Number _____
Priority _____

I 1) Principal Investigator:

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Scott Schnee [Ph.D. Thesis] CfA USA
and several others from many countries, see justification

II **TITLE AND CATEGORY OF INVESTIGATION** *Star Formation/Molecular Clouds*
The COMPLETE Survey: FCRAO Observations, Part 1

III ABSTRACT OF PROPOSED OBSERVATIONS

We request a total of 9 days of observing time this season as an FCRAO contribution to our ongoing "COMPLETE" Survey of 3 star-forming regions. COMPLETE is comprised of **CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission observations of (3 out of the 5) star-forming complexes to be mapped in the upcoming Evans et al. SIRTF Legacy Survey. The SIRTF data, along with HHT mapping to be carried out under COMPLETE, will give unbiased maps of thermal dust *emission*. Dust *extinction* maps are being constructed under COMPLETE using 2MASS (and ulitmately SIRTF Legacy) near-IR data. We plan to use FCRAO to provide all of the fully-sampled large-scale *molecular-line emission* maps of the 3 SIRTF Legacy regions visible from the North (Per, Ser, and ρ-Oph). This proposal represents approximately the first half of the time we will ultimately request.

IV System Configuration: ⊗ SEQUOIA ◯ FAAS ◯ QEF ⊗ Other

V BREAKDOWN OF TIME REQUESTED

Molecule (Transition)	Frequency (GHz)	Days Requested	LST Coverage	Total Hours
1) ^{12}CO (1-0)	115 GHz	8	0-24h	192
2) ^{13}CO (1-0)	110 GHz	same 8	0-24h	same192
3) CS (2-1)	98 GHz	1	0-24h	24
4) N_2H^+ (1-0)	93 GHz	same 1	0-24h	same24

VI SPECIAL SCHEDULING REQUIREMENTS:
Since our time request is large, we are amenable to breaking it into chunks within the winter/spring season.

THE COMPLETE SURVEY: FCRAO OBSERVATIONS, PART 1

This proposal is the first of a series planned for the next 18 months that will request time at FCRAO to carry out molecular spectral-line observations needed for the COMPLETE Survey of Star-Forming Regions, whose goals are described below. We request that you consider FCRAO's participation in the COMPLETE Survey as you would a "Key Project," in that it requests, in total, an unusually large time allocation, but serves the needs of a community much larger than just its proposers.

The COMPLETE Survey is being carried out by a large international collaboration, formed in 2001. The investigators listed on the recently-submitted COMPLETE proposal to NSF are: Alyssa **Goodman** (P.I., Harvard/CfA); Joao **Alves** (ESO, Germany); Paola **Caselli** (Arcetri, Italy); James **diFrancesco** (UC Berkeley); Doug **Johnstone** (HIA, Canada); Mario **Tafalla** (OAN, Spain); and Tom **Wilson** (MPI/HHT)[1]. In addition, the NSF proposal seeks funding for a postdoctoral fellow to join the collaboration. Harvard graduate student Scott Schnee, listed as a co-I on this proposal, will carry out his Ph.D. research using results from the COMPLETE Survey. Although only Goodman and Schnee are explicitly listed as proposers on the cover page here, we anticipate that several other COMPLETE co-I's will participate in acquiring, reducing, and publishing the FCRAO data.

In this proposal, we only briefly explain the goals of the COMPLETE Survey—hoping their worth is readily apparent—and then we describe our plans for a first round of SEQUOIA observations.

Summary of the COMPLETE Survey

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 included in COMPLETE 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.

We have included Appendix A, taken from our NSF proposal, to give just a taste of the kind of questions our Survey will be able to address. We expect to tackle some of these questions within our collaboration, but we also expect than many will be the subject of future research by others, using the on-line COMPLETE database.

Large-scale COMPLETE Observations, and their Status

The COMPLETE collaboration was formed in November 2001. Our goal is to "COMPLETE-ly" observe three of the five star-forming regions to be included in the Evans et al. SIRTF Legacy Survey[2] (Perseus, ρ-Ophiuchus, and Serpens), and our “baseline” specification is two regions (Perseus and Ophiuchus). Figure 1, on the next page, shows how a COMPLETE Survey is quite human(e)ly possible today, even though it was completely unfeasible just five years ago.

Our NSF proposal lays out a detailed three-year plan for executing the COMPLETE Survey. We begin with "fully-sampled" observations of each of the three ~10-pc size star-forming regions. After those large-scale observations are completed (and in a few cases concurrently) higher-resolution observations of a "representative" sample of dense peaks are to be carried out. We focus in this first FCRAO proposal, though, primarily on the large-scale initial observations.

The observations needed to collect the large-scale data we require are as follows:

[1] More information on the COMPLETE Survey, and the full NSF proposal, are available at: http://cfa-www.harvard.edu/~agoodman/research8.html

[2] More information on the Evans et al. SIRTF Legacy program is available at http://peggysue.as.utexas.edu/SIRTF/.

Molecular Probe Line	This FCRAO proposal requests time to begin fully-sampled OTF ^{12}CO and ^{13}CO maps of Perseus, ρ-Ophiuchus, and Serpens. Note that Figure 1 illustrates that the needed observations will take ~1 minute per SEQUOIA footprint, as contrasted with ~1 hour for the same areal coverage with QUARRY, c. 1995.
Extinction	Alves and collaborators will complete the large-scale NICER extinction maps using 2MASS data by the Summer of 2002. This work has already begun, and all needed data are in-hand. "NICER" is the algorithm used to extract extinction maps from near-IR images, and NICER applied to 2MASS data yields a resolution of about 1' at A_V of 5 mag for our targets.
Thermal Emission	**Extended mapping, sub-mm:** Pilot HHT observations to optimize sub-mm dust mapping technique with newly-installed 19-element 850 μm bolometer are already scheduled for February 2002, and the remainder will be completed by 2003. Johnstone will take the lead on this project. **Extended mapping, far-IR; and Point Source Census, near-IR:** The SIRTF launch is currently scheduled for December 2002. With that launch date, the Legacy maps and near-IR censes of Perseus, ρ-Ophiuchus, and Serpens should be available before the end of 2003. Note that our NICER extinction maps will be updated and improved using the SIRTF point source data in lieu of the 2MASS data (see Figure 1).

Next Fall, we will begin proposing the COMPLETE observations that will sample the finer-scale higher-density structures within the extended maps we focus on here. At that time, we will request time on several telescopes to which our team members have special access, including the VLT, Magellan, the JCMT, and the IRAM 30-m. As explained below, we request one day of high-density-tracer (N_2H^+ and CS) observing under this proposal as "pilot" observations aimed at refining our 2nd FCRAO COMPLETE proposal.

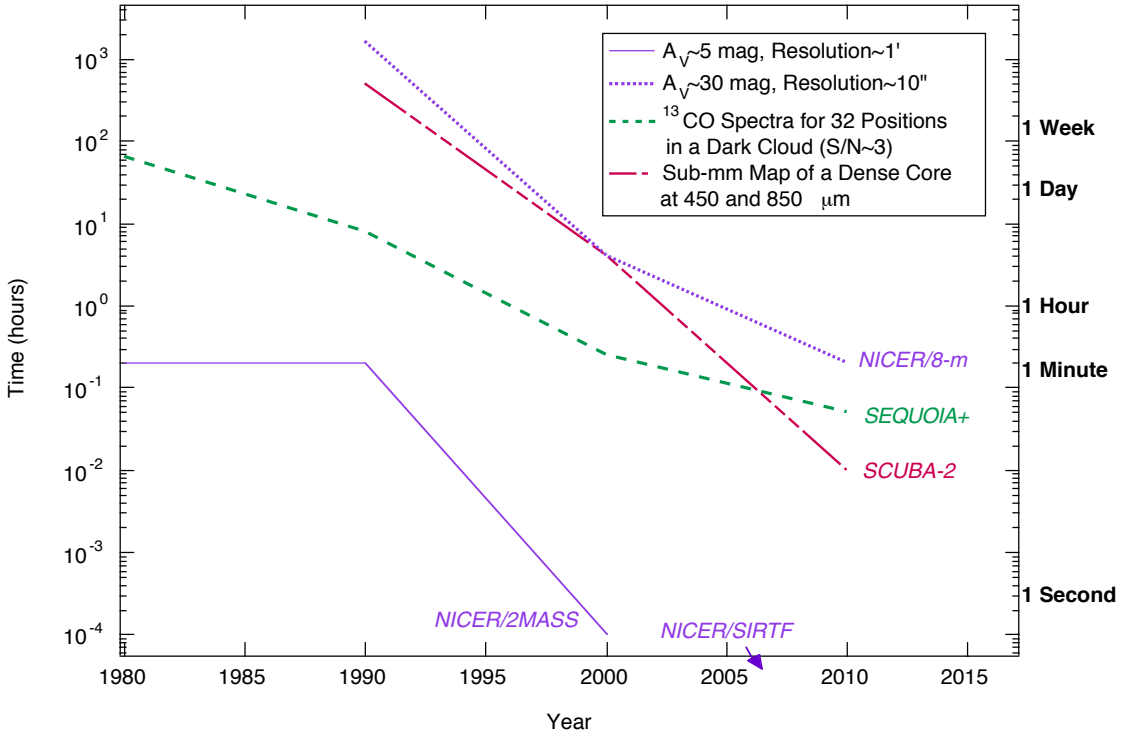


***Figure 1**: **Dramatic improvements in sensitivity** that make a COMPLETE Survey feasible. (Labels for sample instruments are shown near "2010" for graphical clarity, but these instruments will each be ready between now and ~2006. Note that "SEQUOIA+ refers to a SEQUOIA-like array on the LMT.)*

We fully appreciate that even though we have violated the usual "page count" for FCRAO proposals, the scope and aim of COMPLETE may still be hard for those outside our field to appreciate based just upon what is written here. We ask that the TAC consult with Mark Heyer, who has read the full COMPLETE plan, for additional information. The molecular-line observations proposed in COMPLETE are its soul source of kinematic information. Since FCRAO is currently the **only** facility capable of providing these observations, we hope you can consider granting us the kind of "Key Project" time we request with this proposal.

Observing Strategy and Technical Details

CAN WE USE SOME OF THE EXISTING MOLECULAR-LINE OBSERVATIONS?

Large fractions of the regions we plan to observe in the COMPLETE Survey have been mapped before in the tracers we propose to use. So, should we try to use those data, or just repeat the observations? The combination of a 32-pixel SEQUOIA, on-the-fly mapping, and dual IF's makes FCRAO nearly two orders of magnitude faster, and much more reliable, than it (or any other mm-wave telescope) was when most of the extant studies were made. We are open to differing opinions from the TAC, but it is our inclination to just forge ahead and fully map all our regions of interest. (Note that we understand "do it again, right" to be the strategy adopted in the ongoing Galactic Ring Survey (e.g. Simon et al. 2001).)

NEW OBSERVATIONS: ^{12}CO AND ^{13}CO

The P.I.'s most recent experiences with SEQUOIA, in its 16-pixel, no-OTF, single-IF mode, came from an extensive set of ^{12}CO, ^{13}CO, C^{18}O and N_2H^+ observations made with (then-)graduate student Héctor Arce (see Arce & Goodman 2001a, b, c). Based on that experience, and the following assumptions:

- T_{sys} (115 GHz)= 600 K
- T_{sys} (110 GHz)= 300 K
- 1024 channels/IF with either[3]
  - 50 kHz channel spacing, or
  - 25 kHz channel spacing
- 32 pixels
- dual IF's
- OTF-mapping at equivalent of ~1 min/beam

we can expect RMS noise levels of order 0.1 K/beam for both the ^{12}CO and ^{13}CO observations. This noise level will be sufficient to detect ^{13}CO down to about 0.5 mag A_V, which is the sensitivity threshold we targeted for molecular-line observations in designing the COMPLETE Survey. The peak of the ^{12}CO lines will be detected at ridiculously high S/N, but our aim in observing ^{12}CO is not the peak but the line wings—the FCRAO/COMPLETE Survey will find nearly *all* the outflowing gas in these star-forming regions, with absolutely unprecedented sensitivity.

The map of Perseus shown in Appendix A gives a good idea of the areal coverage we require in each of our 3 regions, about 5 by 5 degrees in total. That area translates to about 200,000 FCRAO beams, or the (no-OTF equivalent of) just over 6000 SEQUOIA "pointings". At 1 minute/"pointing", this amounts to ~100 hours of on-source observing time. Assuming an overhead of 30% in OTF mapping, we estimate that a 5 degree by 5 degree map made simultaneously in ^{12}CO and ^{13}CO will take about 5 days of good weather. Therefore, the ^{12}CO/^{13}CO time we request here (8 days) is enough for 1 full map in "average" weather, or 1.5 maps in great weather. We will request the remainder of the time needed to map two , if not all three, SIRTF Legacy regions, in FCRAO proposals over the next 18 months.

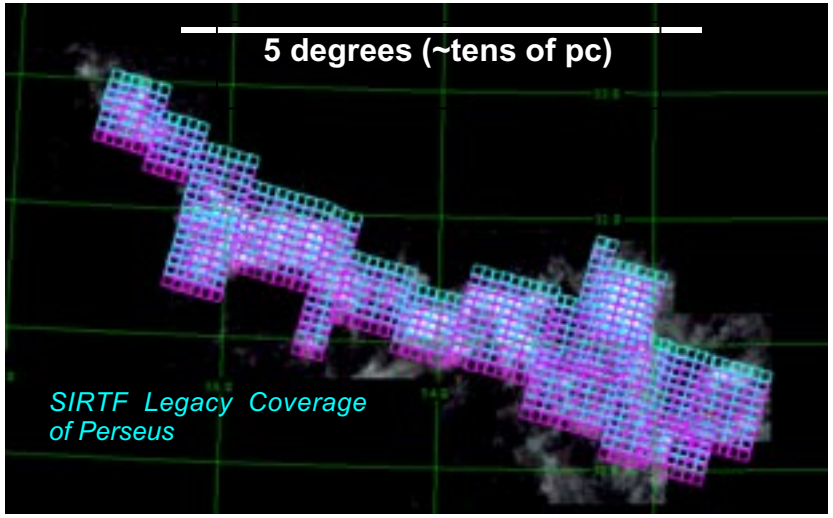
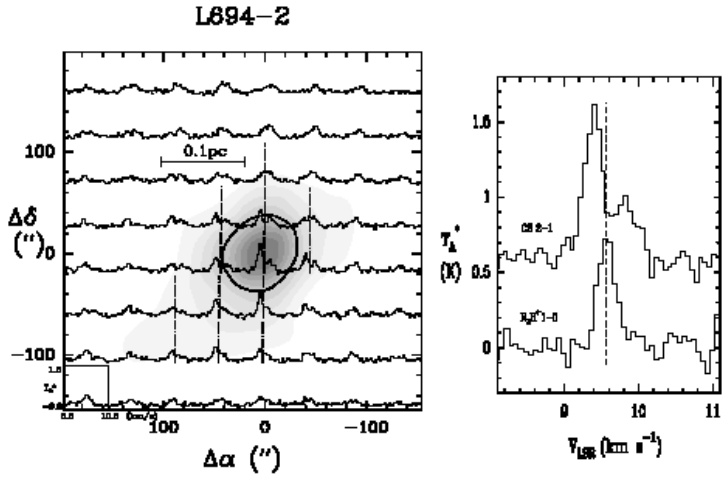
NEW OBSERVATIONS: N_2H^+ AND CS "PILOT" STUDY

In addition to requesting 8 days for ^{12}CO/^{13}CO observing, we request 1 day for N_2H^+/CS simultaneous (dual IF) observations. These observations will serve as "pilot" observations for our next FCRAO/COMPLETE proposal, giving us an idea of how far "out" from a core peak we can go in these high-density tracers, and what we can gain by going deeper in this way. (Most existing high-density tracer maps stop at no less than a 20% contour, but OTF mapping with SEQUOIA will allow us to easily go deeper.) The deep maps will allow many types of analysis that are not usually feasible, including: detailed chemical evolution studies; spatial analysis of line width variations (e.g. Goodman et al. 1998); and most importantly, a search for differential rotation in dense cores. Although the time request for the differential rotation search is minimal, it is important for two reasons. First, we think we have found differential rotation in one core observed recently with FCRAO, and we would like to know if this is an oddity. And, second, student Scott Schnee will be able to carry out the differential rotation study immediately, giving a short-term payoff on this otherwise very long-term project.

After we see what comes of this pilot FCRAO/SEQUOIA/OTF mapping of high-density tracers in dense cores, we will decide how to divvy up the "high-density" observing requests between FCRAO and the IRAM 30-m next year. Our decision will depend not just on the sensitivity of the maps, but on any systematic trends we find and their potential scale-dependence (e.g. is depletion more evident at 30-m resolution than at 14-m resolution?).

[3] We could not find a description of the new correlator on-line. Ideally, we would like to use the finer channel spacing (equivalent to 0.06 km/s) for ^{13}CO, and the wider spacing for ^{12}CO (so as to get a wider, 120 km/s, total BW), but we do not know if such a hybrid is possible. If not, we will use 25 kHz spacing for both lines, which will still give 60 km/s total bandwidth. Barring unforeseen ultra-high-velocity flows, that should be enough to detect outflowing gas in ^{12}CO.

Appendix A: 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 HHT & FCRAO observations + reddening information *~5 degrees mapped with ~5' resolution* • **HHT Observations** give dust column density maps, finds all "cold" sources *~20" resolution on all A_V>2"* • **FCRAO/SEQUOIA ^{13}CO and ^{12}CO Observations** give gas temperature, density and velocity information *~40" resolution on all A_V>1*	• **Combined Thermal Emission (SIRTF/HHT)** 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).*

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