis has shown that no simulation matches a dark cloud complex like the ones we plan to observe in the COMPLETE Survey perfectly, but some come intriguingly close (Padoan & Goodman 2002). The SCF will be a critical tool in analysis of COMPLETE spectral-line data.

The simulations that come closest to matching existing radio spectral-line observations (e.g. Padoan et al. 1998) do so in large part because Monte Carlo radiative transfer has been included in the calculations of synthetic spectral-line maps. Simulations that offer only "density-weighted histograms of velocity" as spectra tend to do worse in the SCF comparisons. Besides passing the "SCF-test" the most realistic simulations make the following predictions, all of which can be tested using the SCF on COMPLETE data:

1. The slope of the clump mass spectrum steepens as one moves toward higher-density regions, and matches the IMF on the scale of "dense cores" (n~10^4 cm^{-3}; see Padoan et al. 2000)).
2. Cores form at "shocked" regions within larger clouds, when streams of gas in a turbulent flow collide (Ballesteros-Paredes, Hartmann & Vázquez-Semadeni 1999, Padoan et al. 2001b).
3. Turbulence dissipates in less than one million years if it is not driven by large-scale forces (e.g. giant outflows; Padoan et al. 1998, Mac Low 1999, Ostriker, Gammie & Stone 1999, Padoan & Nordlund 1999).

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[9] Many workers in addition to Frank Shu and his colleagues have made key contributions to "smooth" theories of star formation. In particular, the work of Telemachos Mouschovias and colleagues has provided important constraints on the structure of magnetically-supported cores.

What's Currently Possible?

As we explained at the outset, "surveys" of star-forming regions abound. To date, these surveys almost all deal with one particular kind of observation, made at a list of positions, scattered around the sky. Such

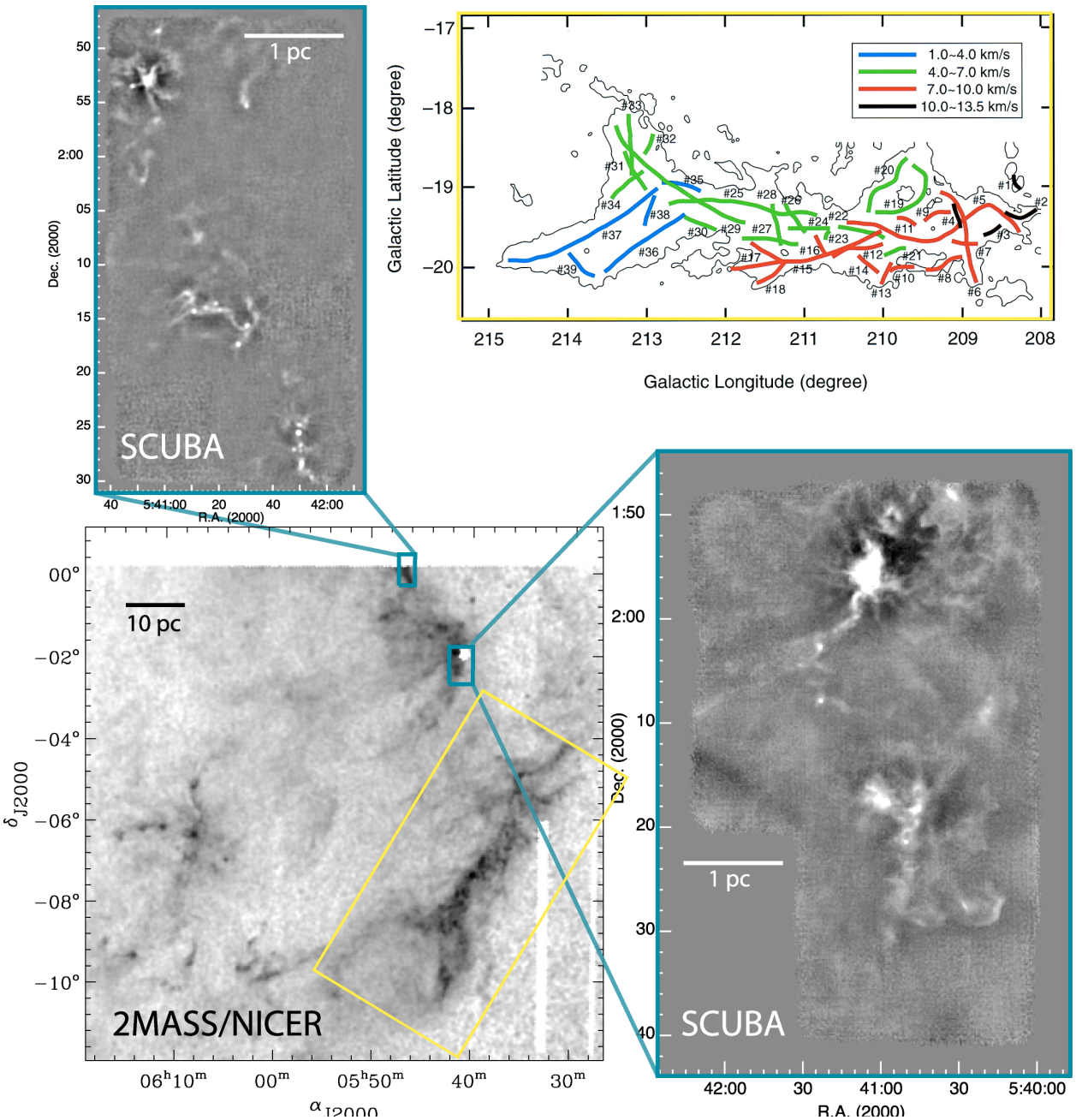

Figure 2: (Un)coordinated Molecular-Probe Line, Extinction and Thermal Emission Observations in Orion.

Upper right panel: Outermost contour from Nagahama et al. 1998 ^{13}CO (1-0) Survey of the Orion A Cloud; colored lines show filament positions and velocities; resolution is 3'. *Lower left panel:* Extinction map of dust distribution made by applying the NICER method to 2MASS infrared camera observations (Lombardi & Alves 2001); resolution is ~5'; yellow tilted rectangle shows outline of Nagahama map. *Upper left and lower right panels*: sub-mm emission from dust, observed at SCUBA by Johnstone et al. 2001; resolution is ~10".

surveys have given tremendous insight into the prevalence of various processes and into the nature of particular types of objects. Trouble is, without advance coordination of observations, even the wealth of data currently available is unable to answer many critical questions. Take a look at Figure 2 as an example. That figure shows absolutely state-of-the-art observations of the Orion star-forming region (arguably the most popular target in the nearby Galaxy), and while they are individually wonderful, and can be fruitfully inter-compared where they do overlap, the lack of general overlap means these data sets cannot be used to draw statistically meaningful conclusions about the density and velocity structure or evolution of the Orion complex as a whole.

What would be better? A COMPLETE Survey

In several recent studies, multiple techniques (e.g. molecular-probe line, extinction, and thermal emission mapping) have been used to observe a single object or small set of objects. These multi-method studies have given *tremendous* insight into the nature of star forming regions whenever they have been done. Perhaps the very best example of (high-resolution) observations with the "COMPLETE" suite of techniques is shown in Figure 3, which summarizes observations of Barnard 68. The extinction and thermal emission observations of B68 have shown it to be a nearly perfect Bonnor-Ebert sphere (see above). When the molecular-line ($C^{18}O$) data shown are compared with either of the column density probes, it is immediately apparent that the $C^{18}O$ abundance declines dramatically toward higher densities. This result, along with similar findings of "depletion" by others has raised very worrying questions about the ability of various molecular-probe lines to trace structure in the innards of dense gas. (On the brighter side, evidence for depletion of particular species is of great interest to astrochemists!) Currently, the $C^{18}O$ and other molecular line observations are being analyzed by Alves, Charles Lada, and collaborators to look for signs of rotation, infall, or outflow associated with B68. Once such kinematic analysis is done, the molecular-line-independent density profiles from the extinction and/or thermal emission data can be used to study how velocity structure depends on density.

To be able to do this kind of multi-method unbiased analysis on a larger scale, fully sampling ~10-pc-scale regions at better-than-arcminute resolution would fulfill the dreams of dozens of star-formation researchers—observers and theorists alike. In fact, the very SIRTF Legacy Survey which COMPLETE is explicitly designed to complement, was proposed on the grounds that "our understanding of star formation is hampered by the lack of complete databases for systematic studies." (This quote comes from a recent letter to P.I from the SIRTF Legacy P.I., Neal Evans. This important letter explains why the SIRTF Legacy team would very much like to see COMPLETE supported by NASA's LTSA program, and it is reproduced in full on p. 32 of this proposal.) The box below contains a small sample of the kinds of questions we and others will be able to address with a combination of the SIRTF Legacy data and the COMPLETE Survey data described in the following section. Nearly all of these questions are unanswerable with the SIRTF data alone, and only a few would be answerable with COMPLETE data alone.

1. Do star-forming cores form in special places, such as "colliding streams" of gas? Are "inflow" line profiles (e.g. lower left figure in Table 1) associated with cores caused by such streams?
2. What is the space density of cores with line width "x" times less than their surroundings? What fraction of that bias-free list of cores contains embedded sources?
3. How do the properties and/or frequency of embedded sources correlate with velocity dispersion, average density, local density, vorticity?
4. Are all regions of a dark cloud "the same" in their density and velocity structure? Can any evidence for time-evolution of any process be found?
5. How well to gas and dust track each other? Which species deplete where?
6. How does dust emissivity vary with density, and/or with velocity dispersion?
7. How prevalent are outflows in molecular clouds? What is their projected long-term effect?
8. Do outflows force molecules off grain surfaces back into the gas?
9. How deceptive does chemical depletion make molecular line maps? Does depletion inhibit our ability to see velocity structure inside dense cores?
10. What is the efficiency of star formation, per unit mass, per unit volume, and/or per unit time?

PROJECT PLAN

Few, if any, of our colleagues would argue that a "complete" survey of any star-forming region could not be used to address the list of questions above—but many might contend that "completeness" or full-sampling with many diverse techniques is unattainable over a wide area on the sky. As Figure 1 shows, though, the transition from "days" to "minutes" over the past several years for so many key types of observations has truly brought us to the day when a COMPLETE Survey is possible.

The dramatic increase in the amount of data obtainable allows for the COMPLETE Survey outlined in Table 1, but it also prohibits even a talented consortium like ours from digesting all of these data ourselves. We have already had several discussions amongst the consortium members to determine which questions from the list above (and others) are of greatest interest to each participant.[10] We expect the fruits of this proposal to include at least twenty papers written by the COMPLETE team in various combinations, along with a tremendously valuable online database that will serve the star formation community for years to come. We fully appreciate that it will take years to answer a full list of questions like the one above—but we also know that valid answers *are not possible* without an unbiased data set to work with. The COMPLETE database will be of at least equal value to its short-term publication list.

What COMPLETE gives to NASA is an *essential* complement to the data that the SIRTF Legacy Survey will offer (see Evans' letter, p. 32). Without COMPLETE's molecular-probe-line mapping, NASA's SIRTF data—and for that matter NASA's 2MASS extinction data—need to be interpreted without comparably "complete" kinematic information. Far-infrared dust emission maps are very sensitive to the hard-to-measure dust temperature and grain size distribution, while near-infrared extinction maps are not. So, without COMPLETE's extinction mapping (which uses 2MASS data at first, and ultimately the SIRTF Legacy data itself), calibration of the dust column density derivable from SIRTF's far-infrared thermal dust emission observations would be perilously unreliable.

The strategy of our Survey is given next, followed by a detailed timeline for the COMPLETE Survey. Table 1 shows which planned observations will yield what type of information and results.

SOURCE SELECTION

When discussing the possibility of a COMPLETE Survey last Summer at the Santa Cruz Star Formation Workshop, it took us no time at all to realize that our target regions should be a subset of the SIRTF Legacy project targets. The Evans et al. SIRTF Legacy project, scheduled for 2003, will map out five molecular cloud complexes in far-infrared emission and take a full (near-IR) census of embedded sources in those complexes. In addition, SIRTF spectroscopy will give information about the mass, age, luminosity, and disk properties of many of the embedded sources. The 70 μm SIRTF maps will provide the shortest-wavelength component of the thermal emission component of COMPLETE (see below). The point sources extracted at a variety of shorter infrared wavelengths will not only provide the key embedded source catalog needed for our study, but will also be used to construct NICE extinction maps of any region SIRTF observes (including those not even included in the Legacy Survey).

Our goal is to observe all three of the SIRTF Legacy regions visible from the Northern Hemisphere in the COMPLETE Survey (Perseus, ρ-Ophiuchus, and Serpens). Some of the data needed for the COMPLETE Survey are already in hand (e.g. SCUBA maps of Ophiuchus by Johnstone et al, pilot COMPLETE observations at FCRAO (taken Spring 2002, see Figure 4)), but the bulk of the work remains to be done.

COORDINATION

The single most important element of the COMPLETE survey is its *coordinated* approach. Dozens of recent papers, many of them ours, fill the Journals with the molecular-line, extinction, and thermal-emission observations of the kind we propose here. In fact, one of the first steps we will take in executing the COMPLETE Survey is a thorough search for any relevant data already available in electronic form[11].

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[10] The interested reviewer is invited to see our consortium's detailed planning documents, including lists of hypothetical papers based on COMPLETE, at http://cfa-www.harvard.edu/~agoodman/research8.html.

[11] We have, in fact, nearly completed this search, and we assure the reviewers of this proposal that The COMPLETE Surveyis indeed necessary. We and our colleagues have not been very good about maintaining our data in electronic

Much of the usable information will be in the form of recently-made molecular-spectral-line and SCUBA maps of known dense cores in our target regions. Please keep in mind that *our principal goal is to link together a diverse set of studies of a pre-selected set of star-forming regions to be observed by SIRTF in the most irrefutable (systematic) way possible.*

MOLECULAR PROBE LINE MAPPING

In the Spring of 2002, the new SEQUOIA array at FCRAO was completed, so that one can now measure the spectrum of two spectral lines at 32 positions on the sky simultaneously. In addition, "on-the-fly" mapping is now possible with the array. As Figure 1 indicates, 32 decent ^{13}CO spectra can be obtained in tens of seconds with SEQUOIA. Both our initial calculations, and now our pilot FCRAO observations (taken April 2002, Figure 4), show that to fully map the A_V>1 gas in the Perseus complex shown in Table 1 in ^{13}CO *and* ^{12}CO would take about 4 days of observing time, if a typical S/N of 5 was desired.

For higher spatial resolution, we will use HERA and other receivers at the IRAM 30-m telescope to map tracers of density, temperature and velocity in the cores mapped at lower resolution with FCRAO. As stated above, the higher-resolution component of our work is not expected to be "complete," in that it will not fully sample every core within each complex. But, several members of our team (Caselli, Tafalla and Goodman) have been very successful in getting and efficiently using 30-m time in the past, so we expect our proposals for more time –especially if they bear the "COMPLETE" label—will be met with favor. The SIRTF Legacy team is planning similar observations, but given 30-m proposal pressure, they are happy to have our interest and cooperation (see letters from Evans and Myers, p. 32).

EXTINCTION MAPPING

2MASS data, analyzed with the methods such as NICER, allow us to create fully-sampled extinction maps of *any* region we choose to study. This work has already begun (e.g. Lombardi & Alves 2001), and should proceed very quickly. In the Summer of 2002, we are beginning a collaboration with Laurent Cambrésy, who is at IPAC, to test various alternative algorithms for mapping extinction using 2MASS data. We have agreed to test the Cambrésy et al. (2002) extinction-mapping method, NICER, and possibly a third method on a single 10-pc-scale COMPLETE field, and to intercompare the results statistically. Once this is done, we will settle on one, or a hybrid, method and produce maps of all the COMPLETE fields before SIRTF is even launched.

NICER-like techniques applied to the near-IR SIRTF data (including, but not limited to, the Legacy data) will allow for extinction mapping with very high resolution—and an unprecedented dynamic range in scales. João Alves, Alyssa Goodman, and Neal Evans have already begun discussions about how the COMPLETE and Legacy teams can work together to carry out SIRTF-based extinction mapping.[12]

At higher resolution, we will rely on our past success with standard proposal mechanisms to get 8-m observing time (e.g. at ESO facilities through Alves and at Harvard and SAO facilities through Goodman, as well as at National facilities). Based on Figure 1, and proposal pressure, we expect it will be possible to do a "B68-like" job (see Figure 3) on just a few cores in each dark cloud studied in the COMPLETE Survey, but that will be enough to connect our measurements of density and velocity structure on larger scales down to the finer scales that NICE can probe given good near-IR data. We will be able to quantify how the transition from a turbulent medium to a Bonnor-Ebert-like starless core is accomplished with this amount of data.

THERMAL EMISSION MAPPING

COMPLETE's thermal emission database and analysis will make use of both the SIRTF Legacy data itself, and ground-based submillimeter (850 μm) data.

The submillimeter data will be obtained by the COMPLETE collaboration *either* at the Submillimeter

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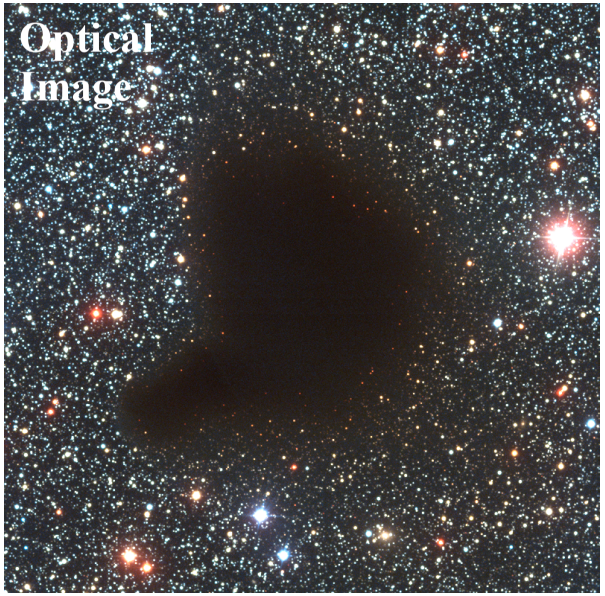
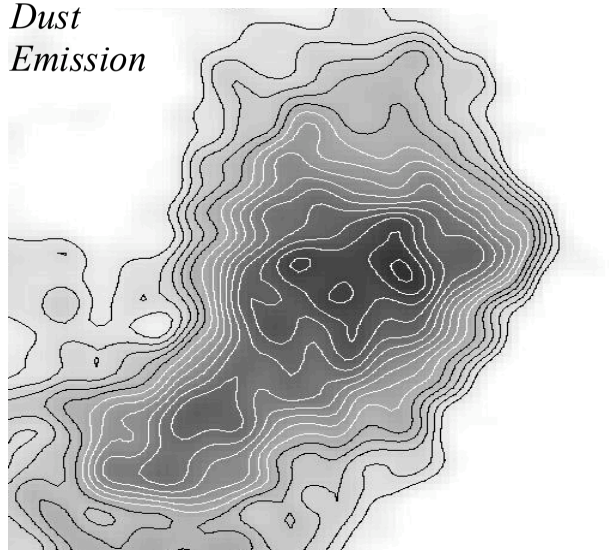
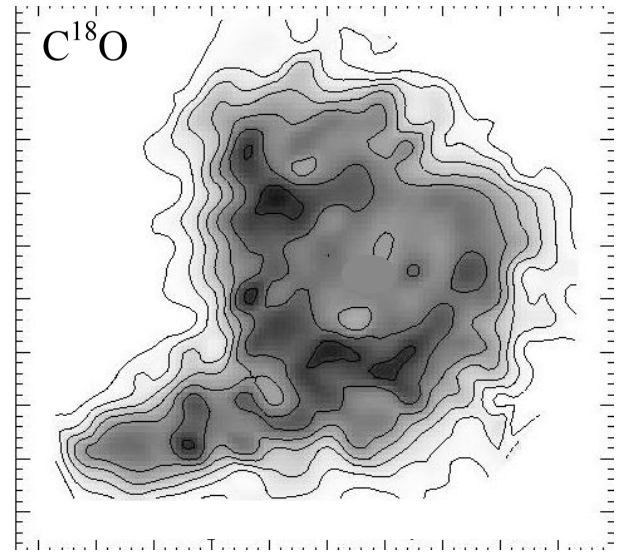
form thus far!

[12] Using a more direct method, Bacmann et al. (2000) used ISO's mid-IR capability to map cores in absorption against the diffuse mid-IR background. It should be interesting to compare NICER point-source-based results with SIRTF mid-IR absorption mapping similar to Bacmann et al's.







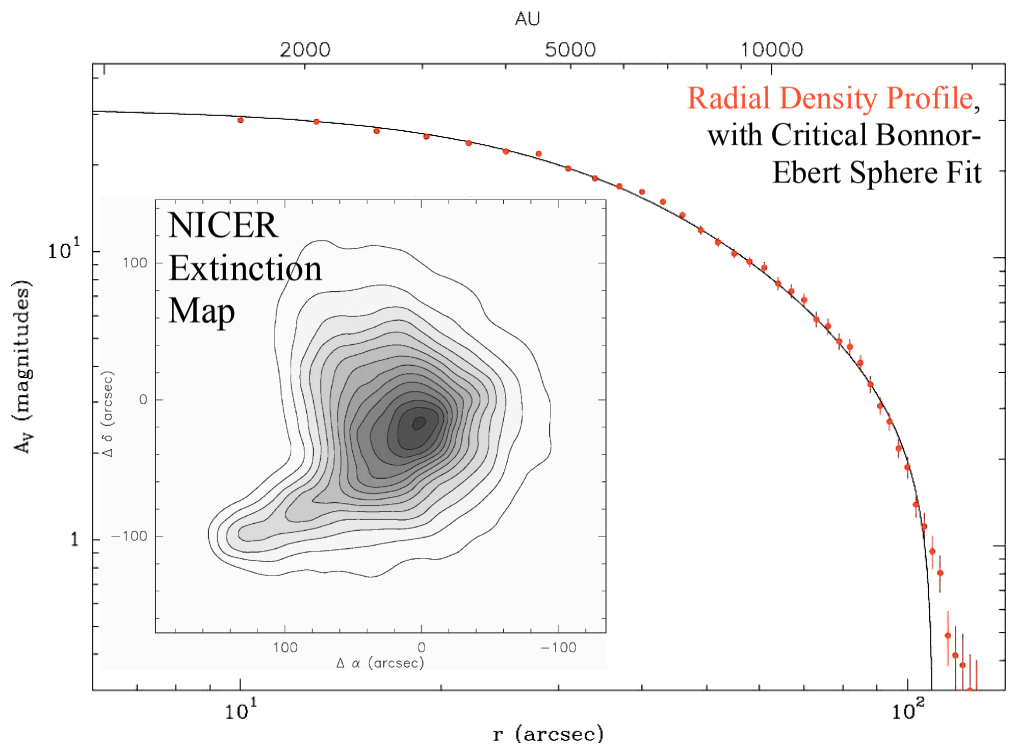
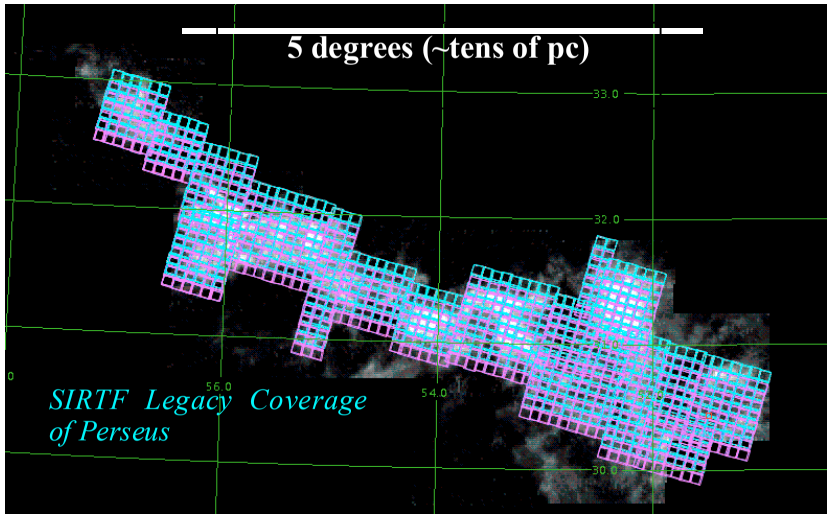
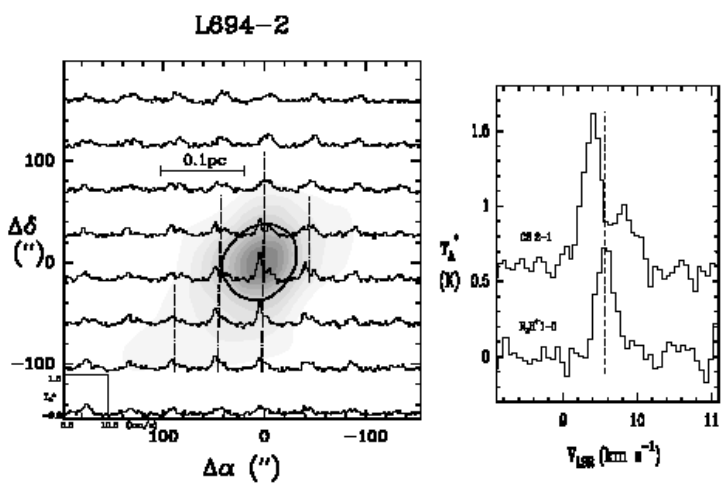


Figure 3: Coordinated Molecular-Probe Line, Extinction & Thermal Emission Observations of Barnard 68

This figure highlights the work of Senior Collaborator **João Alves** and his collaborators. The *top left* panel shows a deep VLT image (Alves, Lada & Lada 2001, *reprint attached*). The *middle top* panel shows the 850 μm continuum emission (Visser, Richer & Chandler 2001) from the dust causing the extinction seen optically. The *top right* panel highlights the extreme depletion seen at high extinctions in $C^{18}O$ emission (Lada et al. 2001). The inset on the *bottom right* panel shows the extinction map derived from applying the NICER method applied to NTT near-infrared observations of the most extinguished portion of B68. The *graph* in the bottom right panel shows the incredible radial-density profile derived from the NICER extinction map (Alves, Lada & Lada 2001, *reprint attached*). Notice that the fit to this profile shows the inner portion of B68 to be essentially a perfect critical Bonner-Ebert sphere

Table 1: COMPLETE SUMMARY

Sample Region	Planned Observations	COMPLETE Results
	• **SIRTF Legacy Observations** give dust temperature and column density maps and information on point sources *~5 degrees mapped with ~15" resolution (at 70 μm)* • **NICER/2MASS Extinction Mapping** gives dust column density maps, used as target list in SMT & FCRAO observations + reddening information *~5 degrees mapped with ~5' resolution* • **SMT or SCUBA Observations** give dust column density maps, finds all "cold" sources *~20" resolution on all A_V>3 mag* • **FCRAO/SEQUOIA ^{13}CO and ^{12}CO Observations** give gas temperature, density and velocity information *~40" resolution on all A_V>1 mag*	• **Combined Thermal Emission (SIRTF/Sub-mm)** data will yield dust spectral-energy distributions, giving emissivity, T_{dust} and N_{dust} • **Extinction/Thermal Emission inter-comparison** will give unprecedented constraints on dust properties and cloud distances, in addition to high-dynamic range N_{dust} map. • **Spectral-line/N_{dust} Comparisons** Systematic censes of inflow, outflow & turbulent motions will be enabled—for regions with *independent* constraints on their density. • **CO maps in conjunction with SIRTF point sources** will comprise outflow census
	*Using target list generated from above column-density-limited surveys:* • **NICER/8-m/IR camera Observations** give best density profiles for dust associated with "cores". *~10" resolution* • **SCUBA Observations** give density and temperature profiles for dust associated with "cores" *~10" resolution* • **FCRAO+ IRAM N_2H^+ Observations** give gas temperature, density and velocity information for "cores" *~15" resolution*	*All of the above combinations & inter-comparisons will be possible, plus:* • **Multiplicity/fragmentation** studies • Detailed modeling of **pressure structure** on <0.3 pc scales • Searches for the "loss" of turbulent energy (**coherence**) *Image at left shows an FCRAO N_2H^+ map with CS spectra superimposed. The two spectra shown in detail are for the central position. Notice how the (thick) CS shows self-absorption, while the (thin) N_2H^+ does not (Lee, Myers & Tafalla 2001).*

Telescope on Mt. Graham, or at the JCMT (using SCUBA) on Mauna Kea. Our aim is to fully map all areas within the three Northern SIRTF Legacy fields that have A_V>3 mag. Pilot COMPLETE observations at the SMT taken by Doug Johnstone in February 2002 showed that: the newly-installed 19-element 850-μm bolometer at the SMT can work with the novel observing scheme Johnstone invented for his SCUBA observations; but also that the signal-to-noise ratio is about a factor-of-two worse than what is theoretically achievable. This makes the SMTO array more than an order-of-magnitude slower than mapping with SCUBA on the JCMT[13]. Furthermore, a recent archival search by Johnstone has revealed that enough high-quality SCUBA data have already been taken to make it possible to fill in the missing A_V>3 mag pieces of the COMPLETE fields with SCUBA alone, without the need to use the SMTO. Over the Summer of 2002, in collaboration with a student, Johnstone and Goodman will use existing published low-resolution column density maps (many of which are based on IRAS) of the COMPLETE fields to determine exactly how much time would be needed to cover all of the gas in the Northern SIRTF Legacy fields at A_V>3 mag with SCUBA. If the amount of time exceeds what it would be possible to get at the JCMT over a 2 year period, (~100 hours), we will re-visit the possibility of a long-duration observing program at the SMTO[14].

The SIRTF Legacy team plans to map several of the highest-density (A_V>10 mag) peaks with the CSO and/or SCUBA on their own, and many of the best-known cores have already been mapped. So, the selection of COMPLETE's SCUBA targets will be made carefully, taking care to coordinate not only with our own efforts at other observatories, but also with the SIRTF Legacy team itself. Our goal, once again, will be to assure a statistically complete database, where all gas with A_V>3 mag within the COMPLETE fields, has been observed at 850 μm, and all of the data are made available online.

Survey Progress, Plan & Management

Page limits, and your patience, do not allow us to describe the entire management plan for this complex project here, so instead we offer the table below. For a more thorough management plan, please see the COMPLETE web site at http://cfa-www.harvard.edu/~agoodman/research8.html. Between the face-to-face meetings listed below, communications amongst the COMPLETE consortium members has been and will be accomplished via email, scheduled teleconferences and live web conferencing. In addition to the all-consortium Collaborators Meetings listed below, smaller, less formal face-to-face meetings will also occur.

Time	Task/Status	Lead (s)[15]
1/02	Submit FCRAO proposal for pilot ^{13}CO observations, to be used in optimizing remote on-the-fly mapping with SEQUOIA. Status: Proposal approved. Sample results shown in **Figure 4**. The FCRAO data (including ^{12}CO, ^{13}CO, N_2H^+ and CS maps of parts of Perseus and Serpens) are phenomenally good—despite being taken in a fluke heat wave. Noise values are at the theoretical limits used in the calculation of Figure 1.	Goodman/ Schnee
2/02	Pilot SMT observations. Status: Despite getting the SMT array to work nearly as expected, we are considering using only SCUBA, and not the SMT in COMPLETE. See detailed discussion on p. 9.	Johnstone/ Wilson
6/02	Collaborator's meeting at Arcetri Observatory, Florence. Status: Goodman, Caselli and Johnstone met to review FCRAO and SMT data in hand so far. Face-to-face discussions led to revised emission plan discussed on p. 9.	Caselli hosted

[13] An exact estimate of the relative speeds will be made in Summer 2002. The calculation is not as straightforward as it might seem, due to mechanical and software constraints on how rapidly one can scan with SCUBA.

[14] When COMPLETE was first conceived, it had been our intention to use about 1 month of observing time at the SMT for 850-μm observations, in exchange for our providing a postdoc to work for a time in Arizona. Such a plan is still a possibility (see letter from Thomas Wilson, p. 34), but our current strategy will only make use of the SMTO if the SCUBA option seems untenable.

[15] "Lead(s)" specifies the person(s) with *primary* responsibility for a given task. Note from the table that **Goodman is responsible for the overall management of COMPLETE; Alves heads the extinction efforts; Johnstone is in charge of thermal emission mapping projects; and Schnee is taking the lead on FCRAO/SEQUOIA observations. Caselli and Tafalla will take the lead on IRAM 30-m observing.** The **integration of** all **COMPLETE** data into one database will be the responsibility of the **postdoc** hired on this grant, but much assistance with this task will be provided by Schnee and NVO programmers.

Spring/ Summer '02	Liteature/online search to find all electronically-available available relevant data. Create initial web site making these data electronically available. Status: All pilot COMPLETE data are now on-line at http://cfa-www.harvard.edu/~sschnee/complete.html. Online search underway.	Goodman/ Schnee/ Borkin[16]
	Measure areal coverage of A_V>3 material in COMPLETE fields, and estimate area already mapped at 850 μm, in order to decide on SCUBA vs. SMT observing. Status: Johnstone has begun archival search. Li to begin coverage mapping.	Johnstone/ Goodman/ Li[17]
	Construct extinction maps using both NICER and Cambrésy technique, of sample COMPLETE region using 2MASS data.	Alves (with Cambrésy)
Fall '02	Collaborators' meeting to decide on needed observing proposals. Invite SIRTF Legacy team members to meeting.	All, at CfA
	Submit observing proposals to SCUBA or SMT	Johnstone
	Request remainder of FCRAO time for large-scale mapping (COMPLETE is already approved for "Key Project" status at FCRAO, if LTSA proposal succeeds.)	Schnee/ Di Francesco
	Submit proposals to 8-m telescope with IR camera for NICER data on already- known cores in target regions.	Alves
12/02	Submit proposals to IRAM 30-m for any molecular-line mapping of cores in target regions not to be mapped by SIRTF Legacy team[18].	Tafalla/ Caselli/Schnee
1/03	**Likely SIRTF Launch**	NASA
2003	Carry out SCUBA/SMT, FCRAO, 8-m, and IRAM observations as time is awarded.	Proposal writers
	Complete reduction of first round of COMPLETE Observations.	All, plus new postdoc.
~6/03	**SIRTF Legacy Observing begins**	NASA/Evans+
Fall '03	Preliminary SIRTF Legacy data should be available. Begin evaluation of these data—revise source lists and observing proposal plans, if necessary.	Postdoc
	Collaborators' meeting to plan initial publications (including on-line database) and second round of COMPLETE observations.	All, at CfA
	Submit JCMT/SCUBA proposals for follow-up to earlier SCUBA/SMT and SIRTF Legacy team sub-mm (e.g. CSO) observations.	Johnstone/ Schnee
Winter '03/ Spring '04	Submit IRAM 30-m proposals for follow-up on SCUBA/SMT, SIRTF Legacy team, and FCRAO observations.	Tafalla/Caselli/ Schnee/ Postdoc
	Submit 8-m-class proposals for NICER follow-up observations based on SMT, SIRTF Legacy team, and FCRAO observations.	Alves
2004	Carry out IRAM, JCMT/SCUBA, and 8-m observations.	Proposal writers
	Review and incorporate newly released SIRTF Legacy Data	All, coordinated by postdoc
Spring '05	Complete reduction of all data acquired for COMPLETE, and assure online availability.	All/NVO staff
Spring '05	Collaborators' meeting to plan out papers[19] to be written based on COMPLETE database, including those incorporating SIRTF Legacy data. Assign primary authors and deadlines for all papers.	All, at CfA

[16] Michelle Borkin is about to begin Harvard as a freshman. She has worked with us before on other successful web design projects, including AG's homepage.

[17] Jason Li is a New York high-school student who has garnered many prizes for his scientific prowess. He will be joining us to working on COMPLETE at the CfA this Summer.

[18] All entries that use the words "SIRTF Legacy Team" imply cooperation and coordination with members of the SIRTF Legacy project. We are already in close contact with P.I. Neal Evans (see his letter in Appendix A) and co-I's Lori Allen and Phil Myers, in order to ensure that our proposed observations are complementary to both the SIRTF data, and the "ancilliary data" the Legacy team plans to acquire.

[19] There will be no embargo on publishing data acquired for COMPLETE before this time. This entry refers to "synthesis" papers coming from the COMPLETE data set, including work addressing questions shown on p. 7.

1/05	Full COMPLETE database available through NVO interface. Any related observations taken by COMPLETE collaborators after 2005 (e.g. SCUBA-2 data) will be considered outside the purview of the Survey, but can be linked to the database if the observer so desires.	Postdoc/NVO staff
2005-6	Host COMPLETE Workshop, open to the entire Star Formation Community, where results will be presented & availability of data advertised further	Goodman
	Schnee completes dissertation based on COMPLETE Survey.	Schnee
2005-7 Summer / Fall 07	Write ~20 papers based on COMPLETE results and on the questions listed in the box on p. 7 for refereed journals. We anticipate that even with our large consortium, it will take ~2 years to generate these papers.	All, with 1st authors having responsibility
Fall 07	Requested NASA Funding ends. All COMPLETE data online through CfA/NVO, and through IPAC, if suitable arrangements with NASA can be made.	Goodman

MANAGEMENT AND AVAILABILITY OF THE DATABASE

The data sets generated by COMPLETE will be numerous, large, and diverse. The P.I. of this proposal and her colleagues were recently awarded two NSF Information Technology Research grants by the NSF to develop the "National Virtual Observatory." The text on p. 20 explains how the COMPLETE Survey will be made available, using the NVO, to anyone with web access.

If data taken in the past had been properly cataloged and preserved in useful electronic format, a large part of the COMPLETE Survey could have been done using the electronic equivalent of "the literature" and "the plate stacks." The paramount goal of COMPLETE is "coordination," and that coordination will extend into data management. When selecting a postdoctoral fellow to work on COMPLETE, we will keep this goal in mind.

Throughout the COMPLETE project, we will be working closely with the SIRTF Legacy team. As shown in the schedule above, at COMPLETE's close, we hope leave a copy of the COMPLETE Survey on IPAC servers, as well as at CfA, to speed data-access and to preserve the COMPLETE Survey for the future.

CONCLUDING REMARKS

We see COMPLETE, in conjunction with the SIRTF Legacy Survey, as the opportunity of a lifetime to finally gather a real statistical sample of the physical properties of star-forming regions—a sample of which we can ask questions we could only dream about legitimately answering in the past. We also look forward to the incredible serendipitous discoveries that always come from unprecedented surveys.[20]

We expect some at the NASA Office of Space Science, looking for deliverables beyond the data itself, would see COMPLETE as providing:

1. An optimized technique for mapping extinction using 2MASS data
2. An optimized technique for mapping extinction using SIRTF data
3. Calibration of SIRTF thermal emission measurements with 2MASS extinction mapping of dust column density
4. Calibration of SIRTF thermal emission measurements by comparison with ground-based 850 μm observations
5. CO observations critical for calibration of C and O abundances in regions observed by SWAS.

Barnard concludes his classic 1919 paper by musing about how desirable a full photographic atlas[21] of dark nebulae would be, and concludes that: "*Their study with the present means of research would be of the highest interest.*" The COMPLETE Survey represents the study of star-forming dark clouds with essentially all "present means of research," and we hope you agree that it would be "of the highest interest."

[20] For example —what exactly are the odd, streamer-like, velocity features North of the B5 region in the new FCRAO/SEQUOIA ^{13}CO map shown in Figure 4??

[21] Barnard completed such a photographic atlas and published in two beautifully made volumes in 1927.

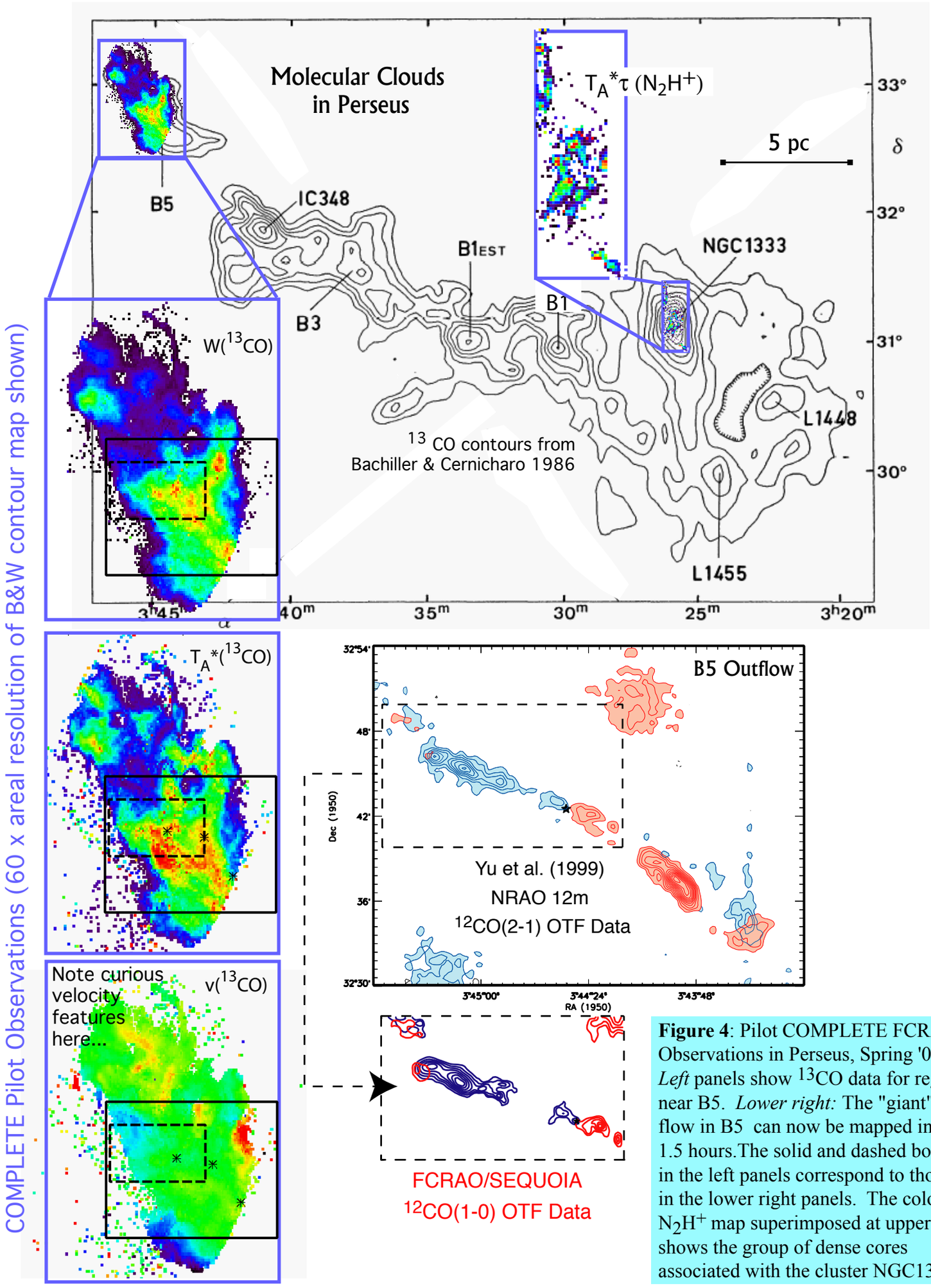


Figure 4: Pilot COMPLETE FCRAO Observations in Perseus, Spring '02. *Left* panels show ^{13}CO data for region near B5. *Lower right:* The "giant" HH flow in B5 can now be mapped in just 1.5 hours.The solid and dashed boxes in the left panels correspond to those in the lower right panels. The color N_2H^+ map superimposed at upper right shows the group of dense cores associated with the cluster NGC1333.

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FACILITIES AND EQUIPMENT

THE NATIONAL VIRTUAL OBSERVATORY

The single most important "facility" available to the COMPLETE project is the ongoing National Virtual Observatory (NVO) effort at the Harvard-Smithsonian Center for Astrophysics (CfA). We are well aware that about half the astronomical community is very skeptical about the NVO, while the other half considers it the next great step in astronomical research. Even skeptics would likely agree, though, that access to some of the world's best astronomical database designers and programmers—at no cost on this proposal—is a great benefit to our project.

The P.I. of the LTSA project is the P.I. of one, and the Co-I of another, NSF grant to Harvard University to be used in establishing the first-generation NVO. The financial details provided in the "Current and Pending Support" section of this proposal cannot give a clear view of what the Harvard/CfA NVO effort is really all about, so we will explain it here.

Alyssa Goodman is the P.I. of the "Data Model" NVO grant, but the project is overseen on a daily basis by Dr. Giuseppina (Pepi) Fabbiano, of the CfA's Chandra Science Center. It is Fabbiano who is the CfA's main link to the NVO project, and Fabbiano's position at the CfA puts her in charge of *all* of the roughly 60 programmers who currently work on the NASA-funded Chandra mission. NASA has held up the Chandra data archive more than once as a model of how modern mission data products should be made available by computer. COMPLETE and the Chandra archive itself serve as two (of three) "demonstration projects" for the "CfA Virtual Observatory" which itself is conceived as a testbed for the NVO. AG's primary role in the NVO project at this time is as liaison to the COMPLETE Survey.

Over the next several years, NASA/Chandra- and NSF/NVO-sponsored programmers at the CfA will work closely with the graduate student(s), postdoc, and P.I. of COMPLETE to make the COMPLETE Survey data available to the community in nearly real time, in NVO-compliant format.

For those of you unfamiliar with the NVO goal, this does not mean that the COMPLETE data will need to be translated into some special "NVO" format, or placed on a special "NVO" computer. Instead, the NVO effort will benefit from close collaboration with the COMPLETE team—learning what "standard" data formats are generated by (radio) molecular probe line, (optical and near-infrared) extinction, and (far-infrared and sub-mm) thermal emission mapping. While meanwhile, the COMPLETE team will be forced to place their data online in a standardized, easy-to-translate, way.

The collaborative efforts between the NVO and COMPLETE teams at CfA have already begun, and are demonstrated at http://cfa-www.harvard.edu/nvo/ and http://cfa-www.harvard.edu/~sschnee/complete.html. Current COMPLETE data are already available online at the latter site.

Lastly, due to COMPLETE's close connection to the NASA/SIRTF Legacy (Evans et al.) project, and the location of several of its participants (Phil Myers, Lori Allen, and Tom Megeath) at the CfA, we expect that the COMPLETE-NVO link will also ultimately allow for a closer connection between the Chandra and IPAC data archives, via a SIRTF-NVO-COMPLETE connection.

THE FIVE COLLEGE RADIO ASTRONOMY OBSERVATORY

The "pilot" molecular-line COMPLETE observations shown in Figure 4 of this proposal were all obtained in Spring 2002 at the 14-m Five College Radio Astronomy Observatory (FCRAO). As explained in Mark Heyer's Letter of Commitment on p. 33, FCRAO is committed to giving the COMPLETE project the observing time necessary to finish the molecular line observations proposed here—on the condition that we receive funding for the postdoctoral fellow requested with this proposal. COMPLETE is now considered a "Key Project" in terms of scheduling at FCRAO, as long as we receive adequate funding.

THE SUBMILLIMETER TELESCOPE OBSERVATORY

If we conclude, after the science-based cost/benefit analysis described on p. 9, to carry out a significant amount (~1 month) of dust emission mapping at the SMTO, we have entered into an agreement with Tom Wilson (former SMTO Director), Peter Strittmatter, and Lucy Ziurys (SMTO Director) which will allow us to trade the COMPLETE postdoc's services for guaranteed observing time at the SMTO.

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EDUCATION

1984	Sc.B., Massachusetts Institute of Technology, Physics
1986	A.M., Harvard University, Physics
1989	Ph.D., Harvard University, Physics

ACADEMIC EXPERIENCE

1999-	Professor, Harvard University Astronomy Department
1995-	Research Associate, Smithsonian Astrophysical Observatory
2001-2	Visiting Professor, Yale University Astronomy Department (sabbatical leave)
1996-1999	Associate Professor, Harvard University Astronomy Department
1995-1997	Head Tutor, Harvard University Astronomy Department
1992-1996	Assistant Professor, Harvard University Astronomy Department
1989-1992	Post-doctoral Fellow, University of California, Berkeley
1984-1989	Research Assistant, Harvard-Smithsonian Center for Astrophysics
1983	Summer Fellow, NASA-Goddard Institute for Space Studies

HONORS AND AWARDS

1998	Bok Prize, Harvard University
1997	Newton Lacy Pierce Prize, American Astronomical Society
1994	National Science Foundation Young Investigator
1994	Pedagogical Innovation Award, Harvard University
1993-1995	Alfred P. Sloan Fellow
1989-1991	President's Fellowship, University of California, Berkeley
1990	First Prize Paper, NATO ASI on Star Formation
1986-1989	Amelia Earhart Fellowships from Zonta International
1985	Francis Lee Freidman Award in Physics, Harvard University
1983	Sigma Pi Sigma, MIT

SOCIETY MEMBERSHIPS

American Astronomical Society; International Astronomical Union; URSI Commission J (Radio Astronomy); American Association for the Advancement of Science; American Association of University Professors

ADVISORY & REVIEW COMMITTEES

NASA-Infrared Space Observatory Key Projects Review (1992); Scientific Working Group for NRAO Green Bank Telescope (1992); Arecibo Users and Scientific Advisory Committee (1993-96); NSF Site Review for Center for Particle Astrophysics (1994); NASA-Astrophysics Data Program Review (1995); Smithsonian Astrophysical Observatory Time Allocation Committee (1995-97); NSF-Caltech Submillimeter Observatory Review (1996); NSF Galactic Astronomy ISM Panel (1996,2000 (chair)); M4 Satellite Science Advisory Group, Chair (1997,2000); Harvard University Faculty Council (1997-98); AAS Publications Board (1998 2001); United States Square Kilometer Array Consortium Representative (1999-present); National Academy of Sciences Committee on Astronomy and Astrophysics (2000-2003); NASA-

SIRTF Legacy Review, Panel Chair (2000); AAS Committee on Astronomy and Public Policy (2000-present); AUI NRAO Director Search Committee (2002)

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B.Sc. in Physics, University of Lisbon, Portugal, 1992

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2001-	Astronomer, European Southern Observatory, Garching, Germany
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EDUCATION

1995	B.A. in Physics, Cornell University
1998	M.S. in Astronomy, Harvard University
2001	PhD in Astronomy, Harvard University

ACADEMIC EXPERIENCE

1992-1995	Research Assistant at Cornell University, Astronomy Department
1996-2001	Research Assistant at Harvard University, Astronomy Department
1996,1998	Teaching Assistant at Harvard University, Astronomy Department
2001-	Postdoctoral position at California Institute of Technology, Astronomy Department

AWARDS

1994	NSF Incentive for Excellence in Scholarship Prize
1995-1998	NSF Minority Graduate Research Fellow
1995-1999	Harvard University Graduate Prize Fellowship
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RELEVANT RECENT PUBLICATIONS

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EDUCATION

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RECENT ACADEMIC EXPERIENCE

July 1995-	Researcher at the Osservatorio Astrofisico di Arcetri, Firenze, Italy
Oct 95-Dec 95	Postdoctoral Fellow at the Max-Planck-Institut fur extraterrestrische Physik, Garching, Germany
1994-Oct 95	Postdoctoral Fellow at the Smithsonian Astrophysical Observatory, Cambridge, MA
1993	Smithsonian Predoctoral Fellow at the Center for Astrophysics, Cambridge, MA
1992	Visiting Student Fellow at the Department of Physics, Ohio-State University, Columbus, OH.
1991	Fellow at the Institute of Molecular Spectroscopy, C.N.R., Bologna, Italy

RECENT HONORS AND AWARDS

June 2001	Visiting Senior Research Fellow at the Department of Physics and Astronomy, University of Leeds, England

SOCIETY MEMBERSHIPS

IAU; IAU Astrochemistry Working Group

SELECTED RELEVANT PUBLICATIONS

Tafalla, M., Myers, P.C., Caselli, P., Walmsley, C.M., and Comito, C. *Systematic Chemical Differentiation of Starless Cores*, ApJ, 569, 815, 2002

Caselli, P., Walmsley, C.M., Zucconi, A., Tafalla, M., Dore, L. and Myers, P.C. 2002, *Molecular Ions in L1544. I. Kinematics*, ApJ, 565, 331.

Caselli, P., Walmsley, C.M., Zucconi, A., Tafalla, M., Dore, L. and Myers, P.C. 2002, *Molecular Ions in L1544. II. The Ionization Degree*, ApJ, 565, 344.

van der Tak, F.F.S., van Dishoeck, E.F. & Caselli, P. 2000, *Abundance profiles of CH_3OH and H_2CO toward massive young stars as tests of gas-grain chemical models*, A&A, 361, 327

Caselli, P., Walmsley, C.M., Tafalla, M., Dore, L. & Myers, P.C. 1999, *CO Depletion in the Starless Cloud Core L1544*, ApJ, 523, L165.

Caselli, P., Walmsley, C.M., Terzieva, R. & Herbst, E. 1998, *The Ionization Fraction in Dense Cloud Cores*, ApJ, 499, 234.

Caselli, P., Hasegawa, T.I. & Herbst, E. 1998, *A Proposed Modification of the Rate Equations for Reactions on Grain Surfaces*, ApJ, 495, 309.

Caselli, P., Hartquist, T.W. & Havnes, O. 1997, *Grain-grain collisions and sputtering in oblique C-type shocks*, A&A, 322, 296.

Caselli, P., Myers, P.C. & Thaddeus P. 1995, *Radio-astronomical Spectroscopy of the Hyperfine Structure of N_2H^+*, ApJ, 455, L77.

Caselli, P. & Myers P.C. 1995, *The Line Width-Size Relation in Massive Cloud Cores*, ApJ, 446, 665.

Caselli, P., Hasegawa, T.I. & Herbst, E. 1993, *Chemical Differentiation Between Star Forming Regions: the Orion Hot Core and Compact Ridge*, ApJ, 408, 548.

JAMES DI FRANCESCO

Born: September 16, 1968 Web site: http://astron.berkeley.edu/~jdifran

EDUCATION

B.Sc. in Physics and Astronomy, Toronto, 1990

Ph.D. in Astronomy, University of Texas, Austin, 1997

RECENT ACADEMIC EXPERIENCE

2002-	Astronomer, Herzberg Institute of Astrophysics, Victoria, Canada
1999-2002	BIMA Postdoctoral Fellow, University of California, Berkeley
1997-1999	Postdoctoral Fellow, Smithsonian Astrophysical Observatory

RECENT HONORS AND AWARDS

1996	David Allen Benfield Scholarship, University of Texas

SOCIETY MEMBERSHIPS

American Astronomical Society

EXTERNAL ADVISORY & REVIEW COMMITTEE WORK

BIMA Telescope Allocation Committee (*proposal reviewer*); NASA Origins Program (*proposal reviewer*); The Astrophysical Journal (*manuscript referee*)

SELECTED RELEVANT PUBLICATIONS

Allen, L. E., Myers, P. C., Di Francesco, J., Mathieu, R., Chen, H., & Young, E. 2002, "*HST-NICMOS Imaging Survey of the Ophiuchus (Lynds 1688) Cluster,*" ApJ, 566, 993

Di Francesco, J., Myers, P. C., Wilner, D. J., Ohashi, N., & Mardones, D. 2001, "*Infall, Outflow, Rotation, and Turbulent Motions within NGC 1333 IRAS 4*," ApJ, 562, 770

Harvey, P. M., Butner, H. M., Colome, C., Di Francesco, J., & Smith, B. J. 2000, "*Far-Infrared Observations of AFGL 2136: Simple Toroid Dust Models*," ApJ, 534, 846

Williams, J. P.., Myers, P. C., Wilner, D. J., & Di Francesco, J. 1999, "*A High Resoluton Study of the Slowly Contracting, Starless Core L1544*," ApJ, 513, L61

Di Francesco, J., Evans, N. J., II, Harvey, P. M., Mundy, L. G., & Butner, H. M. 1998, "*High-Resolution Far-Infrared Studies of Intermediate-Mass Pre-Main-Sequence Objects*," ApJ, 509, 324

Harvey, P. M., Smith, B. J., Di Francesco, J., & Colome, C. 1998, "*Far-Infrared Constraints on Structure and Variability of SSV 13 in NGC 1333*." ApJ, 482, 433

Di Francesco, J., Evans, N. J., II, Harvey, P. M., Mundy, L. G., Guilloteau, S., & Chandler, C. J. 1997, 3

DOUG IAN JOHNSTONE

Born: November 11, 1966 Web site: www.astro.uvic.ca/~johnston

EDUCATION

1989 Undergraduate Degree in Astronomy and Physics, University of Toronto, Canada

1996 PhD in Astrophysics, University of California at Berkeley, USA

ACADEMIC EXPERIENCE

2001- Associate Research Officer, Herzberg Institute of Astrophysics

1999-01 Assistant Professor of Astronomy, University of Toronto

1996-99 Research Fellow, Canadian Institute for Theoretical Astrophysics

AWARDS

1996-97 NSERC Postdoctoral Fellowship

1989-93 NSERC 1967 Postgraduate Fellowship

RELEVANT RECENT PUBLICATIONS

Large Area Mapping at 850 Microns. III. Analysis of the Clump Distribution in the Orion B Molecular Cloud, Johnstone, D., Fich, M., Mitchell, G.F., & Moriarty-Schieven, G. 2001, ApJ, 539,307

Large Area Mapping at 850 Microns. II. Analysis of the Clump Distribution in the ρ-Ophiuchi Molecular Cloud, Johnstone, D., Wilson, C.D., Moriarty-Schieven, G., Joncas, G., Smith, G., & Fich, M. 2000, ApJ, 545, 327

Large Area Mapping at 850 Microns. I. Optimum Image Reconstruction From Chop Measurements, Johnstone, D., Wilson, C.D., Moriarty-Schieven, G., Creighton, J.G., & Gregersen, E. 2000, ApJS, 131, 505

A Submillimeter Dust and Gas Study of the Orion B Molecular Cloud, Mitchell, G.F., Johnstone, D., Moriarty-Schieven, G., Fich, M. & Tothill, N. 2001, ApJ, 565, 215

A Submillimeter View of Star Formation near the HII Region KR140, Kerton, C.R., Martin, P.G., Johnstone, D., \& Ballantyne, D.R. 2001, ApJ, 552, 601

Submillimeter Continuum Emission in the r-Ophiuchus Molecular Cloud: Filaments, Arcs, and an Unidentified Far-Infrared Object, Wilson, C.D., ..., Johnstone, D., ..., 1999, ApJL, 513, 139

JCMT/SCUBA Sub-Millimeter Wavelength Imaging of the Integral Shaped Filament in Orion, Johnstone, D. & Bally, J. 1999, ApJL, 510, 49

OUTREACH

Johnstone has given many public talks across Canada to members of the Royal Astronomical Society of Canada. As well, he is a frequently interviewed specialist on astrophysics for ``Space News" a segment produced for Space: The Imagination Station (a Canadian Cable Channel).

EXTERNAL ADVISORY & REVIEW COMMITTEE WORK

JCMT Canadian Time Allocation Committee; CFHT/Gemini Proposal Reviewer; Canadian ALMA Science Steering Committee; Herschel/HIFI Canadian Steering Committee; SCUBA2 CFI Grant Preparation Committee, Astrophysical Journal/Astronomical Journal/MNRAS/Astronomy & Astrophysics Manuscript Referee

MARIO TAFALLA

Born: 14-February-1963 *Web site: www.oan.es*

PROFESSIONAL PREPARATION

Universidad Autónoma de Madrid (Spain), Physics, B.A.1986

University of California, Berkeley, Astronomy, M.A. 1990

University of California, Berkeley, Astronomy, PhD 1993

Harvard-Smithsonian Center for Astrophysics, postdoc 1993-1997

APPOINTMENTS

1998-	Astronomer, Observatorio Astronómico Nacional, Spain
1997-1998	Researcher, Consejo Superior Investigaciones Científicas, Spain
1993-1997	Postdoctoral Fellow, Harvard-Smithsonian Center for Astrophysics
1991-1993	Research Assistant, University of California, Berkeley
1990-1991	Teaching Assistant, University of California, Berkeley

RECENT RELEVANT PUBLICATIONS

Tafalla, M., Myers, P.C., Caselli, P., Walmsley, C.M., and Comito, C. *Systematic Chemical Differentiation of Starless Cores*, ApJ, 569, 815, 2002

Caselli, P., Walmsley, C.M., Zucconi, A., Tafalla, M., Dore, L. and Myers, P.C. 2002, *Molecular Ions in L1544. I. Kinematics*, ApJ, 565, 331.

Caselli, P., Walmsley, C.M., Zucconi, A., Tafalla, M., Dore, L. and Myers, P.C. 2002, *Molecular Ions in L1544. II. The Ionization Degree*, ApJ, 565, 344.

Bachiller, R., Pérez Gutiérrez, M., Kumar, M.S.N. and Tafalla, M. 2001, *Chemically active outflow L 1157*, A&A, 372, 899.

Lee, C.W., Myers, P.C. and Tafalla, M. 2001, *A Survey of Infall Motions Toward Starless Cores. II. CS(2-1) and N_2H^+(1-0)Mapping Observations*, ApJS, 136, 703.

Bachiller, R., Gueth, F., Guilloteau, S., Tafalla, M. and Dutrey, A. 2000, *The origin of the HH 7-11 outflow*, A&A, 362, L33.

Caselli, P., Walmsley, C.M., Tafalla, M., Dore, L. and Myers, P.C. 1999, *CO Depletion in the Starless Cloud Core L1544*, ApJ, 523, L165.

Lee, C.W., Myers, P.C., and Tafalla, M., *A Survey of Infall Motions Toward Starless Cores. I. CS(2-1) and N_2H^+(1-0) Observations*, ApJ, 526, 788-805, 1999

Tafalla, M., Myers, P.C., Mardones, D. and Bachiller, R. 1999, *A cluster of young stellar objects in L1211*, A&A, 348, 479.

Bachiller, R., Guilloteau, S., Gueth, F., Tafalla, M., Dutrey, A., Codella, C. and Castets, A. 1998, *A molecular jet from SVS 13B near HH 7-11*, A&A, 339, L49.

Tafalla, M., Mardones, D., Myers, P.C., Caselli, P., Bachiller, R., Benson, P.J., *L1544: A Starless Core with Extended Inward Motions*, ApJ, 504, 900-914, 1998

Chen, H., Tafalla, M., Greene, T.P., Myers, P.C. and Wilner, D.J. 1997, *IRAS 20050+2720: an Embedded Young Cluster Associated with a Multipolar Outflow*, ApJ, 475, 163.

Mardones, D., Myers, P.C., Tafalla, M., Wilner, D.J., Bachiller, R., and Garay, G. *A Search for Infall Motions Towards Nearby Young Stellar Objects* ApJ, 489, 719-733, 1997

Tafalla, M., and Myers, P.C. *Velocity Shifts in L1228: the Disruption of a Core by an Outfl*ow, ApJ, 491, 653-662, 1997

Tafalla, M., Bachiller, R., Wright, M.C.H., and Welch, W.J. *A Study of the Mutual Interaction Between the Monoceros R2 Outflow and Its Surrounding Core*, ApJ, 474, 329-345, 1997

THOMAS L. WILSON

Born: Dec 14, 1942

EDUCATION

1964	B. S. in Physics, St. Joseph's College, Philadelphia, PA
1969	PhD in Physics, M. I. T.

ACADEMIC EXPERIENCE

1997-2002	Director of the Sub-Millimeter Telescope Observatory, Steward Obs., Univ of Arizona, Tucson, AZ 85721
1969-	Senior Scientist at the Max-Planck-Inst. f. Radio Astronomy, Bonn, Germany
1969	Postdoctoral Fellow at the National Radio Astronomy Obs., Charlottesville, VA

AWARDS

1995	George Miller Visiting Prof. at Large, Univ. of Illinois, Urbana IL 61801
1990	Max-Planck-Forschungspreis
1964	Woodrow Wilson Fellow
1964-9	NSF Fellow

RELEVANT RECENT PUBLICATIONS

Wilson, T. L., Muders, D., Butner, H. M., Gensheimer, P.D. Uchida, K., Kramer, C.& Tieftrunk, A.R. 2001 in *Science with the Atacama Large Millimeter Array* (ASPConf. Series 235, ed. A. Wootten) "Sub-mm Science with the Heinrich Hertz Telescope", p 257

Wilson, T. L., Muders, D., Kramer, C. & Henkel, C. 2001 *Ap.J.* 557, 240 "Sub-mm CO Line Emission from Orion"

Rodriguez-Franco, A., Wilson, T. L., Martin-Pintado, J. , Fuente, A. 2001 *ApJ* (in press) "A High-Density Layer Confining the H II Region M42: HHT Measurements"

Mao, R.Q., Henkel, C., Schulz, A., Mauersberger, R., Zielinsky, M., Stoerzer, H., Wilson, T.L., Gensheimer, P. 2000 *A&A* 358, 433 "Dense Gas in nearby galaxies: XIII CO submillimeter line emission from the starburst galaxy M82"

Wilson, T. L., Mauersberger, R., Gensheimer, P. D., Muders, D., Bieging, J. H. 1999 *ApJ* 525, 343 "Dense Cores in the Orion Molecular Cloud"

Other Significant Publications

Wilson, T. L. 1999, in *Encyclopedia of Astro & Astrophys.* (ed. P. Murdin) "Millimeter and Sub-Millimeter Astronomy", p. 1740

Wilson, T. L. 1999 *Reports on Progress in Physics* 62, 143 "Isotopes in the interstellar medium and circumstellar envelopes"

Rohlfs, K., Wilson, T. L. 1999 *"Tools of Radio Astronomy",* 3rd Edition, Springer-Verlag, Heidelberg

Wilson, T.L., Huettemeister, S. 2000 "*Tools of Radio Astronomy: Problems and Solutions"*, Springer-Verlag, Heidelberg

CURRENT AND PENDING SUPPORT OF THE P.I.

CURRENT

1. "Developing the Framework for the National Virtual Observatory," **$10M over 3 years** NSF-ITR grant to a long list of Investigators. AG is listed as a Co-I on this project.
2. "Developing the National Virtual Observatory Data Model," **$0.5M over 3 years** NSF-ITR grant, directly to Harvard University. AG is P.I., and Robert Kirshner is Co-I. Pepi Fabbiano (SAO) is the team leader on this project.
3. "Research and Development for the Square Kilometer Array," NSF grant (of **$0.5M over 2 years**) to Square Kilometer Array Consortium. CfA share is ~$30K/year for 2 years.

Alyssa Goodman receives no Summer Salary support, postdoc salary, or graduate student support from either of these "NVO" grants, or from the SKA award. Funds from the NVO grants are used *only* to (partially) support the salaries of programmers at the Harvard-Smithsonian Center for Astrophysics. Funds from the SKA grant are being "banked" to pay the salary of a digital engineer in 2003-4.

PENDING

1. LTSA proposal, for "The COMPLETE Survey of Star-Forming Regions," requesting **$0.8M** for five years.

WHY LTSA?

An earlier (pre-pilot observations) proposal for COMPLETE was submitted to the NSF Galactic Astronomy program in November 2001. The NSF reviewers' and Program Officer's clear response was that COMPLETE's science program is well-designed and tremendously valuable, but that no NSF program had the money to pay for COMPLETE in 2001-2. The NSF Program Officer has urged us to re-apply for funding in 2002-3, but given the nature of the NSF Individual Investigator grants program today (a maximum award of about $300K for 3 years, to the successful 18% of proposers), we are not very optimistic about NSF funding of COMPLETE.

After the NSF news, in May 2002, we consulted with SIRTF Science Center Director, Tom Soifer, about how to secure NASA funding of COMPLETE.

Soifer suggested that we apply to the LTSA program, on the grounds that COMPLETE is clearly in direct support of the SIRTF Legacy project "From Molecular Cores to Planet-forming Disks". Soifer also suggested that including letters of support from Neal Evans and Phil Myers (P.I. and Co-I of the SIRTF Legacy project) commenting on COMPLETE's relevance to NASA's SIRTF Legacy program would help explain the case for LTSA funding, so we have done this (see p. 32). For obvious reasons, Tom Soifer, as SSC Director, could not write his own Letter of Support for our LTSA proposal, but we believe he will be happy to comment on its relevance to NASA's SIRTF mission, if the reviewers would like to contact him.

LETTERS OF SUPPORT AND COMMITMENT

This section begins with letters from representatives of the agencies/observatories critical to COMPLETE's success:

- Neal Evans, on behalf of the SIRTF Legacy Project
- Phil Myers, on behalf of the SIRTF Legacy Project
- Mark Heyer, on behalf of the Five College Radio Astronomy Observatory
- Tom Wilson, on behalf of the Submillimeter Telescope Observatory

The section concludes with Letters of Commitment from each of COMPLETE's Senior Collaborators.

NEAL J. EVANS II, PI SIRTF LEGACY PROJECT "FROM MOLECULAR CORES TO PLANET-FORMING DISKS"

7 June 2002

Dear Alyssa:

As Principal Investigator for the SIRTF Legacy project, From Molecular Cores to Planet-forming Disks, I am pleased to support your proposal to the LTSA program. The COMPLETE project will provide extremely valuable data that is complementary to that of the SIRTF Legacy project.

Combined with our SIRTF data, COMPLETE will provide a much more complete database for the problem of star and planet formation. The proposal notes that our understanding of star formation is hampered by the lack of complete databases for systematic studies. I agree. That was indeed the motivation for our SIRTF Legacy program. Our Legacy team is already planning to add significant ancillary and complementary data to the database, including surveys of the same regions surveyed with SIRTF at 1.2 mm and studies of the isolated cores with SCUBA.

We will coordinate with the COMPLETE team to avoid duplication of effort and to ensure the most efficient use of telescope time. The molecular line mapping that you propose will be a very valuable addition to what we are doing, as will the NICER maps of extinction. The SIRTF data will allow extension of the NICER technique to still more opaque regions, and the combination of these databases will be very powerful.

The data contributed by the COMPLETE project will add considerable value to the SIRTF data. This is an excellent investment in enhancing the value of data acquired by space missions, which are themselves much more expensive.

I strongly support LTSA funding for the COMPLETE proposal.

Neal J. Evans II
Principal Investigator for the SIRTF Legacy Project
From Molecular Cores to Planet-forming Disks

PHIL MYERS, CO-I, SIRTF LEGACY PROJECT

Dear Alyssa:

As a Co-Investigator on the SIRTF Legacy Program "From Molecular Cores to Planet Forming Disks" I am happy to write this letter of support for the "COMPLETE" program of spectral line mapping and extinction analysis that you and your colleagues have proposed.

Our SIRTF Legacy program will give a new view of the stellar content of the youngest and nearest star-forming clouds and complexes, with much better sensitivity, resolution, and spectral coverage that has been available before. In conjunction with these observations our team has begun a program of supporting ground-based observations of the gas and dust in these clouds and complexes. Such observations are important for our understanding of how the gas in these regions forms stars and brown dwarfs in clusters,

groups, binaries, or in isolation.

However none of our planned observational programs would have the extensive coverage that COMPLETE would, matching the largest-scale observations in our SIRTF maps. Therefore it would be extremely valuable to our understanding of these star-forming regions that the COMPLETE program go forward so that the observational results on gas and dust structure from COMPLETE can be analyzed along with the stellar content results from SIRTF.

You and your colleagues who would work on COMPLETE are highly competent and motivated. If supported sufficiently well, the COMPLETE team would produce maps and analysis very useful to our SIRTF program. I believe our groups would work well together, and that the result would be a great benefit both to the astronomy community and to our understanding of star and planet formation.

Sincerely,

Philip C. Myers
Senior Astrophysicist, SAO

MARK HEYER/FCRAO

Letter of support for the COMPLETE proposal
June 10, 2002

The Five College Radio Astronomy Observatory is pleased to participate in the COMPLETE project.

Such focused investigations are essential to understanding the complex phenomena in the molecular interstellar medium. Wide-field imaging of molecular line emission from nearby clouds obtained with FCRAO complements the information derived from SIRTF and NICER extinction maps of the dust component. Armed with this inventory of the gas and dust, the COMPLETE team is well poised to describe the physical and chemical processes in star forming regions.

The COMPLETE proposal to observe with the FCRAO 14m was favorably reviewed in January 2002. We expect to begin scheduling the COMPLETE program on the 14m in September 2002 pending funding of the COMPLETE team.

Sincerely,
Mark H. Heyer
FCRAO, Associate Director

TOM WILSON, DIRECTOR, SUBMILLIMETER TELESCOPE OBSERVATORY (1997-2002)

Nov. 6, 2001

Prof. A. Goodman
Astronomy Dept.
Harvard University
60 Garden St.
Cambridge, Mass., 02138

Dear Prof. Goodman,

We at the Submillimeter Telescope Observatory (SMTO) are very enthusiastic about your proposal to carry out a dust continuum emission survey of nearby molecular clouds with our 19-channel bolometer camera. This survey, COMPLETE, will provide a great deal of the data needed for the interpretation of the SIRTF measurements.

We agree to provide the 21 days of telescope time for this work. In return, we expect you to provide a portion of the salary of a postdoctoral fellow who will be involved in the evaluation of the data.

Sincerely yours,

T. L. Wilson
Director

JOAO ALVES

8 June 2002

Dear Alyssa,

It is a great pleasure to be involved in the COMPLETE project and to work with such a capable team. Our most recent large scale extinction maps of nearby molecular clouds from 2MASS data are extremely encouraging and I am sure that an extinction map of the COMPLETE target areas will be ready and on time for the coordinated comparison between dust extinction, molecular line, and dust emission data envisioned by the project.

I am convinced that a large and multiwavelength view on molecular clouds, the COMPLETE way, is the only way that will lead to a clear understanding of the mysterious origins of these clouds, their physical structure, and their relentless evolution into stars and planets. You can then understand my enthusiasm for this project and you should count on my support.

With best compliments,

João Alves
European Southern Observatory
Garching b. Munich, Germany

HÉCTOR ARCE

25 June 2002

Dear Alyssa,

I am very excited to be part of the COMPLETE project team. A dedicated survey such as the COMPLETE project is the natural next step in star formation and molecular cloud research. In addition, the observations proposed by the COMPLETE project will provide the astronomical community the necessary information to understand the structure and kinematics of the regions to be observed by the SIRTF Legacy project "Form Molecular Cores to Planet Forming Disks". It should go without saying, that if one is to understand how stars and planet forms, a detailed study of the star-forming environment (such as that proposed by the COMPLETE team) is crucial.

From my experience using the on-the-fly mapping technique with the FCRAO/SEQUOIA 32-pixel focal plane array, I can assure you that the proposed molecular line observations for the COMPLETE project are feasible and will be easily completed in the proposed time.

I acknowledge that I am identified by name as Collaborator to the investigation, entitled The COMPLETE Survey of Star-Forming Regions, that is submitted by Alyssa Goodman to the NASA Research Announcement LTSA02, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Best wishes,

Hector G. Arce

California Institute of Technology Pasadena, CA USA

harce@astro.caltech.edu

PAOLA CASELLI

21 June 2002

Reading the COMPLETE proposal I was impressed by its great potential to advance our understanding how cloud cores form and how the process of star formation is initiated. The team in this proposal is at the highest international level and has a mixture of experiences (from observations to theoretical physics, from chemistry to magnetohydrodynamics) which is at the basis for a successful achievement of the proposed projects.

The aim of this proposal has been the dream of all researchers studying the interstellar medium and star formation since the interstellar medium was actually discovered. However, as the applicants point out, only nowadays it is possible to undertake such an extensive and detailed study of molecular clouds in our Galaxy, thanks to the recent great technical improvements which opened up new "windows" to the Universe and improved the angular and spectral resolution of our observations by several orders of magnitude. The large amount of data we propose to collect, necessary to make a COMPLETE picture of the physics and chemistry of the gas and dust in our Galaxy, strongly needs a top level and well coordinated team to avoid "dispersion" of information and a very efficient deduction of the parameters fundamental for our research.

Being an "astrochemist" I can say that unveiling the complex patterns of molecular emission and chemical differentiation observed in dense cloud cores, the future stellar cradles, is fundamental for our understanding of how stars form and to determine the initial conditions of the star formation process. Only when an extensive data set of molecular line and dust continuum emission will be available, to study the interaction of the embedded "small scale structure" with the surrounding environment, we will be able to understand the chemistry and thus the physics and the dynamical evolution of interstellar clouds. This is a unique proposal to achieve this goal.

^^^

Paola Caselli Tel: (+39) 055 2752 253
Osservatorio Astrofisico di Arcetri Fax: (+39) 055 220039

L.go E.Fermi, 5
I-50125 Firenze ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
Italia / e-mail: caselli@arcetri.astro.it \

JAMES DI FRANCESCO

Dear Alyssa,

I believe the COMPLETE project will represent a watershed moment for star formation research. Finally, a single nearby molecular cloud will be observationally characterized at high resolution and sensitivity over a very wide field through numerous, complementary probes. Previously, data of molecular clouds have accumulated in a very piecemeal manner, with only portions of various clouds studied at different resolutions, to different sensitivities, with different probes. These diverse datasets have offered important clues about star formation in molecular clouds. However, a general picture has remained elusive, partly because these datasets have varied so much in intent, scope and quality. The COMPLETE survey will radically transform this inchoate situation, since it is a coordinated effort to provide to the community unbiased, complementary data made using mature observational techniques. Recent technological advances in multi-beam focal plane arrays have made such a project now feasible, and a highly qualified group has assembled to work in concertto ensure its completion. I am excited to be part of this consortium, and look forward to seeing the datasets inter-relate to characterize the star formation process over a molecular cloud scale.

James Di Francesco
jdifran@astron.berkeley.edu

DOUG JOHNSTONE

Sir or Madam,

This note is to stress my support and commitment toward Alyssa Goodman's COMPLETE proposal. Over the last few years I have been involved in the largest, most sensitive, sub-millimeter mapping project of star-forming regions undertaken. It is clear, as Alyssa's proposal emphasizes, that combining this data with extinction mapping, infrared emission, and molecular line observations is paramount to our understanding the physical conditions under which stars form. At the same time, we have only just begun the process of systematically mapping star-forming regions with sufficient sensitivity and resolution and as such, a coordinated effort, across wavelengths, is definitely required. Alyssa Goodman's proposed COMPLETE survey details a plan for such a systematic study and will provide a much-needed resource for the entire star formation community.

I am keenly excited about being an active member of this collaboration. The time is right for a coordinated survey and I am confident that the assembled team, both theorists and observers, will produce results which will be a significant contribution to the study of star formation.

cheers,

doug johnstone

Doug Johnstone Associate Research Officer
Herzberg Institute for Astrophysics (250) 363-8108
National Research Council Canada FAX (250) 363-0045
5071 West Saanich Road doug.johnstone@nrc.ca
Victoria, B.C. V9E 2E7 www.hia.nrc.ca

MARIO TAFALLA

15 June 2002

Dear Alyssa,

I am delighted to be part of the team that will carry out the COMPLETE Survey. The systematic combination of molecular line and extinction observations that the COMPLETE survey proposes is not only unique, but the necessary next step if we are to understand the nature and conditions of molecular clouds. It clearly is going to set the standard for any future work.

Best regards,

Mario Tafalla
Observatorio Astronomico Nacional
Madrid, SPAIN

REPRINTS/PREPRINTS

For anyone interested in learning more about the analysis techniques we propose to use on the COMPLETE data, and the kinds of questions we are interested in answering, we have included the following reprints with this proposal:

The Near Infrared Color Excess (NICE) Extinction-Mapping Technique:

Alves, J., Lada, C.J. & Lada, E.A. 2001, Internal structure of a cold dark molecular cloud inferred from the extinction of background starlight, Nature, 409, 159.

The Interaction of Outflows from Young Stars with Molecular Clouds, on pc-scales:

Arce, H.G. & Goodman, A.A. 2002, The Great PV Ceph Outflow: A Case Study in Outflow-Cloud Interaction, ApJ, astro-ph/0204417

Optimal Acquisition, Analysis and Interpretation of Sub-mm Dust Continuum Maps:

Johnstone, D., Wilson, C.D., Moriarty-Schieven, G., Joncas, G., Smith, G., & Fich, M. 2000, Large Area Mapping at 850 Microns. II. Analysis of the Clump Distribution in the ρ-Ophiuchi Molecular Cloud, ApJ, 545, 327

The Perils and Benefits of Molecular Spectral-Line Mapping of Dense Interstellar Gas:

Tafalla, M., Myers, P.C., **Caselli, P**., Walmsley, C.M., and Comito, C. *Systematic Chemical Differentiation of Starless Cores*, ApJ, 569, 815, 2002

Statistical Analysis of Very Large Spectral-Line Maps of Molecular Clouds[22]:

Rosolowsky, E.W., **Goodman, A.A**., Wilner, D.J. & Williams, J.P. 1999, *The Spectral Correlation Function: A New Tool for Analyzing Spectral Line Maps*, ApJ, 524, 887.

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[22] We have consciously chosen to include only our original paper that first proposed the SCF, rather than one of our more recent papers. Any reviewer desiring an update on the SCF's uses should consult the following:

Padoan, P., Kim, S., **Goodman, A.** and Staveley-Smith, L. 2001, *A New Method to Measure and Map the Gas Scale Height of Disk Galaxies*, ApJ, 555, L33.

Padoan, P., Rosolowsky, E.W. & **Goodman, A.A.** 2001, *The Effects of Noise and Sampling on the Spectral Correlation Function*, ApJ, 547, 862.

Ballesteros-Paredes, J., Vázquez-Semadeni, E. and **Goodman, A.A.** 2002, *Velocity Structure of the Interstellar Medium as Seen by the Spectral Correlation Function*, ApJ, 571, 334.

Padoan, P. & **Goodman, A.** 2002, *The Spectral Correlation Function of MHD Turbulence: Simulations and Molecular Cloud Complexes*, ApJ, to be submitted 8/02, at cfa-www.harvard.edu/~agoodman/research2.html.