COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 11-1		FOR NSF USE ONLY
NSF 05-608	11/15/11	NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)		
AST - GALACTIC ASTRONOMY PROGRAM		

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
				082359691	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS ☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)
042103580	0908159	

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
Harvard University	Harvard University 1350 Masschusetts Avenue Cambridge, MA. 021383846
AWARDEE ORGANIZATION CODE (IF KNOWN) 0021550000	
NAME OF PRIMARY PLACE OF PERF	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE
Harvard University	Harvard University 60 Garden Street Cambridge ,MA ,021381516 ,US.

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **The Hierarchical Structure of Star-Forming Regions in the Milky Way**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 590,920	36 months	07/01/12	

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

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ EAGER* (GPG II.D.2) ☐ RAPID** (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________
PHS Animal Welfare Assurance Number ________
☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ________
Exemption Subsection ________ or IRB App. Date ________
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
____
☒ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
Harvard College Observatory	Harvard University Astronomy Department 60 Garden Street--MS 42 Cambridge, MA 02138 United States
PI/PD FAX NUMBER 617-495-7345	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME Alyssa A Goodman	PhD	1989	617-495-9278	agoodman@cfa.harvard.edu
CO-PI/PD Robert Benjamin	PhD	1994	262-472-5114	benjamir@uww.edu
CO-PI/PD Thomas M Dame	PhD	1982	617-495-7334	tdame@cfa.harvard.edu
CO-PI/PD Mark J Reid	PhD	1975	617-495-7470	mreid@cfa.harvard.edu
CO-PI/PD Erik W Rosolowsky	PhD	2005	250-807-9623	erik.rosolowsky@ubc.ca

Intellectual Merit In September of 2011, several of us attended a meeting in Rome called "Milky Way 2011," organized to showcase the plethora of recent surveys of star-forming material in our Galaxy. We were simultaneously excited and disappointed by the meeting: excited by the wealth of new data; and disappointed to see the lack of coordinated analysis of it. We went home determined to create a collaborative project offering a more synthetic understanding of star formation in the Milky Way.

We, and many other astrophysicists, want to know how, where, and when a galaxy like the Milky Way forms stars. Presently, it is easier to answer this question empirically in nearby galaxies, thanks to our "external" vantage point with respect to those systems. But, that vantage point is far away, so our ability make predictive physical models of star formation based on observations of external spiral galaxies is limited, even with new instruments like ALMA.

In the Milky Way, we have tremendously detailed studies of star-forming regions within a few hundred pc of the Sun, but none of these nearby regions contains any massive (O) stars characteristic of the star-forming regions observationally detected in external galaxies. Here, we propose to evaluate the star-forming potential of gas under the *full variety of conditions* observed the Dame et al. (2001) CO Survey of Molecular Gas in the Milky Way. We will not study only nearby clouds, or only massive star-forming regions, but instead every environment our Galaxy has on offer.

Our work, using hierarchical "dendrogram" trees to deconstruct molecular gas emission, will be distinguished from previous analyses of star-forming clouds in the Milky Way by how it identifies significant structures within the gas. Essentially all previous work has divided up gas along sharp boundaries, without taking into account the obvious hierarchical nature of the gas. By analogy, this non-hiearchical approach is like dividing up whole metro Minneapolis-St. Paul into just two parts defined by a unique boundary between the cities. This approach takes no account of the fact that these two separate cities are surrounded by a combined "metropolitan area," and further surrounded by a state called Minnesota that also contains other cities, like Duluth, each of which has its own identity, likely determined in part by its surroundings. We suspect that environment does matter, and that the artificial division of gas into non-overlapping clumps has masked important physical effects.

By combining the hierarchical decomposition of star-forming material we will create with catalogs of associated dense star-forming "cores" and young stars, we will evaluate which of several potential physical processes is key to the formation of stars. In particular, we will study whether a feature's self-gravity, its internal density or pressure distributions, or external pressure–or a combination of those–is most predictive of fecundity. Our results will clarify our understanding of star-formation in the Milky Way, and offer physical insights into empirical trends measured in other galaxies.

Broader Impact The PI and several Co-Is are known for their work on data visualization, data sharing, and science education. All the products created in this work, including a 3D visualization of star-forming gas in the Milky Way, will be made available online through the universe3d.org, Astronomy Dataverse, Seamless Astronomy, and WorldWide Telescope sites, all of which the PI has had a hand in creating. The Astronomy Dataverse is presently being deployed as an NSF-data-management-plan-compatible solution for short-term distribution and long-term preservation of astronomical data, and this project will serve as a key demonstrator of the Dataverse's utility. The new Milky-Way shaped *Haus der Astronomie* visualization and outreach facility in Heidelberg will play host to a meeting on "Star-Formation in the Milky Way, in 3D," co-sponsored by the Max-Planck Institute for Astronomy as part of this project.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.B.2.

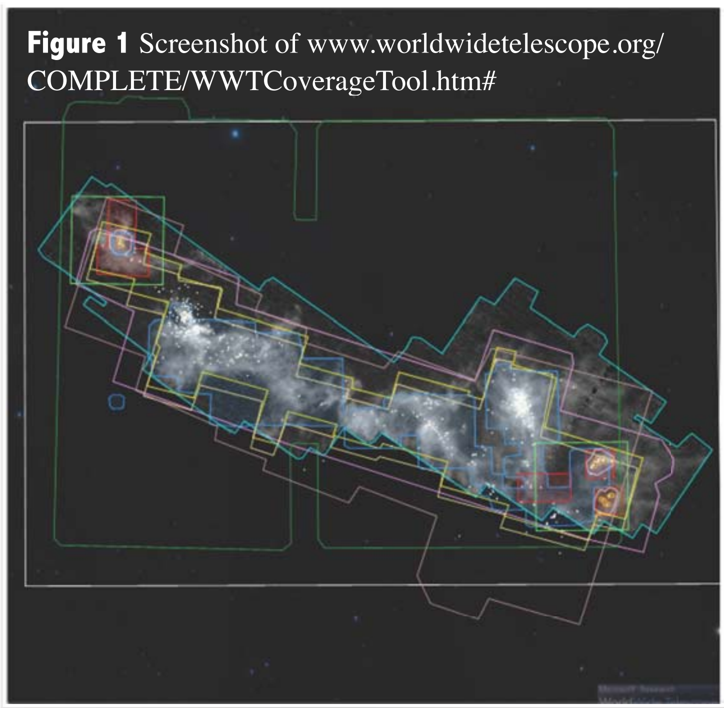
*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

The Hierarchical Structure of Star-Forming Regions in the Milky Way

1. RESULTS FROM PRIOR NSF-SPONSORED WORK

1.1. COMPLETE Survey (Goodman, Alves, Rosolowsky)

Supported by NSF AST-0407172 and NSF AST-0908159 to Goodman.



COMPLETE Data Available

Center on Perseus | Center on Ophichus | Center on Serpens

Dataset	Show	Perseus	Ophiuchus	Serpens	Link
Full-Cloud Data (Phase I, All Data Available)					
GBT: HI Data Cube	☑	√	√	∅	Data
IRAS: Av/Temp Maps	☑	√	√	√	Data
FCRAO: 12CO	☑	√	√	√	Data
FCRAO: 13CO		√	√	√	Data
JCMT: 850 microns	☑	√	√	∅	Data
Spitzer c2d: IRAC 1,3 (3.6,5.8 μm)	☑	√	√	√	Data
Spitzer c2d: IRAC 2,4 (4.5,8 μm)	☑	√	√	√	Data
CSO/Bolocam: 1.2-mm	☑	√	∅	∅	Data
Spitzer MIPS: Derived Dust Map	☑	√	∅	∅	Data
Targeted Regions (Phase II, Some Data Not Yet Available)					
CTIO/Calar Alto: NIR (J,H,Ks)	☑	√	√	∅	Data
IRAM 30-m: N2H+ and C18O	☑	√	∅	∅	Data
IRAM 30-m: 1.1-mm continuum	☑	√	∅	∅	Data
Megacam/MMT: r,i,z images	☑	√	∅	∅	Data
Catalogs & Pointed Surveys					
NH3 Pointed Survey	☑	√	∅	∅	Data
YSO Candidate list (c2d)	☑	√	√	√	Data

Figure 1 Screenshot of www.worldwidetelescope.org/COMPLETE/WWTCoverageTool.htm#

A decade ago, a group of researchers realized that it would be possible to *coordinate* their work so as to observe *the same* nearby star forming regions, rather than only their favorite regions. We realized that if a "**CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission" Survey were to be done, much more could be learned about the physics of local star formation than if the haphazard approach continued. So, a small team (including Goodman (PI) & Alves, and later Rosolowsky and others) was formed (2002), proposals for very large amounts of observing time (2003-2010) were written, data were taken, and ~40 papers[1] were written between 2002 and 2011. Today, COMPLETE serves as a seminal source of information on the gas and dust distributions in nearby molecular clouds, and its findings have been used in the literature ~1000 times.[2] The COMPLETE Survey (cf. Ridge et al. 2006) was coordinated with the Spitzer "Cores-to-Disks" Survey (cf. Evans et al. 2009), so that three nearby extended star-forming regions (Perseus, Ophiuchus and Serpens) visible from the Northern Hemisphere were observed. Figure 1 shows a summary of the data available from the

1 A full listing of refereed publications from the COMPLETE collaboration is at http://www.cfa.harvard.edu/COMPLETE/results.html, and in the ADS Private Library linked there.

2 The ADS Labs link at http://tinyurl.com/completeimpact lists the ~600 papers that have now cited papers in the COMPLETE collection, ~1000 times. Clicking on "View as..." shows networks of paper and author relationships.

COMPLETE and c2d Surveys in Perseus.[3] The insights afforded by COMPLETE range from newfound understanding of the limitation of various column density tracers (Goodman, Pineda, & Schnee 2009a), to the first direct evidence for velocity coherence in a dense core (Pineda et al. 2010; 2011), to appreciation of the effect of line-of-sight superpositions on dust emission (Shetty et al. 2009), to surprising results concerning the "slow" motions of dense star-forming cores with respect to their environs (Kirk et al. 2010), to revelations about the role of spherical stellar winds in cloud support (Arce et al. 2011), and more.

Thanks to COMPLETE and other similar recent "multi-tracer" efforts, it is now clear that: dust extinction is the most reliable mass tracer; dust emission is still valuable for measuring temperature; and spectral-lines are critical (and unique) for studies of kinematics, and for dis-entangling regions along the line of sight.

1.2. Dendrograms (Goodman & Rosolowsky)

Supported by NSF AAPF AST-0502605 to Rosolowsky and above NSF AST grants to Goodman.

In COMPLETE, we mapped 10°-scale regions in spectral lines of ^{12}CO and ^{13}CO with 40" resolution at FCRAO, yielding spectral-line data cubes with hundreds of thousands of spectra each. We also mapped denser regions within the three main clouds with higher-density tracers such as CS, $C^{18}O$, N_2H^+, NH_3 and with several dust tracers. We sought analysis tools that would help us understand how, where, and why denser objects are arranged "inside" lower-density gas.

At first, we tried what had been tried before, which was to use non-hierarchical segmentation[4] routines like CLUMPFIND (Williams, de Geus, & Blitz 1994) to divide emission into sensible "clouds." This did not work well at all. In fact, we found that CLUMPFIND was so sensitive to input parameters that one could cause it to find slopes of the "clump mass function" ranging anywhere from the shallow slope Lada, Bally & Stark (1991) first found for extended molecular gas to the much steeper IMF itself (Pineda, Rosolowsky, & Goodman 2009)!

The problem with CLUMPFIND is a critical one for our present proposal, and it is demonstrated in Figure 2b and in §2.5. Non-hierarchical segmentation routines like CLUMPFIND cannot offer a provision for one feature to be inside of another, so when a region of *"position-position-velocity"* space[5] is crowded with emission, CLUMPFIND and related tools (e.g. SExtractor, Gaussclumps) are forced into **cutting apart features that are really all part of one entity**. We thought we could

---

[3] Figure 1 is a screen shot of the interactive data coverage tool online at http://www.worldwidetelescope.org/COMPLETE/WWTCoverageTool.htm. All data are available for public download through http://www.cfa.harvard.edu/COMPLETE and the Astronomy Dataverse (see Data Management Plan).

[4] Within many fields of science, including medical imaging and computer visualization, to "segment" means to define significant structures within an entity. In Astronomy, terms like "feature extraction" or "clumpfinding" are often used in lieu of "segmentation." Here, we use "segmentation," not just to be formal, but also so as to include all possible topologies, including hierarchical ones.

[5] Position-position-velocity (or "*p-p-v*") is the coordinate system used to express the intensity of emission in a spectral-line map. Spectra are observed in position-position (e.g. RA-Dec) space on the sky, and each spectrum measures intensity of a transition as a function of frequency. The lines are observed as offset from their rest frequencies due to gas motion, and the simple Doppler formula allows for the conversion from frequency to velocity. The broadening of the lines in the cold ISM is due to particle motions, so the line shape gives the velocity distribution, *modulo* radiative transfer effects.

perhaps address this problem by adjusting thresholds, but this does not work because not all significant peaks are of similar intensity. Think of trying to find all the "named" mountains on Earth, but only being allowed to set one altitude threshold. Mt. Everest would surely show up on every list, but a threshold low enough to also show little Scottish peaks would include meaningless bumps and ridges on high plains and on side slopes of big mountains as well. And, the (underwater) Mariana trench wouldn't show until the threshold was very low indeed! Changing thresholds is just not a good way to capture hierarchy in a system with a large dynamic range of local maxima.

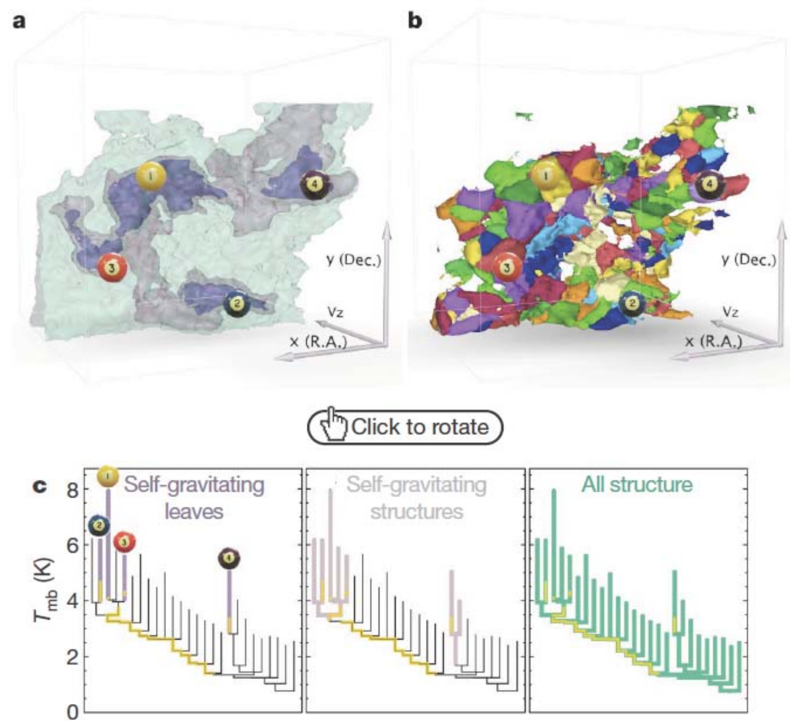


Figure 2 Dendrogram (a) and CLUMPFIND (b) decompositions of ^{13}CO in the L1448 region of Perseus shown in *p-p-v* space. Panels in (c) show dendrograms, colored to match surfaces in (a). Yellow highlights in (c) mark bound regions according to a virial analysis. In the published PDF version of Goodman et al. (2009b), this figure is interactive. Interested readers can download the paper from *Nature*, or visit tinyurl.com/Nature3Dpdf for a video demo.

So, we sought to find and develop a good algorithm for quantifying the structure of interstellar matter. Recalling the work of Houlahan & Scalo (1990, 1992) on "structure trees," we thought about tree diagrams as a good way to characterize the inherently hierarchical nature of interstellar gas. Co-I Rosolowsky implemented a hierarchical segmentation routine known as "dendrograms,"[6] and we have since applied dendrograms to COMPLETE and other data to great effect.

Figure 2 shows an excerpt from an article we published on *A Role for Self-Gravity at Multiple Length Scales in the Process of Star Formation* (Goodman et al. 2009b). This article appeared in *Nature* with Figure 2 as the first interactive "3D PDF" ever in a major scholarly journal: readers who click on panels **a** or **b** can rotate the view, turn particular surfaces on and off, and more. Here though, we wish to stress the content of Figure 2. Panel **a**, resulting from a dendrogram segmentation, offers a sensible (hierarchical) decomposition of the emission into dense blobs[7] surrounded by less dense ones. Panel **b**, from CLUMPFIND, shows a representation of the cloud as a set of tiny blobs all

[6] Interest in segmenting emission using dendrograms is on the rise, especially given the recent large data sets coming from Herschel. To share the algorithm and associated visualization tools with the community, we distribute the code freely as part of our "Seamless Astronomy" efforts at http://projects.iq.harvard.edu/seamlessastronomy/software.

[7] A simple 1:1 match between conventional terms, such as "blob," "cloud," "core," etc. and dendrogram tree terms like "trunks," "branches," and "leaves," is not possible, owing both to the inconsistent use of terminology in the literature, *and* to the varying physical regimes dendrogram features can represent depending on the tracer used and the amount of hierarchy detected.

filling an extended region of space, and appears unphysical. The lower panel (**c**) shows a tree diagram (dendrogram) where the features calculated to be "bound" according to the virial theorem (see §2.3) are highlighted in yellow. Note that the dendrogram's *y*-axis shows line intensity for various features within the hierarchy, but the *x*-axis is re-sorted to make the topology clear, and so should not be thought of as spatially-meaningful.

We explain how dendrograms work, and why they are valuable, in §2.5, below. The principal conclusions of Goodman et al. (2009b) and Rosolowsky et al. (2008) are that: 1) dendrograms offer physically-sensible hierarchical deconstructions of molecular gas in star-forming regions; 2) a simple form of the virial theorem applied to dendrogram-identified structures seems able to predict where, within extended clouds, cores and young stars will be found; and 3) relevant simulations (Padoan et al. 2006) fail to reproduce observations when dendrograms are used as the tool for comparison.

1.3. Bolocam Galactic Plane Survey (Rosolowsky)

Supported by NSF AST-0708403 to J. Bally et al. with followup from AST-1008577 to Y. Shirley and J. Glenn, and support from the Natural Sciences and Engineering Research Council Canada to BGPS collaborator Rosolowsky.

The Bolocam Galactic Plane Survey (BGPS) surveyed the Galactic plane in 1.1 mm continuum emission over the region $|b| < 1°$ from $-10° < l < 90°$ plus some portions of the outer Galaxy, using Bolocam on the (NSF-supported) CSO. The survey was the first publicly released view of long wavelength, optically thin, dust continuum emission at high resolution (33"). The BGPS provides a window into the total column density of the interstellar medium (ISM) as traced by dust, but sensitivity and spatial filtering effects means the BGPS primarily detects pc-scale dense gas concentrations, sometimes called "clumps"[7] (Rosolowsky et al. 2010a). Since these clumps are associated with star cluster formation and most stars form in clusters (Lada & Lada 2003), the BGPS presented the first public census of the principal star-forming structures in the Milky Way.

Follow-on dense gas (NH_3, N_2H^+, HCO^+) spectroscopy of >4000 BGPS sources has shown these clumps to be spread throughout the disk, with a distribution of source properties does not appear to depend on distance (Dunham et al. 2011). *The BGPS survey team is presently using Bayesian methods to estimate probability distribution functions for the distances to each BGPS object* (Rosolowsky, Ginsburg, & Ellsworth-Bowers 2010b). This so-called "Distance Omnibus" aims to use *all* available data in determining the distances to sources, quantifying the uncertainty when different measures disagree. These distance *probability density functions* (a.k.a. PDFs) are informed by the spectroscopy, association with other known distances (e.g. from masers, see §1.4), and association with infrared features. These distance estimates enable BGPS sources to be used as "signposts" in the hierarchical ISM.

1.4. BeSSeL: Maser-based Distance Determinations in the Milky Way (Reid, Dame)

The VLBA is funded by NSF, through NRAO and BeSSeL's 5000 hours of VLBA time amounts to "implicit" funding of $1.2M/year.

The BeSSeL Survey (Bar and Spiral Structure Legacy Survey) is a VLBA Key Science project. Mark Reid is PI of BeSSeL, and Tom Dame is Co-I. The goal of the survey is to study the spiral structure and kinematics of the Milky Way, by measuring distances and proper motions to ~400 high mass star forming regions between 2010 and 2015. The target sources are methanol and water masers that are associated with young massive stars and compact HII regions that trace spiral structure.

Accurate distance measurements facilitate the definition of spiral arms, and absolute proper motions allow determination of 3D motions of massive young stars.

BeSSeL's parallax accuracy is presently between 5 and 20 microarcsec, corresponding to 5% and 20% for a source at a distance of 10 kpc. The survey will result in a catalogue of accurate distances to most Galactic high-mass star forming regions visible from the northern hemisphere and very accurate (1%) measurements of fundamental parameters such as the distance to the Galactic center, the rotation velocity of the Milky Way at the Sun, and the rotation curve of the Milky Way.

Seven papers detailing results from BeSSeL have appeared to date, and Reid et al. 2009 (cited 200 times already) summarizes the implications of the new distance and proper motion measurements for Galactic structure.

2. HIERARCHY, PRESSURE, AND STAR FORMATION IN THE MILKY WAY

2.1. What would we like to do, and why?

Our understanding of star formation in the Universe is ultimately tied to the best observations we can make in our own Milky Way. *Without a detailed knowledge of how the molecular gas in the Milky Way, and the associated stars, are arranged in three dimensions, we cannot hope to put our own Galaxy into context*.

Our collaboration's long-term goal is to construct a three-dimensional map of gas, dust, and stars in the Milky Way. In the proposed project, we seek to take three important first steps toward this goal:

1. create a hierarchical, *three-dimensional* atlas of molecular gas as viewed in CO;
2. integrate online surveys of dust and young stars with the molecular view; and thus
3. understand the role played by "external" pressure in establishing the properties of star-forming regions.

As we detail below, many recent theories of star formation, and of the distribution of star-forming regions, in the Milky Way, invoke "external pressure" or the "weight of the envelope" around a cloud to explain everything from cloud lifetimes to fecundity. Arguments rage about whether clouds are self-gravitating, pressure-bound, and/or magnetically supported, and on what scales. But, we claim that the definition of "cloud" is essential to settling these arguments, and key to comparing synthetic observations of simulations with observations of the Milky Way. At present, one person's "external" pressure is another's "internal" or "turbulent" pressure, and the situation cannot be resolved or understood without the kind of rigorous, robust, decomposition of structures that a physically-motivated hierarchical segmentation algorithm like dendrograms can offer.

2.2. What kind of data can we use, and what do we mean by "3D"?

The iconic CO map of the Milky Way (Dame, Hartmann, & Thaddeus 2001) created using the "CfA mini" 1.2-m telescope continues to be the definitive guide to the molecular gas and structure of our Galaxy (Figure 3). This "map" is in fact a "*p-p-v* **cube"** where the intensity of ^{12}CO emission is recorded as a function of position, position and velocity. Most people only ever see this cube as shown in Figure 3, where either: the velocity dimension (v) is compressed out (giving a plane-of-the-sky "*l-b*" map as in the *top panel*); or a spatial dimension (b) is compressed out (giving an "*l-v*" position-velocity diagram like the *bottom panel*). Rich as these standard displays are, they hide from view the full *p-p-v* structure of the molecular gas in the Milky Way. Plane-of-the-sky maps

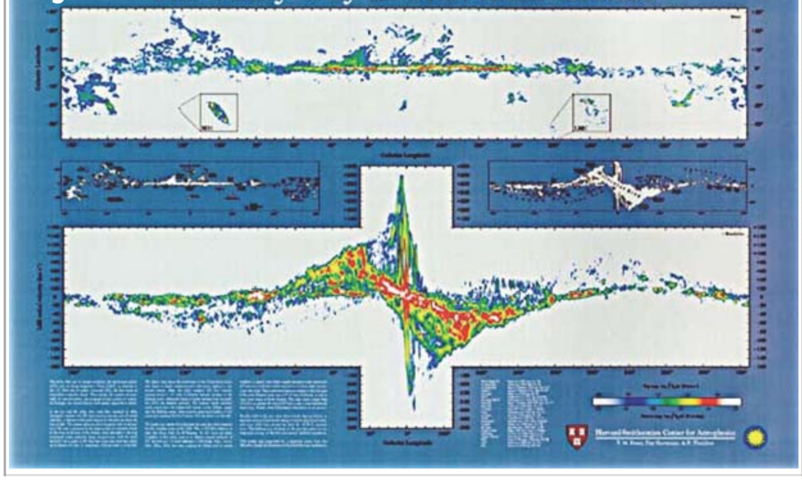


Figure 3: The Milky Way in Molecular Clouds

completely hide velocity structure, and *l-v* diagrams can show gross features like galactic rotation, but they shed no light on the vertical structure of gas in the Milky Way.

As we explain in §2.5, we will deconstruct the Milky Way's molecular gas using the hierarchical dendrogram algorithm[8] discussed in §1.2. Once we create a set of robust *p-p-v* features we will have a choice of working with those features in their native "3D" *p-p-v* space, or attempting a transformation back to real 3D *p-p-p* space. Such a transformation (§2.6) can be made using the Galaxy's rotation curve, in concert with distance information provided by BeSSeL (§1.4), the Distance Omnibus (§1.3) and other surveys. Specific physical questions favor one "3D" space over the other, but we need to explain those questions, and their motivation, further before going into operational details.

2.3. What is "External" Pressure, and Where Does it Matter?

The Virial Theorem is one of the most fundamental and useful constructs in astrophysics. It equates changes in the second time derivative of an object's moment of inertia to a sum of terms describing the effects of gravity, thermal pressure, bulk motions, radiation, and magnetic fields. Some effects (e.g. of magnetic fields or kinetic pressure) are separated into terms representing forces acting within a volume, and those that act at that volume's surface. In much of modern star-formation research, all terms in the virial theorem except self-gravity (***W***) and internal kinetic pressure (***T)*** are ignored. In such a picture, one can define (cf. Bertoldi & McKee 1992), a so-called "virial parameter"

$$\alpha \equiv \frac{5\sigma_v^2 R}{GM}$$

which expresses the ratio of ***T*** to ***W***, *modulo* geometric factors, where σ_v is a 1D velocity dispersion, R is a size, and M is a mass. Field, Blackman and Keto (2011) refer to this $0=2\boldsymbol{T}+\boldsymbol{W}$ form of the virial theorem as "SVE," or "Simple Virial Equilibrium." The standard interpretation is that if α>>1 then a cloud is "unbound" or "pressure confined," and that if α~1, then a cloud is "bound." In Figure 2, yellow highlighting shows portions of the cloud which SVE would imply are bound.

In Larson's classic (1981) analysis, he showed that SVE combined with one of two empirically determined relationships between line width and size ($\sigma \propto R^{0.5}$) and density and size ($n \propto R^{-1}$) can predict the third relation, forming a self-consistent picture[9]. These empirical relations have come to be known as "Larson's Laws." In 1988, Myers & Goodman showed that limiting the line widths

[8] For interested readers, videos showing how this deconstruction works, and what the Dame et al. (2001) data look like within it, are available at tinyurl.com/dendrograms. The 2 minute clip at http://tinyurl.com/dendroviz is best.

[9] Larson actually found an exponent on the linewidth-size relation of 0.38, which has since been interpreted as 0.5 given subsequent observational data.

(motions) in molecular clouds to ~the Alfvén speed explains Larson's line width-size relation naturally for magnetic field strengths similar to those observed. Over the twenty years since, controversy as to the detailed origin of the (potentially magnetically-limited) non-thermal motions has ebbed and flowed, as has discussion about the potentially significant role of external pressure (set =0 in SVE) in the structure of molecular clouds (e.g. Bertoldi & McKee 1992, Ballesteros-Paredes 2006; Dib et al. 2007). Oddly enough, the two regimes where observers agree that external pressure is important in Galactic clouds are at opposite density extremes, in: 1) low-density high-latitude unbound so-called "pressure-confined" clouds (Keto & Myers 1986); and 2) dense star-forming cores where the Bonnor-Ebert model seems a better fit to data than does an infinite singular isothermal sphere (e.g. B68, Alves, Lada, & Lada 2001).

In 2009, Heyer and colleagues upset the Larson's Laws-abiding world view, by re-analyzing data from Solomon et al.'s original 1987 ^{12}CO FCRAO survey in concert with newer ^{13}CO BU-FCRAO Galactic Ring Survey data (Jackson et al. 2006). Heyer et al. (2009) find that the coefficient of proportionality of Larson's linewidth size relation ($=\sigma^2/R$) is not constant, but instead depends on cloud surface density (Σ). Field, Blackman & Keto (2011) proposed to explain Heyer et al.'s finding by invoking varying amounts of **external pressure** present to confine molecular clouds.

Figure 4 shows Field et al.'s comparison of Heyer et al.'s ^{13}CO results with both SVE (α=1, diagonal dark line) and with SVE + various values of external confining pressure, indicated by the set of V-shaped curves (cf. Chieze 1987 and Keto & Myers 1986). Field et al. point out that the observed ^{13}CO points (shown in blue on Figure 4) seem to follow the locus of minima (red *'s) in the V-shaped curves better than they follow any single value of external pressure. The minima correspond to a critical mass for dynamical stability *determined only by the value of external pressure*, and so Field et al. argue that a range of pressures is needed to account for the large range of cloud properties observed.

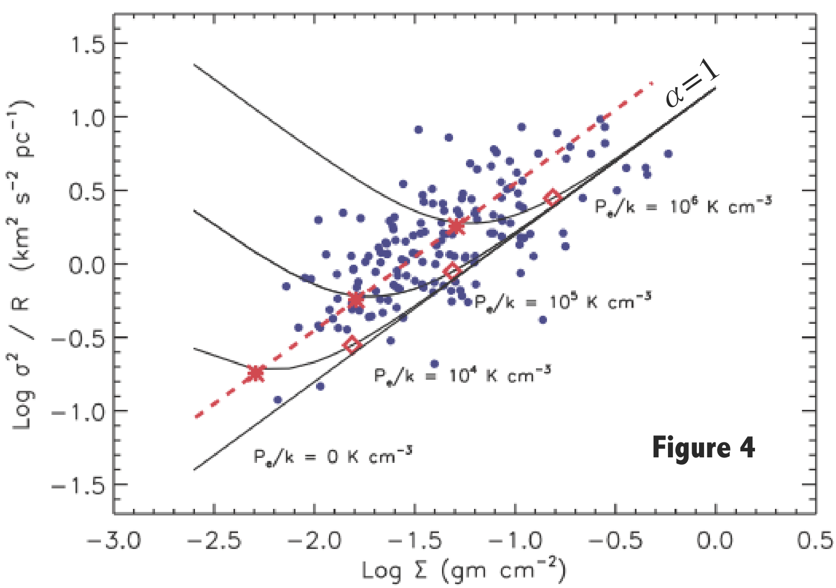


Figure 4

The Heyer et al. (2009) and Field et al. (2011) results raise the very real possibility that external pressure on a cloud is a key determinant of its state and its fate, and theoretical work on the inadequacy of SVE agrees (Ballesteros-Paredes 2006; Dib et al. 2007). But, what is "external" pressure and what is a "cloud"? *To define "external" as opposed to "internal," one needs to define a meaningful, well-understood, boundary for a "cloud."* And, the same definitional problem raises its gnarly head when one tries to calculate the gravitational pressure on the "outside" of a cloud, often referred to as the "weight of the envelope"–again, what is "inside" v. "outside"?

On Galactic scales, the role of gas pressure, and the meaning of equilibrium, have come under similar scrutiny of late.

In the vertical direction, hydrostatic equilibrium predicts that the mid-plane interstellar pressure should equal the weight of over-lying column of interstellar gas. And, this gross prediction is borne out by the observed density and pressure distributions in the solar neighborhood (Boulares & Cox 1990; Ferrière 2001). But, this simple picture is complicated by the fact that *non-thermal* sources of pressure provide much of the support on large scales while gas pressure is assumed set by the *thermal* balance of heating and cooling on small scales. Recently, these apparently discrepant prescriptions for determining interstellar pressure have been reconciled in a single model, that also purports to explain how this pressure balance determines star formation (Ostriker, McKee, & Leroy 2010). The initial model was applied to conditions in the solar neighborhood, and has now been extended to the low pressure regimes of outer galaxy disks (Ostriker & Shetty 2011) and the high pressure regimes of central starbursts (Kim, Kim, & Ostriker 2011). Meanwhile, other work (e.g. Krumholz, McKee, & Tumlinson 2009) argues the apparent mis-match of pressures at the purported "boundaries" of GMCs with more extended gas in the mid-plane means that the internal workings of GMCs (including star formation) are nearly independent of external conditions.

Figure 5

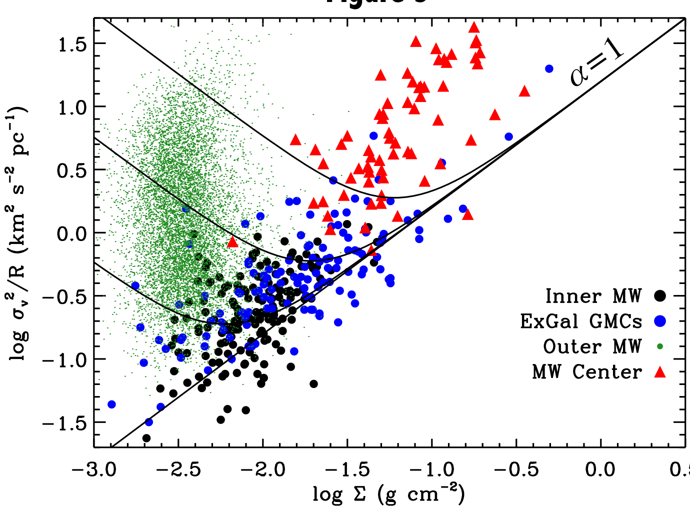


Figure 5 puts the inner Milky Way data (Heyer et al. 2009) into context with data from: the outer Milky Way (Heyer, Carpenter, & Snell 2001); extragalactic GMCs (Rosolowsky & Blitz 2005; Bolatto et al. 2008); and the Galactic center (Oka et al. 2001). Notice how the outer MW clouds appear much more unbound (α>>1) than those in the inner MW, and how very unbound the Galactic Center clouds appear (Spergel & Blitz 1992). All of these systems appear to require modified versions of Larson's Laws, and these modifications could result from the changing pressure across different galactic environments (a conjecture we propose to test with the means described below).

Figure 5's rough regional breakdown is already useful for comparisons with the galaxy-scale models discussed above, but the hierarchical breakdown of gas proposed here will allow for more refined model comparisons. Theories predict significant changes in pressure on smaller scales within the disk, which should then manifest in changes in cloud structure. For example, the classical expectation for the pressure distribution *within* a spiral arm comes from spiral density wave theory (Lin & Shu 1964). In this picture, the zone of maximum pressure/density lies just behind the spiral shock, classically interpreted as the dust-lanes in external spirals, with an increase in star formation (and presumably pressure) downstream from the original shock (cf. Elmegreen, Elmegreen, & Genzel 1992). However, this pressure distribution depends on the equation of state for the gas. An isothermal equation of state (which is explicitly assumed in thermal pressure-balance models) will produce a large thermalization and pressure jump, while for a "stiffer" equation of state (where magnetic fields play a role), there is an increase in gravitational potential energy, i.e. hydraulic jumps, and smaller pressure jumps (Gómez & Cox 2004). Alternative models for the production of spiral structure include: interaction-driven spirals (Purcell et al. 2011); bar driven spirals (Englmaier &

Gerhard 1999); swing-amplification (D'Onghia, Vogelsberger, & Hernquist 2011); and "constrained chaos" models (Athanassoula, Romero-Gómez, & Masdemont 2009).

2.4. How will we compare with theory (simulations)?

The hierarchical deconstruction of clouds we outline below can be applied to models of star forming regions on any scale, as well as to real data. Over the past several years, it has become possible, and increasingly popular, to create synthetic observations (e.g. in CO) of numerical models. Our group, as well as others, have had gained tremendous insight from statistical comparisons of real and synthetic observations (cf. Goodman 2011), and we will employ such comparisons here.

Intriguing recent modeling of the virial parameter in GMCs under a variety of physical assumptions (e.g. Dobbs, Burkert, & Pringle 2011) offers estimates of α based on measurements made in real (*p-p-p*) space, which is *fully inaccessible to observations*. Our own recent work (Shetty et al. 2010) has shown that the virial parameter calculated based on *p-p-v* data may not be a good estimate of the "true" value of α in *p-p-p* space, due to the effects of line of sight confusion, and feature blending. But, happily, it is possible to create synthetic *p-p-v* cubes from simulations, and comparing models and observations in *p-p-v* space has already proven valuable (e.g. Padoan et al. 2006; Offner et al. 2008; Goodman et al. 2009b; Offner & Krumholz 2009; Offner et al. 2011). We highlight the key role comparison of real and synthesized *p-p-v* cubes will play in our overall project in §2.7.

2.5. What methods will we use to analyze and organize the data?

We are definitely not the first to seek a way to gain back the richness offered by a full *p-p-v* cube of the Milky Way (e.g. Scoville et al. 1987; Solomon et al. 1987 and references to either), but the segmentation and visualization methods we propose here are new, and as-such we believe they will lead to important new insights.

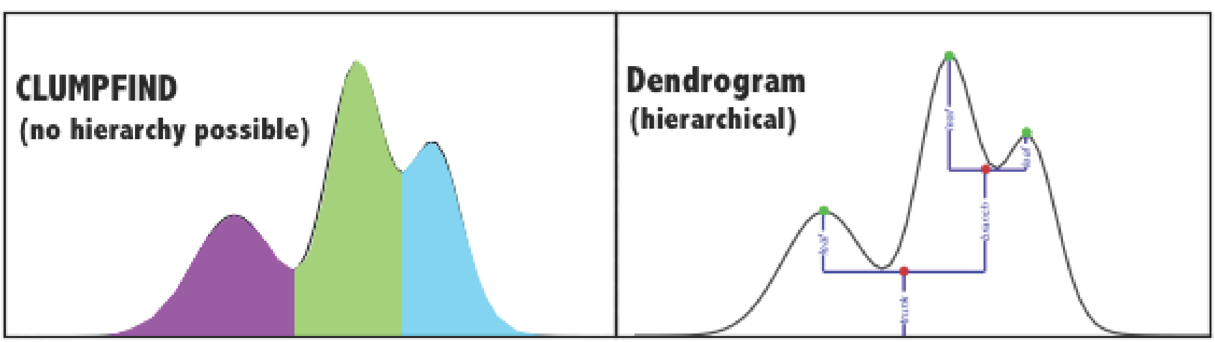


Figure 6

We will use the **dendrogram** algorithm described in §1.2 to segment emission in the Milky Way into a hierarchy of structures representing the nesting of ever-denser, more compact regions. This approach is a major departure from previous work because it never splits objects into discrete, non-overlapping clouds based on (often arbitrary) algorithmic choices. At the basic level, the dendrogram algorithm provides a means to dramatically reduce *p-p-v* data into hierarchical trees.

Figure 6 offers a simple schematic view of the difference between non-hierarchical (CLUMPFIND-like) and hierarchical segmentation. It shows a 1D profile and how it gets divided, down to a minimum threshold, by CLUMPFIND or its ilk. In contrast, the dendrogram tree preserves information about the "trunk" that contains the "branches" and "leaves" of the profile. The two interactive panels of Figure 2 just show a higher-dimensional view of the same kinds of non-overlapping vs. nested structures.

We can mesh the CO-derived dendrograms with our limited knowledge of distances to structures in the ISM *without* first dividing the emission into objects. By associating pieces of the dendrogram tree with distance distributions (see §2.6), we can probabilistically calculate *physical* properties of the nested emission surfaces, such as velocity dispersion, size, and mass. We can thus create a *new type of catalog* of the Milky Way's star-forming interstellar medium, potentially dividing the tree at different levels based on *physical* properties rather than intensity cuts on fixed angular scales (a first example of using the virial parameter to identify clouds is in Rosolowsky et al. 2008). The resulting catalog will encompass the full range of physical scales and types of objects detected in the data.

From the CO-based catalog alone, we will be able to learn how key derived properties like kinetic pressure ($\sim(M/R^3)\sigma_v^2$) or α depend on the nature of the hierarchy, and vice-versa. For example, because we will be able to clearly define what is external to what, the idea of "external" pressure will finally have clear meaning.

As proof-of-concept, we offer Figure 7. Recall that in Figure 2c, we show a dendrogram tree for ^{13}CO emission in the L1448 region of Perseus with "self-gravitating" features (α<2) highlighted. Figure 7 shows, for the very same region, the *same tree* but now color-coded by kinetic pressure.

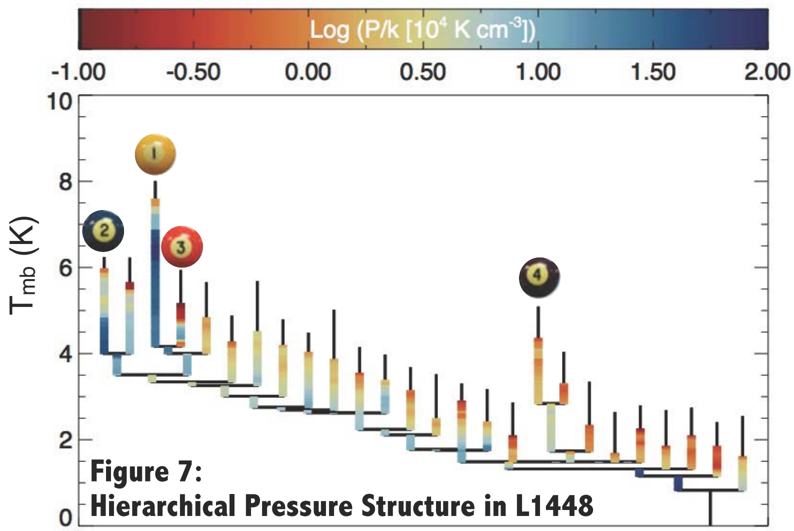


Figure 7: Hierarchical Pressure Structure in L1448

In a one-dimensional emission profile as shown in Figure 6, the dimensional correspondence of emission and dendrogram is literal, in that each point along the vertical lines in the dendrogram represents points on the profile. In dendrograms of emission as a function of three dimensions, though, each point along the vertical lines represents a *surface*. Thus, Figure 7 shows the *pressure distribution within the nested structures* shown in *p-p-v* space in Figure 2a.

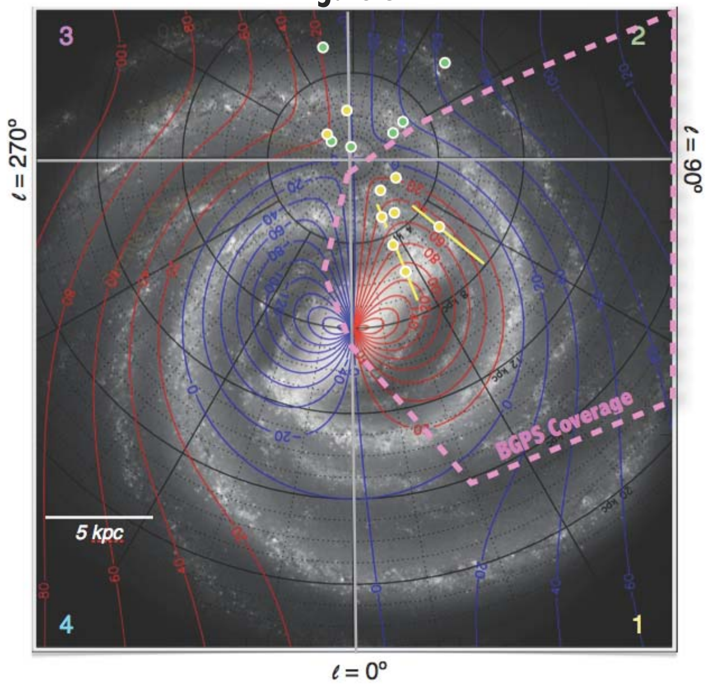
Comparison of Figures 7 and Figure 2c shows that not each of the "self-gravitating" features (marked with billiard balls) has similar pressure structure. Instead, peak #1 seems clearly at the highest pressure (shown as blue), and it is associated with much more star formation than the others (see Goodman et al. 2009b). Furthermore, the dark blue near the tree's base implies that the pressure "outside" (most of) L1448 is high, perhaps suggesting pressure confinement.

Once we have deconstructed the full Milky Way data cube, we will be able to test where, when, and how often the pressure external to a surface regulates other phenomena (e.g. turbulent motions, star formation activity, etc.) inside that surface. Tree-based decompositions of continuum structures (e.g. from BGPS, ATLASGAL, HiGAL), alongside surveys of dense gas features (e.g. MALT90, HOPS) and protostars (e.g. from Spitzer)[10] will make it possible to use our dendrogram-derived CO decomposition to build a contextualized view of star formation in the Milky Way.

[10] A hyperlinked visual summary of all ongoing relevant surveys, prepared by the PI as a reaction to the Rome meeting, is online at universe3d.org. See Broader Impact for more information.

2.6. A 3D model of Star Formation in the Milky Way?

Figure 8



In principle, it is possible to convert the gross features of a *p-p-v* map of the Milky Way into a *p-p-p* map using a modeled rotation curve. This procedure has been used for decades (e.g. Oort, Kerr, & Westerhout 1958), and its main shortcoming is the infamous “near-far” distance ambiguity. Figure 8 shows how line-of-sight velocity (red and blue contours) maps to distance for a particular rotation curve (McClure-Griffiths & Dickey 2007).

Recently, there have been several concerted efforts to resolve near-far ambiguities for star-forming regions, using a variety of clever methods (e.g. absorption lines, extinction mapping, morphological associations, recombination line studies of HII regions). And, in cases where star-forming regions host masers, the BeSSeL (cf. Reid et al. 2009) and VERA surveys (cf. Nagayama et al. 2011) are able to find distances based on parallax. The Distance Omnibus project described in §1.3 is using these parallax-based distances, along with kinematic and other estimates, to ascribe a distance “distribution” to several thousand star forming regions. And, very recently, Kainulainen et al. (2011a) have shown that NIR extinction mapping using UKIDSS data can successfully produce distance estimates and column density maps for massive star forming regions (IRDCs) in the Inner Galaxy, and that the extinction results agree with those based on CO.

As explained in §2.7, we will combine results from ongoing distance-estimation projects with our dendrogram results to study the properties of the Galaxy’s star forming regions. But, even *within* regions of well-known distance, *we can never uniquely convert internal p-p-v structure into p-p-p*.

Nonetheless, we can and will synthesize a real-space Milky Way by placing spatially-nested spherical translucent volumes of size appropriate to their (CO-derived) density at inferred galactocentric distances within a 3D visualization. The transparency of the blobs will be proportional to the certainty about a feature’s distance and properties, such that the final visualization will be sharper where data give better information.

Even though this *p-p-p* 3D view will have more uncertainty built into it than the *p-p-v* views, the demand for it, both from professionals who study galactic structure, and from the public who just wants to know what our Galaxy looks like, is so high that we’ll do it anyway. As we said at the outset, a data-driven 3D Milky Way is a *long-term* goal of ours. We comment further on this goal under Broader Impact (§3), below.

2.7. Research Plan

Our team is distributed across the US, Germany, Austria, and Canada. We have already gotten good (in preparing this proposal) at collaborating online, and much of the research described here will be orchestrated by the PI over the internet. In addition, though, we plan two face-to-face meetings.

The first meeting will take near the end of Year 1 (at the CfA), and the second near the end of Year 2 (at MPIA, see Broader Impact.) We now describe planned research projects, year by year.

Year 1

We have already begun (as part of a 2011-12 Harvard Senior thesis) to construct dendrograms and visualizations of the Dame et al. (2001) *p-p-v* cube, and the full deconstruction should be finished during Year 1. The project is computationally challenging, but manageable.[11] Goodman, Dame, Rosolowsky and their students (including a **new graduate student** to be supported with this grant) and postdocs will be primarily responsible for this initial set of deconstructions. Early analyses will be of the distributions of pressure and virial parameter distributed over the hierarchy, for regions of well-known distance. At least one <u>publication</u> should result from these straightforward first efforts. We will also compare the resulting ensembles of dendrogram-derived features with those produced from non-hierarchical segmentations, including CLUMPFIND, in at least one additional <u>publication</u>.

Thoughtful high-dimensional visualization[8] of results (e.g. Figure 2) has been key in our COMPLETE work, and it always inspires tests of hypotheses not anticipated in advance. Thus, we will extensively use the interactive tools we have developed to investigate linkages between features in quantitative statistical graphics (such as tails in pressure PDFs, unusually branchy dendrograms, etc.) and 3D *p-p-v* visualizations to search for unexpected new trends. To facilitate participation beyond our collaboration, all the full decompositions will be <u>published</u> online (see Broader Impact and Data Management Plan), alongside software tools needed to view and analyze them.

It will be critical to put our results into context with surveys of higher density material and young stars. In particular, toward the end of Year 1 we will focus on the region of the Milky Way covered under the Bolocam Galactic Plane Survey (pink dashed outline in Figure 8). We have carefully analyzed all of the surveys of dense gas and young stars now underway or recently completed[9], and it is clear that the combination of BGPS, plus its spectral follow up projects, undertaken to determine distances, plus the availability of maser-derived distances from BeSSeL favors analysis of the 1st and 2nd galactic quadrants. (Yellow and green circles in Figure 8 show early BeSSeL results (Reid et al. 2009) but ~400 such distance measurements will be added between *l* of 0 and 240 by 2015.)

In Year 1 (and Year 2), Rosolowsky will lead efforts to link the velocities from >4000 dense gas spectra sources of BGPS sources to the CO velocities, uniquely identifying the dense gas locations in the *p-p-v* hierarchy. Using these BGPS "waypoints", the dendrogram branches will be associated with the PDF of distances determined from the Distance Omnibus project.

Robitaille is an expert on modeling young stars' spectral energy distributions (Robitaille et al. 2006; Robitaille et al. 2007), and he and his colleagues also maintain the best inventories of the distribution of young sources in the Milky Way (e.g. Robitaille et al. 2008; Robitaille & Whitney 2010). Beginning in Year 1 and continuing into Year 2, Robitaille will lead efforts (also involving Goodman, Rosolowsky, Reid, and the new graduate student) to identify which sets of young stars and clusters are hosted by which features identified in the dendrogram decomposition of CO.

Goodman and the funded graduate student will work with Robitaille et al. to identify and incorporate newly-discovered faint and/or distant star forming regions into the analysis. In particular, the GBT HII Region Discovery Survey has already doubled the number of known HII regions in the Galaxy

[11] As explained in the Budget Justification, we have access to the "Odyssey" cluster at Harvard, and the usage time we need on the full cluster (>1000 nodes) comes at the small price of adding just a bit of hardware to the system.

(Bania et al. 2010; Anderson et al. 2011). These HII regions have been found using recombination lines with well-measured velocities, so they are easy to contextualize in *p-p-v* analyses.

Year 2

The cross-matching efforts of Rosolowsky et al. (using BGPS) and Robitaille et al. (using young stars) and Goodman et al. (using HII regions and more) will be combined into one or more online catalogs (and publications) offering statistical associations amongst various objects and regions. These catalogs will enable the grant-funded graduate student, and others, to cross-correlate gas properties (e.g. α, pressure structure, column density PDF) with evidence for the formation of pre-stellar cores and stars. The star formation efficiency calculations (and publication) made possible by these correlations will be the most statistically rigorous to date, and as such they will be of great value to the Galactic and extragalactic (e.g. Kennicutt-Schmidt) star-formation communities.

While the investigation of column density PDFs is not specifically the subject of this proposal, ongoing work by Alves, Goodman and collaborators, and by others, has begun to suggest that so-called column density "thresholds" for star formation may be caused by the pressure or magnetic environment of the dense gas (e.g. Kainulainen et al. 2011b). In Year 2, an effort led by Alves and Goodman will combine extinction-based column density analyses (cf. Kainulainen et al. 2011a), dust-emission-based segmentations (e.g. from Herschel), and our new CO-based segmentation of the Milky Way. This multi-method approach will allow for powerful tests of both observed and theoretically predicted (§2.3) relationships amongst column density, volume density and pressure, and at least one publication will result from it.

Beginning in Year 2, Benjamin, Dame, and Reid will lead efforts to integrate results into our understanding of the Milky Way's galactic structure. Benjamin, who is an expert on modeling the Galaxy's structure using the stellar distribution, will work (primarily with Dame, Reid, and Rosolowsky) to investigate the pressure structure of the gas on spiral-arm scales. The unprecedented *p-p-v* view of the gas and its physical state that our work will offer will be presented in a rich visualization online, as well as in at least one publication on pressure structure on arm/galaxy scales.

Offner is an expert on synthetic observations of simulations. While CO is the best spectral-line tracer observers can offer, it is not a perfect linear tracer of H_2, and we can only measure its distribution in *p-p-v* space. *Throughout the proposed projec*t, Offner will work with Goodman et al., and with simulators presently working to incorporate spectral-line radiative transfer into their calculations, so as to create synthetic maps of numerical models. These synthetic models will then be run through telescope simulators before statistical comparisons are made, so as to account for resolution, noise, and other biases. We have already begun discussions about creating synthetic CO observations of the D'Onghia et al. (2011) model with Lars Hernquist's group, and dendrogram-based comparisons of D'Onghia et al.'s and others' models with the Dame et al. view will be published in Year 2.

Year 3

We expect that by Year 3 of this project we will understand our data well enough to attempt transformation of *p-p-v* results to "real" *p-p-p* space.

Transforming our results to real 3D space will facilitate comparisons with other spiral galaxies. Rosolowsky, in ongoing collaboration with A. Leroy (NRAO) is leading an observational consortium to survey 10 nearby disk galaxies with ALMA and single-dish telescopes to obtain high resolution, external views of their star-forming gas. The dendrogram algorithm will be applied to those external galaxies. By transforming the unbiased, albeit low linear resolution, views of the ISM in ~face-on external galaxies into equivalent *l-b-v* diagrams that would be observed within the disk of those galaxies, we can compare the Milky Way to the external galaxies. In so-doing, we will better understand the biases present in transforming the Milky Way into "real" 3D space, and we will publish a paper on how the structure of star-forming gas in the Milky Way apparently compares to nearby spirals.

Before the proposed project is done, we will use the structure-modeling efforts and expertise from our team to create the best visualization of star-forming regions in the Milky Way ever made. Goodman will lead this effort with substantial collaboration from Robitaille and Alves. The visualization will be described in a publication, and it will be distributed and usable through several online outlets, including universe3d.org, as described further under "Broader Impact."

We realize that our plans sound extremely ambitious, but we are confident that the wide array of expertise and resources assembled, our network of ongoing collaborations, and the uniqueness of the Milky Way CO map, makes our goals realistic. The resource this work will provide, not just for the student we seek to fund, but for the community, should make the investment extremely worthwhile.

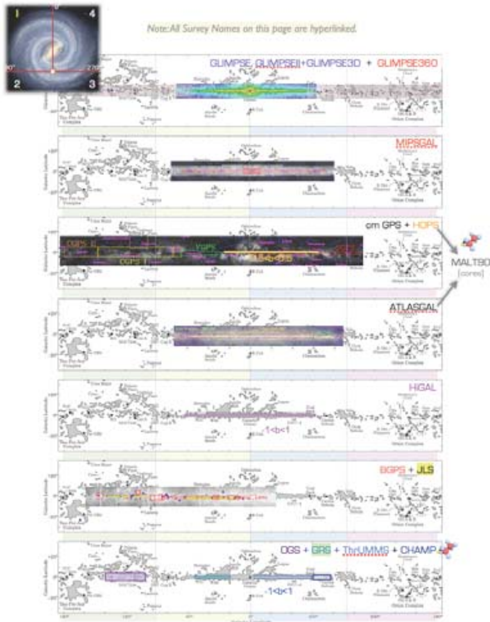
3. BROADER IMPACT

Our project will be of interest to many communities within astrophysics, ranging from those who study the formation of stars to those who study the formation and evolution of galaxies in general, and the Milky Way in particular.

Open Meeting Because of our work's broad appeal, we plan to follow our group's second (Year 3) team meeting with a small open workshop on the structure of Milky Way star-forming regions at MPIA. There are three reasons we plan to have this workshop in Heidelberg. First, Goodman has recently begun a collaboration on high-dimensional visualization with colleagues at the brand-new *Haus der Astronomie* (HdA) outreach and visualization center at the MPIA in Heidelberg. The center hosts a large tilted-dome auditorium, making it one of very few locations in the world offering an immersive environment in which to appreciate 3D data. Second, the HdA (see aerial photo) is built *in the shape of the Milky Way*! And, third, Robitaille and his group are located at MPIA, and they are more than willing to serve as local hosts. We only request funds here to bring proposal participants to this meeting, as MPIA will host the event.

Public Data Our results will be made available online in usable standard formats as they are created for anyone to use. As the "Prior Work" and "Data Management Plan" sections describe, we have followed this open-access policy for COMPLETE and for the CO 1.2-m survey already, and so we have proven our capabilities to effectively serve the kind of data and results to be produced under this proposal.

universe3d.org The results of this proposal will serve as key content at a new site we have founded called "universe3d.org." The idea for this collaborative site arose at the recent Rome Milky Way 2011 meeting, where it became clear that people could not even understand what parts of the Milky Way each other had observed using what technique(s)–let alone actually *use* each other's data. The small inset below shows a mini-version of what is actually a detailed hyperlinked overview of Milky Way star formation surveys posted by Goodman at universe3d.org. The plan for universe3d.org is to



begin by hosting discussions and links to data, software, and projects, and then, as more and more data and easy-to-use viewers become available, for the site to offer a *data-driven, interactive, rich 3D visualization of the Solar System, the Galaxy, and the Universe*.

The full functionality of universe3d.org may sound like a pipe dream to some, but we are optimistic that our team's experience and involvements give us an excellent chance of realizing the full vision in the coming decade for several reasons: 1) Goodman is the astronomer who works most closely with Microsoft Research to develop and improve the WorldWide Telescope (WWT) Universe Information System. WWT, which can run in a web browser on PC or Mac, already offers a rich environment that links all-sky surveys as well as targeted imagery to the literature (via ADS), to data (via VO-compatible tools), and to software (via resource hubs like SAMP). Through Goodman's work with ADS Labs, ADS literature searches now offer relevant links back to objects on the Sky, via WWT. 2) Goodman was the Founding Director of the Initiative in Innovative Computing at Harvard, and she teaches data visualization at Harvard. 3) Robitaille is widely known both for his prowess in astrophysics *and* as one of the most savvy software developers in our field. 4) Alves leads the EU-based team (which also includes Goodman) tasked with developing visualizations strategies for the upcoming GAIA database, so as to make it useful in studies of star formation and Galactic structure. And, 5) Benjamin already led the effort to create the synthesized "3D" model of the Milky Way that led to the the Milky Way illustration by Robert Hurt seen in Figure 8 and all over the literature and the web.

Visualization and STEM Education We have already begun researching how best to visualize "3D" (both *p-p-v* and *p-p-p*) Milky Way data, in research and in public contexts. Ultimately, well-supported viewers like WWT, which can already handle 3D content[12], should be able to access our data, and so should amateur-created tools like Are Uppman's Universe, and planetarium-inspired software like the AMNH Digital Universe.

Goodman is the founding PI of the WorldWide Telescope Ambassadors Program, which trains volunteer experts (including retirees) around the world to use WWT in educational settings. Much of the program revolves around WWT Tours, which take explorers through the Sky (2D) or the Universe (3D) on guided journeys created by experts seeking to educate, by students seeking to learn, or by anyone who wants to communicate about the Sky and the Universe. Goodman has authored several WWT Tours, which have already had literally millions of downloads. One Tour (called "Dust and Us") explains star formation in the Milky Way, and it will surely be augmented and supplanted as a result of this work!

In addition to featuring our project's science content in our outreach work, we will also create a visualization explaining all of the transformations and assumptions needed to go from *p-p-v* space to *p-p-p* space. We imagine this explanation will be of use to professionals as well as to the public.

---

[12] Interested readers can search online for "John Huchra's Universe" and find a WWT Tour that highlights the use of 3D data (redshift surveys) in a tribute to the late John Huchra. Both video and "tour" formats are available (link).

BIBLIOGRAPHY

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, 159-161

Anderson, L. D., Bania, T. M., Balser, D. S. & Rood, R. T. 2011, *The Green Bank Telescope H II Region Discovery Survey. II. The Source Catalog*, ApJS, 194, 32

Arce, H. G., Borkin, M. A., Goodman, A. A., Pineda, J. E. & Beaumont, C. N. 2011, *A Bubbling Nearby Molecular Cloud: COMPLETE Shells in Perseus*, arXiv:1109.3368

Athanassoula, E., Romero-Gómez, M. & Masdemont, J. J. 2009, *Rings and spirals in barred galaxies - I. Building blocks*, MNRAS, 394, 67-81

Ballesteros-Paredes, J. 2006, *Six myths on the virial theorem for interstellar clouds*, MNRAS, 372, 443-449

Bania, T. M., Anderson, L. D., Balser, D. S. & Rood, R. T. 2010, *The Green Bank Telescope Galactic H II Region Discovery Survey*, ApJ, 718, L106-L111

Bertoldi, F. & McKee, C. F. 1992, *Pressure-Confined Clumps in Magnetized Molecular Clouds*, ApJ, 395, 140-157

Bolatto, A. D., Leroy, A. K., Rosolowsky, E., Walter, F. & Blitz, L. 2008, *The Resolved Properties of Extragalactic Giant Molecular Clouds*, ApJ, 686, 948-965

Boulares, A. & Cox, D. P. 1990, *Galactic hydrostatic equilibrium with magnetic tension and cosmic-ray diffusion*, ApJ, 365, 544-558

Chieze, J. P. 1987, *The fragmentation of molecular clouds. I - The mass-radius-velocity dispersion relations*, Astronomy and Astrophysics (ISSN 0004-6361), vol. 171, no. 1-2, Jan. 1987, p. 225-232.,

D'Onghia, E., Vogelsberger, M. & Hernquist, L. 2011, *Stochastic Spiral Arms in Disk Galaxies*, Bulletin of the American Astronomical Society, 43, 41706

Dame, T. M., Hartmann, D. & Thaddeus, P. 2001, *The Milky Way in Molecular Clouds: A New Complete CO Survey*, ApJ, 547, 792-813

Dib, S., Kim, J., Vázquez-Semadeni, E., Burkert, A. & Shadmehri, M. 2007, *The Virial Balance of Clumps and Cores in Molecular Clouds*, ApJ, 661, 262-284

Dobbs, C. L., Burkert, A. & Pringle, J. E. 2011, *Why are most molecular clouds not gravitationally bound?*, MNRAS, 413, 2935-2942

Dunham, M. K., Rosolowsky, E., Evans II, N. J., Cyganowski, C. & Urquhart, J. S. 2011, *The Bolocam Galactic Plane Survey. VII. Characterizing the Properties of Massive Star-Forming Regions*, ApJ, 741, 110

Elmegreen, B. G., Elmegreen, B. G. & Genzel, R. 1992, *Large-scale dynamics in the Interstellar Medium*, in Saas-Fee Advanced Course 21: The Galactic Interstellar Medium, ed. W. B. Burton, 157-274

Englmaier, P. & Gerhard, O. 1999, *Gas dynamics and large-scale morphology of the Milky Way galaxy*, MNRAS, 304, 512-534

Evans, N. J., II, Dunham, M. M., Jørgensen, J. K., Enoch, M. L., Merín, B., van Dishoeck, E. F., Alcalá, J. M., Myers, P. C. et al. 2009, *The Spitzer c2d Legacy Results: Star-Formation Rates and Efficiencies; Evolution and Lifetimes*, ApJS, 181, 321-350

Ferrière, K. M. 2001, *The interstellar environment of our galaxy*, Rev. Mod. Phys., 73, 1031-1066

Field, G. B., Blackman, E. G. & Keto, E. R. 2011, *Does external pressure explain recent results for molecular clouds?*, MNRAS, 416, 710-714.

Gómez, G. C. & Cox, D. P. 2004, *Three-Dimensional Magnetohydrodynamic Modeling of the Gaseous Structure of the Galaxy: Description of the Simulations*, ApJ, 615, 744-757

Goodman, A. A., Pineda, J. E. & Schnee, S. L. 2009a, *The "True" Column Density Distribution in Star-Forming Molecular Clouds*, ApJ, 692, 91-103

Goodman, A. A., Rosolowsky, E. W., Borkin, M. A., Foster, J. B., Halle, M., Kauffmann, J. & Pineda, J. E. 2009b, *A role for self-gravity at multiple length scales in the process of star formation*, Nature, 457, 63-66

Goodman, A. A. 2011, *A Guide to Comparisons of Star Formation Simulations with Observations*, in IAU Symposium, eds. J. Alves, B. G. Elmegreen, J. M. Girart & V. Trimble, 511-519

Heyer, M., Krawczyk, C., Duval, J. & Jackson, J. M. 2009, *Re-Examining Larson's Scaling relationships in Galactic Molecular Clouds*, ApJ, 699, 1092-1103

Heyer, M. H., Carpenter, J. M. & Snell, R. L. 2001, *The Equilibrium State of Molecular Regions in the Outer Galaxy*, ApJ, 551, 852-866

Houlahan, P. & Scalo, J. 1990, *Recognition and Characterization of Hierarchical Interstellar Structure. I. Correlation Function*, ApJS, 72, 133-152

Houlahan, P. & Scalo, J. 1992, *Recognition and characterization of hierarchical interstellar structure. II - Structure tree statistics*, ApJ, 393, 172-187

Jackson, J. M., Rathborne, J. M., Shah, R. Y., Simon, R., Bania, T. M., Clemens, D. P., Chambers, E. T., Johnson, A. M. et al. 2006, *The Boston University-Five College Radio Astronomy Observatory Galactic Ring Survey*, ApJS, 163, 145-159

Kainulainen, J., Alves, J., Beuther, H., Henning, T. & Schuller, F. 2011a, *Mass reservoirs surrounding massive infrared dark clouds: A view by near-infrared dust extinction*, arXiv: 1109.6017

Kainulainen, J., Beuther, H., Banerjee, R., Federrath, C. & Henning, T. 2011b, *Probing the evolution of molecular cloud structure*, A&A, 530, A64

Keto, E. R. & Myers, P. C. 1986, *CO observations of southern high-latitude clouds*, ApJ, 304, 466

Kim, C.-G., Kim, W.-T. & Ostriker, E. C. 2011, *Regulation of Star Formation Rates in Multiphase Galactic Disks: Numerical Tests of the Thermal/Dynamical Equilibrium Model*, arXiv:1109.0028

Kirk, H., Pineda, J. E., Johnstone, D. & Goodman, A. 2010, *The Dynamics of Dense Cores in the Perseus Molecular Cloud. II. The Relationship Between Dense Cores and the Cloud*, ApJ, 723, 457-475

Krumholz, M. R., McKee, C. F. & Tumlinson, J. 2009, *The Star Formation Law in Atomic and Molecular Gas*, ApJ, 699, 850-856

Lada, C. J. & Lada, E. A. 2003, *Embedded Clusters in Molecular Clouds*, ARA&A, 41, 57-115

Lada, E. A., Bally, J. & Stark, A. A. 1991, *An Unbiased Survey for Dense Cores in the Lynds 1630 Molecular Cloud*, ApJ, 368, 432-444

Larson, R. B. 1981, *Turbulence and Star Formation in Molecular Clouds*, M.N.R.A.S., 194, 809-826

Lin, C. C. & Shu, F. H. 1964, *On the Spiral Structure of Disk Galaxies.*, ApJ, 140, 646

McClure-Griffiths, N. M. & Dickey, J. M. 2007, *Milky Way Kinematics. I. Measurements at the Subcentral Point of the Fourth Quadrant*, ApJ, 671, 427-438

Myers, P. C. & Goodman, A. A. 1988, *Indirect Evidence for Magnetic and Virial Equilibrium in Molecular Clouds*, ApJ, 329, 392

Nagayama, T., Omodaka, T., Handa, T., Honma, M., Kobayashi, H., Kawaguchi, N. & Ueno, Y. 2011, *Astrometry of Galactic Star-Forming Region G48.61+0.02 with VERA*, Publications of the Astronomical Society of Japan, 63, 719-725

Offner, S. S. R., Krumholz, M. R., Klein, R. I. & McKee, C. F. 2008, *The Kinematics of Molecular Cloud Cores in the Presence of Driven and Decaying Turbulence: Comparisons with Observations*, AJ, 136, 404-420

Offner, S. S. R. & Krumholz, M. R. 2009, *The Shapes of Molecular Cloud Cores in Simulations and Observations*, ApJ, 693, 914-921

Offner, S. S. R., Lee, E. J., Goodman, A. A. & Arce, H. 2011, *Radiation-Hydrodynamic Simulations of Protostellar Outflows: Synthetic Observations and Data Comparisons*, arXiv:1110.5640

Oka, T., Hasegawa, T., Sato, F., Tsuboi, M., Miyazaki, A. & Sugimoto, M. 2001, *Statistical Properties of Molecular Clouds in the Galactic Center*, ApJ, 562, 348-362

Oort, J. H., Kerr, F. J. & Westerhout, G. 1958, *The galactic system as a spiral nebula (Council Note)*, MNRAS, 118, 379

Ostriker, E. C., McKee, C. F. & Leroy, A. K. 2010, *Regulation of Star Formation Rates in Multiphase Galactic Disks: A Thermal/Dynamical Equilibrium Model*, ApJ, 721, 975-994

Ostriker, E. C. & Shetty, R. 2011, *Maximally Star-forming Galactic Disks. I. Starburst Regulation Via Feedback-driven Turbulence*, ApJ, 731, 41

Padoan, P., Juvela, M., Kritsuk, A. & Norman, M. L. 2006, *The Power Spectrum of Supersonic Turbulence in Perseus*, ApJ, 653, L125-L128

Pineda, J. E., Rosolowsky, E. W. & Goodman, A. A. 2009, *The Perils of Clumpfind: The Mass Spectrum of Substructures in Molecular Clouds*, ApJ, 699, L134-L138

Pineda, J. E., Goodman, A. A., Arce, H. c. G., Caselli, P., Foster, J. B., Myers, P. C. & Rosolowsky, E. W. 2010, *Direct Observation of a Sharp Transition to Coherence in Dense Cores*, ApJ, 712, L116-L121

Pineda, J. E., Goodman, A. A., Arce, H. G., Caselli, P., Longmore, S. & Corder, S. 2011, *Expanded Very Large Array Observations of the Barnard 5 Star-forming Core: Embedded Filaments Revealed*, ApJL, 739, L2

Purcell, C. W., Bullock, J. S., Tollerud, E. J., Rocha, M. & Chakrabarti, S. 2011, *The Sagittarius impact as an architect of spirality and outer rings in the Milky Way*, Nature, 477, 301-303

Reid, M. J., Menten, K. M., Zheng, X. W., Brunthaler, A., Moscadelli, L., Xu, Y., Zhang, B., Sato, M. et al. 2009, *Trigonometric Parallaxes of Massive Star-Forming Regions. VI. Galactic Structure, Fundamental Parameters, and Noncircular Motions*, ApJ, 700, 137-148

Ridge, N. A., Di Francesco, J., Kirk, H., Li, D., Goodman, A. A., Alves, J. F., Arce, H. G., Borkin, M. A. et al. 2006, *The COMPLETE Survey of Star-Forming Regions: Phase I Data*, AJ, 131, 2921-2933

Robitaille, T. P., Whitney, B. A., Indebetouw, R., Wood, K. & Denzmore, P. 2006, *Interpreting Spectral Energy Distributions from Young Stellar Objects. I. A Grid of 200,000 YSO Model SEDs*, ApJS, 167, 256-285

Robitaille, T. P., Whitney, B. A., Indebetouw, R. & Wood, K. 2007, *Interpreting Spectral Energy Distributions from Young Stellar Objects. II. Fitting Observed SEDs Using a Large Grid of Precomputed Models*, ApJS, 169, 328-352

Robitaille, T. P., Meade, M. R., Babler, B. L., Whitney, B. A., Johnston, K. G., Indebetouw, R., Cohen, M., Povich, M. S. et al. 2008, *Intrinsically Red Sources Observed by Spitzer in the Galactic Midplane*, AJ, 136, 2413-2440

Robitaille, T. P. & Whitney, B. A. 2010, *The Present-Day Star Formation Rate of the Milky Way Determined from Spitzer-Detected Young Stellar Objects*, ApJ, 710, L11-L15

Rosolowsky, E. & Blitz, L. 2005, *Giant Molecular Clouds in M64*, ApJ, 623, 826-845

Rosolowsky, E., Dunham, M. K., Ginsburg, A., Bradley, E. T., Aguirre, J., Bally, J., Battersby, C., Cyganowski, C. et al. 2010a, *The Bolocam Galactic Plane Survey. II. Catalog of the Image Data*, ApJS, 188, 123-138

Rosolowsky, E., Ginsburg, A. & Ellsworth-Bowers, T. 2010b, *The BGPS Distance Omnibus Project*, Astronomical Society of the Pacific Conference Series, 438, 76

Rosolowsky, E. W., Pineda, J. E., Kauffmann, J. & Goodman, A. A. 2008, *Structural Analysis of Molecular Clouds: Dendrograms*, ApJ, 679, 1338-1351

Scoville, N. Z., Yun, M. S., Sanders, D. B., Clemens, D. P. & Waller, W. H. 1987, *Molecular clouds and cloud cores in the inner Galaxy*, The Astrophysical Journal Supplement Series, 63, 821-915

Shetty, R., Kauffmann, J., Schnee, S., Goodman, A. A. & Ercolano, B. 2009, *The Effect of Line-of-Sight Temperature Variation and Noise on Dust Continuum Observations*, ApJ, 696, 2234-2251

Shetty, R., Collins, D. C., Kauffmann, J., Goodman, A. A., Rosolowsky, E. W. & Norman, M. L. 2010, *The Effect of Projection on Derived Mass-Size and Linewidth-Size Relationships*, ApJ, 712, 1049-1056

Solomon, P. M., Rivolo, A. R., Barrett, J. & Yahil, A. 1987, *Mass, luminosity, and line width relations of Galactic molecular clouds*, ApJ, 319, 730

Spergel, D. N. & Blitz, L. 1992, *Extreme gas pressures in the Galactic bulge*, Nature, 357, 665-667

Williams, J., de Geus, E. & Blitz, L. 1994, *Determining Structure in Molecular Clouds*, ApJ, 428, 693-712

Biographical Sketch for Alyssa A. Goodman, November 2011

Professional Preparation

Massachusetts Institute of Technology, ScB in Physics, 1984

Harvard University, AM in Physics, 1986 and PhD in Physics, 1989

University of California at Berkeley, President's Fellowship, 1989-92

Appointments

1999–	Professor of Astronomy, Harvard University
1995–	Research Associate, Smithsonian Astrophysical Observatory
2008- 2011	Scholar-in-Residence, WGBH Boston (sabbatical & *pro bono* consulting)
2008–2010	Core Member, Harvard Initiative in Innovative Computing
2005–2008	Founding Director, Harvard Initiative in Innovative Computing
2001–2002	Visiting Fellow, Yale University (sabbatical)
1996–1999	Associate Professor of Astronomy, Harvard University
1995–1997	Head Tutor, Harvard University Astronomy Department
1992–1996	Assistant Professor of Astronomy, Harvard University
1989–1992	President's Fellow, University of California, Berkeley

Recent Relevant Publications *(*=most closely related to this proposal)*

Arce, H. G., Borkin, M. A., Goodman, A. A., Pineda, J. E. & Beaumont, C. N. 2011, *A Bubbling Nearby Molecular Cloud: COMPLETE Shells in Perseus*, ArXiv e-prints, 3368 (in press for ApJ)

Beaumont, C. N., Williams, J. P. & Goodman, A. A. 2011, *Classifying Structures in the Interstellar Medium with Support Vector Machines: The G16.05-0.57 Supernova Remnant*, ApJ, 741, 14

*Goodman, A. A., Pineda, J. E. & Schnee, S. L. 2009, *The "True" Column Density Distribution in Star-Forming Molecular Clouds*, ApJ, 692, 91-103

*Goodman, A. A., Rosolowsky, E. W., Borkin, M. A., Foster, J. B., Halle, M., Kauffmann, J. & Pineda, J. E. 2009, *A role for self-gravity at multiple length scales in the process of star formation*, Nature, 457, 63-66

*Kirk, H., Pineda, J. E., Johnstone, D. & Goodman, A. 2010, *The Dynamics of Dense Cores in the Perseus Molecular Cloud. II. The Relationship Between Dense Cores and the Cloud*, ApJ, 723, 457-475

Pineda, J. E., Goodman, A. A., Arce, H. G., Caselli, P., Foster, J. B., Myers, P. C. & Rosolowsky, E. W. 2010, *Direct Observation of a Sharp Transition to Coherence in Dense Cores*, ApJ, 712, L116-L121

*Pineda, J. E., Rosolowsky, E. W. & Goodman, A. A. 2009, The Perils of Clumpfind: The Mass Spectrum of Substructures in Molecular Clouds, The Astrophysical Journal Letters, 699, L134-L138

*Rosolowsky, E. W., Pineda, J. E., Kauffmann, J. & Goodman, A. A. 2008, *Structural Analysis of Molecular Clouds: Dendrograms*, ApJ, 679, 1338-1351

Rosolowsky, E. W., Pineda, J. E., Foster, J. B., Borkin, M. A., Kauffmann, J., Caselli, P., Myers, P. C. & Goodman, A. A. 2008, *An Ammonia Spectral Atlas of Dense Cores in Perseus*, ApJS, 175, 509-521

Shetty, R., Kauffmann, J., Schnee, S., Goodman, A. A. & Ercolano, B. 2009, *The Effect of Line-of-Sight Temperature Variation and Noise on Dust Continuum Observations*, ApJ, 696, 2234-2251

Synergistic Activities

Public Understanding of Science/WGBH In 2008-9 AG helped create (and appeared in) an episode of *Fetch! with Ruff Ruffman*, focusing on multi-wavelength sensing. The episode was nominated for a 2010 Emmy. During 2009-11, she and colleagues developed a proposal for a broadband+TV project code-named *Prediction,* aimed at explaining the critical role played by computer simulation in today's world. At present, AG's collaboration with WGBH is focused on the WWTA Program described below.

Initiative in Innovative Computing (IIC) & e-Science In AG's IIC Directorship, she built a new institution at Harvard, hosting dozens of researchers, whose mission was to address and answer scientific questions that are unanswerable without bringing domain scientists and computer scientists into closer collaboration. IIC efforts brought a host of new courses, scholars, and events to Harvard, much of which recently became a formal part of the Harvard School of Engineering and Applied Science (see "IACS"). Since the IIC work, AG has served on several committees concerned with e-Science, including the National Academy's Board on Research Data and Information, which analyzes the use of government-sponsored data in US research and education.

Scientific Visualization For the past decade, AG has taught Harvard undergraduates data visualization in her course known as the "Art of Numbers." AG's research at IIC included starting and leading the *Astronomical Medicine* effort, which created now-deployed software tools for visualizing three-dimensional astronomy data using tools developed for medical research. This work also led, in 2009, to the first 3D PDF to be published in *Nature* (see Publications). AG organized a special session at the AAAS called "Seeing Science," in 2008. Since the AAAS event, AG has given many invited presentations on visualization to audiences around the world, both within and beyond the astronomical community.

WorldWide Telescope/WWT Ambassadors Since 2007, AG has been and is the lead astronomical consultant/collaborator in the creation of the WorldWide Telescope program from Microsoft Research. In 2009, she founded the "WorldWide Telescope Ambassadors" program, which recruits and trains volunteers to use WWT in educational settings worldwide. In related work, AG serves on the Science Advisory Committee for the US Virtual Astrophysical Observatory.

AAAS AG served as Chair of the Astronomy Section of the American Association for the Advancement of Science in 2008. In 2010, she joined the Science/AAAS Online Advisory Committee, established to "understand the ways scientists in the field, the lab, and the classroom are using the Web and networked information to further their work and careers."

Collaborators & Other Affiliations

Non-student Collaborators
Alan, D., *MIT*
Alves, J., *U. Vienna*
Audit, E., *CEA, France*
Bontemps, S., *CEA, France*
Bourke, T., CfA
Caselli, Paola, *U. of Leeds, UK*
Cantó, J., *U. Mexico*
Collins, D.C., *ITA Heidelberg*
Corder, S., *NRAO, ALMA*
Csengeri, T., *DSM, CEA, France*
Dib, S., DSM, *CEA, France*
Dowell, C., *Caltech*
Enoch, M., *UC Berkeley*
Ercalano, B., *CfA*
Gómez, L., *U. Mexico*
Halle, M., *MGH*
Henning, T, *ITA Heidelberg*
Hennebelle, P.,*UMR France*
Hildebrand, R., *U. Chicago*
Johnstone, D., *NRC/HIA,*
Kauffmann, J., *JPL*
Kainulainen, J., *ITA, Germany*
Kirk, H., *CfA*
Lada, E. A., *U. Fl. Gainesville*
Launhardt, R. ITA Heidelberg
Li, J. *CfA*
Li, H-B, *CfA*
Loinard, L., *U. Mexico*
Longmore, S., *ESO, Germany*
Norman, M., *UCSD*
Noriega-Crespo, A., *SSC*
Novak, G., *Northwestern*
Padgett, D., *SSC*
Pillai, T., *JPL*
Quanz, S.P., *ETH, Zurich*
Raga, A.C., *U. Mexico*
Rebull, L., *SSC*
Robitaille, T., *CfA*
Román-Zúñiga, C., *CA, ES*
Rodríguez, L. F, *U. Mexico*
Sargent, A. I., *Caltech*
Sayers, J., *JPL*
Schmalzl, M. *ITA Heidelberg*
Shetty, R., *ITA Heidelberg*
Strom, S., *NOAO, AZ*
Taffalla, M., *CSIC, Spain*
Tanner, T., *Yale*
Terebey, S., *Cal State, LA*
Udomprasert, P., *CfA*
Valva, A., *WGBH, Boston, MA*
William, J.P., *U. Hawaii*
Wong, C., *Microsoft*

Graduate Advisor
Philip Myers, *CfA*

Students Advised
Prof. Héctor Arce, *Yale*
Prof. Javier Ballesteros-Paredes, *UNAM*
*Chris Beaumont, *U. Hawaii/Harvard*
*Michelle Borkin, *Harvard '06*
Prof. Joseph Barranco, *UC Berkeley*
*Hope Chen, Harvard University
*Chris Faesi, Harvard
Dr. Cassandra Fallscheer, *MPI*
Dr. Jonathan Foster, *BU*
Sebastien Guillot, *McGill*
Katherine Guenthner, *U. Leipzig*
Prof. Sheila Kannappan, *UNC Chapel Hill*
Dr. Kishore Kuchibhotla, *Harvard Medical School*
David Kosslyn, *Harvard* '11
Jason Li, *Harvard '08*
Tom Laakso, *Harvard '06*
Dr. Jaime Pineda, *Manchester, UK*
Prof. Subu Mohanty, *Imperial College, London*
Tom Rice, Harvard '12
Prof. Erik Rosolowsky, UBC Okanagan
Dr. Karin Sandstrom, *UC Berkeley*
Dr. Scott Schnee, *Caltech*
Sanjana Sharma, *Yale*
Dr. Matthew Sumner, *Caltech*
Lawrence Valverde, *Harvard '10*
Nathan Whitehorn, *U. Wisconsin*
*=currently AG's graduate student

BIOGRAPHICAL SKETCH FOR ROBERT A. BENJAMIN, NOVEMBER 2011

Professional Preparation

Carleton College	Physics and Mathematics	B. A. 1987
University of Texas at Austin	Astronomy	M.A. 1990
University of Texas at Austin	Astronomy	Ph.D. 1994

Appointments

2003 -	Assistant Professor of Physics, University of Wisconsin-Whitewater
2000 - 2003	Assistant Scientist, Dept of Physics, University of Wisconsin-Madison
1997 - 2000	Post-doctoral Physicist, University of Wisconsin-Madison
1994 - 1997	Post-doctoral Astronomer, University of Minnesota

Five Relevant Publications

Churchwell, E. & Benjamin, R.A. "The Infrared Milky Way Galaxy" in Stars and Stellar Systems: Galactic Structure, ed. G. Gilmore, in press (2012).

Benjamin, R.A. *"How Does the Galaxy Work?"* in *Astronomy: Special Galaxy Edition*, (2008).

Benjamin, R.A., Draine, B.T., Indebetouw, R., Lada, C.J., Majewski, S.R., Reid, I.N., Skrutskie, M.F. "*The Warm Spitzer Mission: Opportunities to Study Galactic Structure and the Interstellar Medium*" in The Science Opportunities of the Warm Spitzer Mission Workshop, AIP Conference Proceedings, 943, 101 (2007). http://adsabs.harvard.edu/abs/2007AIPC..943..101B

Benjamin, R.A., Churchwell, E., Babler, B.L., Indebetouw, R., Meade, M.R., Whitney, B.A., Watson, C., Wolfire, M.G., Wolff, M.J., Ignace, R., Bania, T.M., Bracker, S., Clements, D.P., Chomiuk, L., Cohen, M., Dickey, J.M., Jackson, J.M., Kobulnicky, H.A., Mercer, E.P., Mathis, J.S., Stolovy, S.R., Uzpen, B. *"First GLIMPSE Results on the Stellar Structure of the Galaxy",* Astrophysical Journal Letters, 630, 149 (2005). http://adsabs.harvard.edu/abs/2005ApJ...630L.149B

Benjamin, R.A., Churchwell, E., Babler, B.L., Bania, T.M., Clements, D.P., Cohen, M., Dickey, J.M., Indebetouw, R., Jackson, J.M., Kobulnicky, H.A., Lazarian, A., Marston, A.P., Mathis, J.S., Meade, M.R., Seager, S., Stolovy, S.R., Watson, C., Whitney, B.A., Wolff, M.J., Wolfire, M.G. *"GLIMPSE: A SIRTF Legacy Project to Map the Inner Galaxy*", Publication of the Astronomical Society of Pacific, 115, 953 (2003). http://adsabs.harvard.edu/abs/2003PASP..115..953B

Five Additional Publications

Hill, A.S. Benjamin, R.A., Kowal, G., Reynolds, R.J., Haffner, L.M., Lazarian, A. "*The Turbulent Warm Ionized Medium: Emission Measure Distribution and MHD Simulations*", Astrophysical Journal, 686,363 (2008). http://adsabs.harvard.edu/abs/2008arXiv0805.0155H

Rand, R.J., Benjamin, R.A. "*Vertically Extended Neutral Gas in the Massive Edge-on Spiral NGC 5746*", Astrophysical Journal, 676, 991 (2008). http://adsabs.harvard.edu/abs/2008ApJ...676..991R

Lockman, F.J., Benjamin, R.A., Heroux, A.J., Langston, G.I. "*The Smith Cloud: A High-Velocity Cloud Colliding with the Milky Way*", Astrophysical Journal Letters, 679, L21 (2008), http://adsabs.harvard.edu/abs/2008ApJ...679L..21L

Everett, J.E., Zweibel, E.G., Benjamin, R.A., McCammon, D., Rocks, L., Gallagher, J.S, "*The Milky Way's Kiloparsec-Scale Wind: A Hybrid Cosmic-Ray and Thermally Driven Outflow*", Astrophysical Journal, 674, 258 (2008). http://adsabs.harvard.edu/abs/2008ApJ...674..258E

Heald, G.H., Rand, R.J., Benjamin, R.A., Collins, J.A. "*Integral Field Unit Observations of NGC 4302: Kinematics of the Diffuse Ionized Gas Halo",* Astrophysical Journal, 663, 933 (2007). http://adsabs.harvard.edu/abs/2007ApJ...663..933H

Synergistic Activities

- Director or co-director of University of Wisconsin-Madison Astronomy REU program: 2002-present.
- Service on AAS Committee for Status of Minorities in Astronomy; contributor to SPECTRUM: The Committee for Status of Minorities in Astronomy Newsletter (Jan 2003).
- Ten live radio interviews on Madison WORT (89.9 FM) science show "Perpetural Notions" (Madison, WI) and several public lecture at University of Wisconsin-Space Place
- Coordinated effort with Robert Hurt to develop "Artist's conception" image of Galaxy released at 212th AAS meeting in June 2008: http://ipac.jpl.nasa.gov/media_images/ssc2008-10b1.jpg
- Organizer of AAS Special Session, "The Spiral Structure of the Galaxy", at 212th AAS meeting in St. Louis, MO (June 2008) at which a new spiral arm was announced by Tom Dame (CfA).

Collaborators and Co-Editors

Dinshaw Balsara (Notre Dame), Tom Bania (Boston), Ed Churchwell (Wisconsin), Jungyeon Cho (Wisconsin), Dan Clemens (Boston U), Martin Cohen (UCB), Joe Collins (Colorado), Donald P. Cox (Wisconsin), John Dickey (Tasmania), Bruce Draine (Princeton), Alejandro Esquivel (UNAM), John Everett (Wisconsin), Gilberto C. Gomez (UNAM), Matt Haffner (Wisconsin), George Heald (SRON), Rémy Indebetouw (Virginia), Henry Kobulnicky (Wyoming), Grzegorz Kowal (Wisconsin), Charlie Lada (Harvard-CfA), Jay Lockman (NRAO), Steve Majewski (Virginia), John Mathis (Wisconsin), Dan McCammon (Wisconsin), Emily Mercer (Michigan), Rich Rand (New Mexico), Neill Reid (StScI), Ron Reynolds (Wisconsin), Evan D. Skillman (Minnesota), Steve Thorsett (UCSC), Bart P. Wakker (Wisconsin), Barb Whitney (SSI), Mike Wolff (SSI), Mark Wolfire (Maryland), Kenneth Wood (St Andrews), Ellen Zweibel (Wisconsin)

Graduate and Postdoctoral Advisors

Graduate advisor: P. R. Shapiro, University of Texas at Austin
Post-doctoral advisors: D. P. Cox, University of Wisconsin-Madison
E.D. Skillman, University of Minnesota

BIOGRAPHICAL SKETCH OF THOMAS M. DAME, NOVEMBER 2011

Professional Preparation

Boston University, Astronomy and Physics, B.A. (Magna cum Laude), 1976

Columbia University, Astronomy, M.A., 1978

Columbia University, Astronomy, M. Phil., 1979

Columbia University, Astronomy, PhD, 1983

NASA Goddard Institute for Space Studies, NRC Resident Research Associate, Radio Astronomy, 1983-84

Appointments

1986 –	Radio Astronomer, Smithsonian Astrophysical Observatory
1988 –	Lecturer on Astronomy, Harvard University
1988	Teaching Fellow, Core Program, Harvard University
1985–86	Research Associate, Columbia Univ., Dept. of Astronomy

Relevant Publications

"Trigonometric Parallaxes of Massive Star-Forming Regions. IX. The Outer Arm in the First Quadrant," Sanna, A., Reid, M. J., Dame, T. M., Menten, K. M., Brunthaler, A., Moscadelli, L., Zheng, X. W., and Xu, Y. 2011, Astrophysical Journal, in press.

"A Molecular Spiral Arm in the Far Outer Galaxy," Dame, T. M., and Thaddeus, P. 2011, Astrophysical Journal, 734, L24.

"Planck Early Results: Properties of the interstellar medium in the Galactic plane,", Abergel, A. et al. 2011, Astronomy & Astrophysics, in press.

"Trigonometric Parallaxes of Massive Star-Forming Regions. VII. G9.62+0.20 and the Expanding 3 Kpc Arm," Sanna, A., Reid, M. J., Moscadelli, L., Dame, T. M., Menten, K. M., Brunthaler, A., Zheng, X. W., and Xu, Y. 2009, Astrophysical Journal, 706, 464.

"A New Spiral Arm of the Galaxy: The Far 3-Kpc Arm," Dame, T. M., and Thaddeus, P. 2008, Astrophysical Journal, 683, L143.

"On the Distance and Molecular Environment of Westerlund 2 and HESS J1023–575," Dame, T. M. 2007, Astrophysical Journal, 665, L163.

"A Comparative Analysis of Molecular Clouds in M31, M33 and the Milky Way," Sheth, K., Vogel, S. N., Wilson, C. D., and Dame, T. M. 2008, Astrophysical Journal, 675, 330.

"High-Latitude Molecular Clouds as g-Ray Sources for GLAST," Torres, D. F., Dame, T. M., and Digel, S. W. 2005, Astrophysical Journal, 621, L29.

"Supernova remnants and g-ray sources," Torres, Diego F., Romero, Gustavo E., Dame, Thomas M., Combi, Jorge A., and Butt, Yousaf M. 2003, Physics Reports, 382, 303.

"The Milky Way in Molecular Clouds: A Complete CO Survey," Dame, T. M., Hartmann, D., and Thaddeus, P. 2001, Astrophysical Journal, 547, 792.

Synergistic Activities

Dame is responsible for the operation of CfA 1.2 m telescope, which has for over two decades been an exceptionally good pedagogical tool. A total of 24 PhD dissertations have so far been written based on observations or instrumental work with this telescope or its twin in Chile. The telescope is largely operated by a team of 3-4 undergraduates from Harvard and surrounding institutions, providing them with a fine opportunity to participate in scientific research with a state-of-the-art instrument. The telescope has also for many years been an integral part of at least two Astronomy courses at Harvard each year. As the only operating research telescope at the CfA, it is a standard stop for virtually every public tour of the observatory, including those for monthly observatory nights and visiting school groups.

Collaborators over Past 48 Months

Andreas Brunthaler Max-Planck-Institut fur Radioastronomie, Germany

M. C. Johnson, Haystack Observatory

T. Le Bertre, Observatorie de Paris, France

Y. Libert, IRAM, France

Lynn Matthews, Haystack Observatory

Karl Menten Max-Planck-Institut fur Radioastronomie, Germany

George Moellenbrock NRAO

Luca Moscadelli Arcetri Observatory, Italy

Alberto Sanna, MPIfR, Germany

Patrick Thaddeus, Harvard-Smithsonian CfA

Yuan-Wei Wu Nanjing University, China

Ye Xu Purple Mountain Observatory, China

Bo Zhang Nanjing University, China

Xing-Wu Zheng Nanjing University, China

PhD and postdoctoral Advisor

Prof. Patrick Thaddeus, Harvard-Smithsonian Center for Astrophysics

Postgraduate-Scholar Sponsor

Tulun Ergin, (2008-2010), now at U. Turkey

Mark Jonathan Reid

Professional Preparation:

University of Calif., San Diego	Physics	B.A. 1971
California Institute of Technology	Planetary Sci. and Ast.	Ph.D. 1975
Harvard-Smithsonian CfA	Postdoc: Radio Astronomy	1975 – 1977

Awards:

2008	Beatrice M. Tinsley Prize, American Astronomical Society
1999	Humboldt Senior Award

Appointments & Awards:

1988–	Senior Radio Astronomer, Smithsonian Astrophysical Observatory
1992-1997	Assoc. Director, Radio & Geoastronomy Division, Harvard-Smithsonian CfA.
1979–1988	Radio Astronomer, Smithsonian Astrophysical Observatory
1979	Associate Scientist, National Radio Astronomy Observatory
1977–1978	Assistant Scientist, National Radio Astronomy Observatory

Related Publications:

Reid, M, J. et al. "Trigonometric Parallaxes of Massive Star-Forming Regions. VI. Galactic Structure, Fundamental Parameters, and Noncircular Motions" 2009, Ap. J. 700, 137

Reid, M. J., Menten, K. M., Zheng, X. W., Brunthaler, A. & Xu, Y. "A Trigonometric Parallax of Sgr B2" 2009, Ap. J., 705, 1548

Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W., Moscadelli, L. & Xu, Y. "Trigonometric Parallaxes of Massive Star-Forming Regions. I. S 252 & G232.6+1.0" 2009, Ap. J., 693, 397

Reid, M. J. "Is There a Supermassive Black Hole at the Center of the Milky Way?" 2009, International J. of Modern Physics D, 18, 889

Reid, M. J. & Brunthaler, A. "The Proper Motion of Sagittarius A*. II. The Mass of Sagittarius A*", 2004, Ap. J., 616, 872

Reid, M. J. "The Distance to the Galactic Center" 1993, Annual Reviews of Astron. & Astropy. 31, 345

Synergistic Activities:

Reid wrote the majority of software used for spectral line VLBI data reduction and subsequently incorporated in the NRAO AIPS package. Reid developed new methods to calibrate radio interferometric data, now standard in the field, including novel approaches to astrometry and to the use of spectral line data to cross-calibrate continuum data.

Reid's Graduate & Postdoctoral Advisors

Duane Muhleman	Ph.D. advisor; California Institute of Technology
James Moran	Postdoc advisor: Harvard-Smithsonian CfA

Thesis Advisor & Postgraduate-Scholar Sponsor for

Larry Molnar	Graduate Student; now at Calvin College
Vincent Fish	Graduate Student; now at Haystack Observatory
Mayumi Sato	Graduate Student; now at MPIfR, Germany

Alberto Sanna	Graduate Student; now at MPIfR, Germany
Katherina Immer	Graduate Student: Univ. Bonn, Germany

Collaborators (not listed above) & Affiliations:

Alice Argon	Harvard-Smithsonian CfA
Anna Bartkiewicz	Nicolaus Copernicus University, Poland
James Braatz	NRAO
Avery Broderick	Perimeter/Waterloo, Canada
Andreas Brunthaler	Max-Planck-Institut für Radioastronomie, Germany
Chris Carilli	NRAO
Yoon Choi	Max-Planck-Institut für Radioastronomie, Germany
James Condon	NRAO
Thomas Dame	Harvard-Smithsonian CfA
Heino Falcke	Radboud Universiteit Nijmegen, Netherlands
Jan Forbrich	Harvard-Smithsonian CfA
Reinhard Genzel	Max-Planck-Institut für extraterrestriche Physik
Stefan Gillessen	Max-Planck-Institut für extraterrestriche Physik
Jenny Greene	Princeton University
Lincoln Greenhill	Harvard-Smithsonian CfA
Harm Habing	Leiden University, Netherlands
Kazuya Hachisuka	NAOJ, Japan
Christian Henkel	Max-Planck-Institut für Radioastronomie, Germany
Tomoya Hirota	NAOJ, Japan
Mareki Honma	NAOJ, Japan
Liz Humphreys	ESO, Garching, Germany
Viollette Impellizzeri	NRAO
Cheng-Yu Kuo	ASIAA, Taiwan
Huib van Langevelde	JIVE, Netherlands
Fred Lo	NRAO
Abraham Loeb	Harvard University
Lynn Matthews	Haystack Observatory
Karl Menten	Max-Planck-Institut für Radioastronomie, Germany
George Moellenbrock	NRAO
Luca Moscadelli	Arcetri Observatory, Italy
Ramesh Narayan	Harvard University
Nimesh Patel	Harvard-Smithsonian CfA
Kazi Rygl	INAF, Rome, Italy
Anders Winnberg	Onsala Space Observatory, Sweden
Yuan-Wei Wu	Nanjing University, China
Ye Xu	Purple Mountain Observatory, China
Kenneth Young	Harvard-Smithsonian CfA
Farhad Yusef-Zadeh	Northwestern University
Bo Zhang	Nanjing University, China
Luis Zapata	Max-Planck-Institut für Radioastronomie
Xing-Wu Zheng	Nanjing University, China

Biographical Sketch for Erik William Rosolowsky

PROFESSIONAL PREPARATION

Swarthmore College – B.A. in Astrophysics with Highest Honors, June 1998

University of California at Berkeley – M.A. in Astrophysics, May 2001

University of California at Berkeley – Ph. D. in Astrophysics, May 2005

Harvard-Smithsonian Center for Astrophysics – NSF Astronomy & Astrophysics Postdoctoral Fellow – 2005-2007

PROFESSIONAL APPOINTMENTS

2008 – Present	Assistant Professor, University of British Columbia, Okanagan Campus
2005 – 2007	NSF Astronomy & Astrophysics Postdoctoral Fellow
2003 – 2005	NASA Fellow in the Graduate Student Research Program
1999 – 2002	National Science Foundation Graduate Research Fellow

RELATED PUBLICATIONS

⋆ = Most relevant to current proposal

⋆ "The Bolocam Galactic Plane Survey. VII. Characterizing the Properties of Massive Star-Forming Regions" Dunham, M. K., Rosolowsky, E., Evans, N J., II, Cyganowski, C. J., & Urquhart, J. S. 2011, *The Astrophysical Journal*, **741**, 110

⋆ "The Bolocam Galactic Plane Survey. II. Catalog of the Image Data" Rosolowsky,E., Dunham, M., Ginsburg, A., Bradley, E., Aguirre, J., Bally, J., Battersby, C., Cyganowski, C., Dowell, D., Drosback, M., Evans, N., Harvey, P., Stringfellow, G., Walawender, J., Williams, J., 2010, *Astrophysical Journal Supplements*, **188**, 123-138

⋆ "The Perils of Clumpfind: The Mass Spectrum of Substructures in Molecular Clouds" Pineda, J., Rosolowsky, E.,& Goodman, A., *Astrophysical Journal Letters*, 2009, **699**, 134

⋆ "Structural Analysis of Molecular Clouds: Dendrograms" **Rosolowsky, E.**, Pineda, J., Kauffmann, J., Goodman, A., 2008 *Astrophysical Journal*, **679**, 1338.

"An Ammonia Spectral Atlas of Dense Cores in Perseus" Rosolowsky, E., Pineda, J., Foster, J., Kauffmann, J., Borkin, M., Caselli, P., Myers, P. & Goodman, A., 2008 *Astrophysical Journal Supplements*, **175**, 509.

"Giant Molecular Clouds in M31. I. Molecular Cloud Properties" Rosolowsky, E., 2007 *Astrophysical Journal*, **654**, 240.

"The Role of Pressure in Giant Molecular Cloud Formation II: The H_2-Pressure Relation" Blitz, L. & Rosolowsky, E., 2006 *Astrophysical Journal*, **650**, 933

⋆ "Bias-free Measurement of Giant Molecular Cloud Properties" Rosolowsky, E. & Leroy, A., 2006, *Publications of the Astronomical Society of the Pacific*, **118**, 590-610.

"Giant Molecular Clouds in M64" Rosolowsky, E. & Blitz, L., 2005, *The Astrophysical Journal*, **623**, 826.

SYNERGISTIC ACTIVITIES

Member of the Canadian Overseas Telescopes Time Allocation Committee for NRC/HIA (2009 - Present), Chair of Galactic Panel (2010 - Present)

Instructor in Summer Institute for Education, helping secondary school teachers update their curriculum to new astronomy standards.

Co-organizer of the NSF Astronomy & Astrophysics Postdoctoral Fellows Symposium (Jan. 2007 in Seattle, WA)

Co-instructor for "Scientists Teaching Science" course at Harvard University; ongoing activities at professional development for astronomers teaching science (2005-2006)

COLLABORATORS

James Aguirre (U. Pennsylvania) • Hector Arce (Yale) • John Bally (U. Colorado) • Cara Battersby (U. Colorado) • Frank Bigiel (U. Heilderberg, Germany) • Leo Blitz (Berkeley) • Stephane Blondin (Harvard) • Alberto Bolatto (U. Maryland) • Michelle Borkin (Harvard) • Eric Todd Bradley (U. Central Florida) • Elias Brinks (Hertfordshire, UK) • Fabio Bresolin (Hawaii) • Chrisof Buchenbender (IRAM, Spain) • R. Paul Butler (Carnegie Obs.) • Paola Caselli (U. Leeds) • Richard Chamberlain (California Insitute of Technology) • David Collins (UC San Diego) • Michael Cooper (U. Arizona) • Edvige Corbelli (INAF Arcetri, Italy) • Claudia Cyganoswski (Harvard) • W.J. DeBlok (U. Cape Town, South Africa) • Meredith Drosback (U. Colorado) • Gaelle Dumas (MPIA, Germany) • Miranda Dunahm (Yale) • Timothy Ellsworth-Bowers (U. Colorado) • Charles Engelbracht (U. Arizona) • Melissa Enoch (Berkeley) • Barbara Ercolano (Harvard) • Neal J. Evans II (U. Texas) • Alexi Filippenko (Berkeley) • Jonathan Foster (Boston U.) • Ryan Foley (Harvard) • Yasuo Fukui (Nagoya University, Japan) • Mohan Ganeshalingam (Berkeley) • Yu Gao (Purple Mountain Observatory, China) • Avishay Gal-Yam (Weizmann Insitute of Science) • Mark Gieles (European Southern Observatory) • Adam Ginsburg (U. Colorado) • Jason Glenn (U. Colorado) • Alyssa Goodman (Harvard) • Karl Gordon (STSci) • Pierre Gratier (U. Bordeaux, France) • Paul Harvey (U. Texas) • Gregory Herczeg (MPE, Germany) • Rodrigo Herrera-Camus (U. Maryland) • Katherine Jameson (U. Maryland) • Katherine Johnston (NRAO Soccoro) • Douglas Johnstone (HIA, Canada) • Vicky Kaspi (McGill, Canada) • Akiko Kawamura (Nagoya University, Japan) • Jens Kauffmann (Harvard-Smithsonian Center for Astrophysics) • Robert Kirshner (Harvard) • Helen Kirk (Harvard) • Carsten Kramer (IRAM, Spain) • Glenn Laurent (U. Colorado) • Wedong Li (Berkeley) • Adam Leroy (NRAO) • Hua-Bai Li (MPIfR, Germany) • L. A. Lopez (UC Santa Cruz) • Paolo Mazzali (MPIA, Germany) • Norikazu Mizuno (Nagoya University, Japan) • Phil Myers (Harvard) • Michael Norman (UCSD) • Peter Nugent (LBNL) • Paolo Padoan (UCSD) • Jaime Pineda (Manchester, UK) • Richard Plambeck (Berkeley) • Jurgen Ott (NRAO, Soccoro) • Gnat Orly (Caltech) • Ferdinando Patat (ESO, Germany) • Robert Quimby (Caltech) • Nurur Rahman (U. Maryland) • Karin Sandstrom (MPIA, Germany) • Anniela Sargent (California Institute of Technology) • Daniel Sauer (Stockholm U., Sweden) • David Schenk (Arizona) • Wayne Schlingman (Arizona) • Scott Schnee (California Institute of Technology) • Andreas Schruba (U. Heidelberg, Germany) • Karl Schuster (IRAM, France) • Rahul Shetty (Harvard-Smithsonian Center for Astrophysics) • Yancy Shirley (Arizona) • Jeffrey Silverman (Berkeley) • Josh Simon (Carnegie Observatories) • Ingrid Stairs (U. British Columbia, Canada) • G. Stasinska (CNRS, France) • Guy Stringfellow (U. Colorado) • A. Russ Taylor (Calgary, Canada) • Mario Tafalla (IGN, Spain) • Antonio Usero (OAS, Spain) • John Vaillancourt (California Institute of Technology) • J. Vilchez (CSIC, Spain) • Stuart Vogel (Maryland) • Steven Vogt (UCO/Lick Observatory) • Josh Walawender (U. Hawaii) • Fabian Walter (MPIA, Germany) • Andrew West (Boston U.) • Axel Weiss (MPIfR, Germany) • Craig Wheeler (Texas) • Jonathan Williams (U. Hawaii) • Helmut Wiesemeyer (MPIfR, Germany) • Tony Wong (U. Illinois) • Rui Xue (U. Illinois)

GRADUATE AND POSTDOCTORAL ADVISERS

Graduate: Leo Blitz (U. of California, Berkeley)

Postdoctoral: Steve Willner (Smithsonian Astrophysical Observatory)

GRADUATE AND POSTDOCTORAL ADVISEES

Robert Stutz (High School Teacher in Kuonming, China)

BIOGRAPHICAL SKETCH FOR JOAO ALVES, NOVEMBER, 2011

Professional Preparation

University of Lisbon, B.A. Physics, 1992

University of Lisbon, M.A. Astrophysics, 1995

Astrophysics Harvard-Smithsonian Center for Astrophysics & University of Lisbon, Ph.D, Magna Cum Laude ,1999

Appointments

2010-now — Deputy Director, Institute of Astronomy, University of Vienna

2010-now — Full Professor of Stellar Astrophysics, University of Vienna

2006-2010 — Director of the Calar Alto Observatory

2006-now — Adjunct-Professor at the University of Oporto

2003-2006 — Head of ESO-VISAS

2001-2003 — ESO staff astronomer

1998-2001 — ESO Post-Doctoral Fellow

Recent Relevant Publications

"2MASS wide field extinction maps. IV. The Orion, Monoceros R2, Rosette, and Canis Major star forming regions", Lombardi, M., Alves, J., Lada, C. 2011, A&A, 535, 16

"Mass reservoirs surrounding massive infrared dark clouds: A view by near-infrared dust extinction", Kainulainen, J., Alves, J., Beuther, H., Henning, T., Schuller, F. A&A in press

"Deep Near-infrared Survey of the Pipe Nebula. II. Data, Methods, and Dust Extinction Maps", Román-Zúñiga, C., Alves, J., Lada, C., Lombardi, M. 2010, ApJ, 725, 2232

"Star Formation in the Taurus Filament L 1495: From Dense Cores to Stars", Schmalzl, M., Kainulainen, J., Quanz, S., Alves, J., Goodman, A., Henning, T., Launhardt, R., Pineda, J., Román-Zúñiga, C. 2010 ApJ, 725, 1327

"On the Star Formation Rates in Molecular Clouds", Lada, C., Lombardi, M., Alves, J. 2010, ApJ, 724,687

"2MASS wide field extinction maps. III. The Taurus, Perseus, and California cloud complexes", Lombardi, M., Lada, C., Alves, J. 2010, A&A, 512, 67

"A Spitzer Census of Star Formation Activity in the Pipe Nebula", Forbrich, J., Lada, C., Muench, A., Alves, J., Lombardi, M. 2009, ApJ, 704, 292

Synergistic Activities

Gaia Archive Preparation group (2011-2012)

ERC starting grant evaluation committee (2008-2011)

Telescope time allocation committee, Calar Alto (2006-2010)

Collaborators over Past 48 Months

Hector Arce (Yale) • Joana Ascenso (ESO) • John Bally (U. Colorado) • Cara Battersby (U. Colorado) • Yuri Belesky (ESO) • Edwin Bergin (Michigan) • Leo Blitz (Berkeley) • Herve Bouy (ESA-Spain) • Andi Burkert (USM, Munich) • Mark Casali (ESO) • Paola Caselli (U.Leeds) • Barbara Ercolano (Munich) • Jonathan Foster (Boston U.) • Alyssa Goodman (Harvard) • Alvaro Hacar (OAN, Spain) • Jouni Kainulainen (MPIA, Heildelberg) • Jens Kauffmann (Harvard-Smithsonian Center for Astrophysics) • Carsten Kramer (IRAM, Spain) • Charles Lada (CfA) • Elizabeth Lada (U. Florida) • Marco Lombardi (U. Milan, Italy) • André Moitinho (SIM, Portugal) • Jaime Pineda (Manchester, UK) • Jill Rathborne (CSIRO, Australia) • Carlos Román-Zúñiga (Ensenada, Mexico) • Sebastian Sanchez (CAHA, Spain) • Mario Tafalla (OAN, Spain) • Paula Teixeira (U. Vienna, Austria)

PhD and postdoctoral Advisers

Graduate: Charles Lada (CfA)

Postdoctoral: ESO Fellowship (self-advised)

PhD and postdoctoral Advisees

Postdocs

Carlos Roman Zuniga ((Ensenada, Mexico)

Paula Teixeira (U. Vienna, Austria)

PhD students

Joana Ascenso (ESO, Germany)

Jouni Kainulainen (MPIA, Heildelberg)

Yuri Belestsky (ESO, Germany)

Silvia Vicente (*CIEMAT, Madrid, Spain)*

Master students

Sofia Fernandes (Universidade de Lisboa, Portugal)

BIOGRAPHICAL SKETCH FOR Thomas P. Robitaille, NOVEMBER 2011

Professional Preparation

University of St Andrews (UK), MPhys in Astrophysics 2005
University of St Andrews (UK), PhD in Astrophysics 2008
Harvard-Smithsonian Center for Astrophysics, *Spitzer* Fellowship, 2008-11

Appointments

2011– *Max Planck Research Group Leader*
Max Planck Institute for Astronomy, Heidelberg, Germany

2008–2011 *Spitzer Postdoctoral Fellow*, Harvard-Smithsonian Center for Astrophysics

Recent Relevant Publications *(*=most closely related to this proposal)*

An, D., S. V. Ramírez, K. Sellgren, R. G. Arendt, A. C. Adwin Boogert, T. P. Robitaille, M. Schultheis, A. S. Cotera, H. A. Smith, & S. R. Stolovy, 2011, *Massive Young Stellar Objects in the Galactic Center. I. Spectroscopic Identification from Spitzer Infrared Spectrograph Observations*, ApJ, 736, p 133

*Dunham, M. K., T. P. Robitaille, N. J. Evans II, W. M. Schlingman, C. J. Cyganowski, & J. Urquhart, 2011, *A Mid-infrared Census of Star Formation Activity in Bolocam Galactic Plane Survey Sources*, ApJ, 731, p 90

Elia, D., et al., 2010, *A Herschel study of YSO evolutionary stages and formation timelines in two fields of the Hi-GAL survey*, A&A, 518, L97

*Forbrich, J., A. Tappe, T. Robitaille, A. A. Muench, P. S. Teixeira, E. A. Lada, A. Stolte, & C. J. Lada, 2010, *Disentangling Protostellar Evolutionary Stages in Clustered Environments Using Spitzer-IRS Spectra and Comprehensive Spectral Energy Distribution Modeling*, ApJ, 716, pp 1453-1477

Mottram, J. C., M. G. Hoare, J. S. Urquhart, S. L. Lumsden, R. D. Oudmaijer, T. P. Robitaille, T. J. T. Moore, B. Davies, & J. Stead, 2011, *The Red MSX Source survey: the bolometric fluxes and luminosity distributions of young massive stars*, A&A, 525, A149

*Robitaille, T. P. & B. A. Whitney, 2010, *The Present-Day Star Formation Rate of the Milky Way Determined from Spitzer-Detected Young Stellar Objects*, ApJ, 710, pp L11-L15

*Robitaille, T. P., et al., 2008, *Intrinsically Red Sources Observed by Spitzer in the Galactic Midplane*, AJ, 136, pp 2413-2440

*Robitaille, T. P., B. A. Whitney, R. Indebetouw, & K. Wood, 2007, *Interpreting Spectral Energy Distributions from Young Stellar Objects. II. Fitting Observed SEDs Using a Large Grid of Precomputed Models*, ApJS, 169, pp 328-352

Robitaille, T. P., B. A. Whitney, R. Indebetouw, K. Wood, & P. Denzmore, 2006, *Interpreting Spectral Energy Distributions from Young Stellar Objects*. I. A Grid of 200,000 YSO Model SEDs, ApJS, 167, pp 256-285

Smith, N., M. S. Povich, B. A. Whitney, E. Churchwell, B. L. Babler, M. R. Meade, J. Bally, R. D. Gehrz, T. P. Robitaille, & K. G. Stassun, 2010, *Spitzer Space Telescope observations of the Carina nebula: the steady march of feedback-driven star formation*, MNRAS, 406, pp 952-974

Synergistic Activities

Development of Python-based Astronomy tools: TR has led the development a number of Astronomy tools publicly released to the community under open-source licenses. Two notable examples are APLpy (http://aplpy.github.com/), a package to visualize and produce publication-quality figures of astronomical image data, and ATpy (http://atpy.github.com/), a package to seamlessly handle the input, manipulation, and output of tables of astronomical tables of data. TR is also one of the three coordinators of a community-wide effort to develop a 'core' Python package for Astronomy (http://www.astropy.org). This project involves over 80 astronomers and software developers across many US and international institutions.

Collaborators and Other Affiliations

Collaborators
Babler, B., *U. Wisconsin*
Beaumont, C., *CfA*
Benjamin, R., *U. Wisconsin*
Beuther, H., *MPIA, Germany*
Bonnell, I., *St Andrews, UK*
Boyer, M., *STScI*
Bressert, E., *ESO, Germany*
Carlson, L., *Johns Hopkins*
Chakrabarti, S., *Berkeley*
Churchwell, E., *U. Wisconsin*
Cohen, M., *Berkeley*
Cyganowski, C., *CfA*
Dunham, M., *Yale*
Elia, D., *INAF, Rome, Italy*
Ercolano, B., *LMU, Germany*
Evans, N., *U. Texas*
Forbrich, J., *CfA*
Goodman, A., *CfA*
Gordon, K., *STScI*
Hora, J., *CfA*
Indebetouw, R., *U. Virginia*
Johnston, K., *MPIA, Germany*
Lada, C., *CfA*
Meade, M., *U. Wisconsin*
Meixner, M., *STScI*
Molinari, S., *INAF, Rome, Italy*
Mottram, J., *Leiden, Netherlands*
Offner, S., *CfA*
Pineda, J., *Manchester, UK*
Povich, M., *Penn State U.*
Sewiło, M., *STScI*
Simon, J., *Carnegie*
Smith, N., *Berkeley*
Srinivasan, S., *IAP*
Urquhart, J., *Leeds, UK*
Watson, C., *U. Manchester*
Whitney, B., *U. Wisconsin*
Wood, K., *St Andrews, UK*
van Loon, J., *Keele, UK*

Graduate Advisors
Bonnell I., *St Andrews*
Wood K., *St Andrews*

FACILITIES, EQUIPMENT, AND OTHER RESOURCES: HCO

Computer

The Harvard College Observatory (HCO), which is a member of the Harvard-Smithsonian Center for Astrophysics (CfA), maintains an extensive network of UNIX, Linux, and MacOSX computers used for data storage and processing.

Additionally, the PI has access to the Odyssey system, which is is a high-performance computing cluster managed by the FAS Sciences Division's Research Computing Group. Odyssey is a heterogeneous ~1300 node Linux cluster which has access to approximately 3000TB of storage, and it is available to researchers in the Faculty of Arts and Sciences and their collaborators.

Office

Ample office space is provided to all research scientists. Offices all contain phone and an Internet connection.

Other

The CfA has a library containing books and journals on astronomy and astrophysics, with access to all of Harvard University's libraries including online subscriptions to relevant journals.

The 1.2-meter Millimeter-Wave Telescope at the CfA has been studying the distribution and properties of dense, star-forming molecular clouds in our Galaxy and its nearest neighbors for over three decades.   We will have access to this telescope for any needed followup studies in this work.

The Viz-e-Lab at the Harvard-Smithsonian Center for Astrophysics was founded in 2011, as a place where researchers develop and test new visualization and e-Science approaches in research and education. The lab has several workstations, a 55-inch high resolution monitor, and state-of-the art haptic input devices, such as a Kinect.

DATA MANAGEMENT PLAN

1.Introduction

Our group is in a strong position when it comes to offering a Data Management Plan. In work separate from that proposed here, the PI leads an effort known as *Seamless Astronomy*. A key part of that effort is the establishment of the *Astronomy Dataverse*, which is a system based on the highly-successful and robust *Dataverse Network* run out of the Harvard Institute for Quantitative Social Science. The up-and-running Astronomy Dataverse (theastrodata.org) is expressly designed to let researchers connect data to literature and other resources through the use of persistent identifiers ("handles"; see http://thedata.org/book/standard-0). The COMPLETE data, as well as all of the surveys collected to produce the joined surveys in Dame et al. 20001 have already been deployed in the Dataverse, at theastrodata.org.

2.Data Types, Standards & Metadata

Within the Dataverse, one can create "collections," which are groupings of smaller data sets called "studies." In the Astronomy Dataverse, studies often contain several FITS files. Each FITS file contains metadata in its header, and additional metadata is added by the user at the time of deposition of data in the Dataverse. Information (data or metadata) can be added to the Dataverse at any point in the research process, and version control is built-in. We plan to use the Dataverse to store every significant intermediate result discussed in the Year-by-Year research plan above, as those results are obtained. When results are published, we can and will link particular referred-to data sets within papers, using in-text references to persistent (hdl) identifiers the Dataverse assigns to each study as it is deposited.

Some of this project's results will take the form of data cubes (e.g. in FITS format), but others will be simple ASCII tables and catalogs. Since essentially any data format can be stored in the Dataverse, and metadata can be added when information is deposited (and is then searchable), the system is flexible enough to handle all of the information we discuss distributing in the proposal. In addition, we will use, and Dataverse deposit, table formats compatible with the IVOA "VOTable format" wherever possible, so that any VO-compliant software can access our results.

3.Data Access and Preservation

The Dataverse has built-in provisions to move data from a private work area to the public domain. As stated in our proposal, it is our intention to make data public as soon as possible, and certainly by the time any related publication appears. We will request attribution (using literature citations and/or Dataverse handles), but not permission, in the re-use of our data and results. When our results cite and/or use data beyond our control (e.g. Herschel data) the subsets of data used will be as clearly described as possible within the Dataverse, and (cross-correlated) catalogs will be deposited at the very least.

In order to assure reproducibility of our results, we will (continue to) make our code as well as our data sets public. At http://projects.iq.harvard.edu/seamlessastronomy/software/dendrograms, we already maintain a site that distributes dendrogram code in IDL, C++ and Python, as well as Java and IDL visualization tools.

The Dataverse at Harvard is hosted on servers that the University has agreed to maintain and backup longterm.

We will also ensure that our data and visualizations are accessible to a broad audience, by making sure as results are distributed in VO-compliant formats. The WorldWide Telescope (WWT) software described in our "Broader Impact" statement, as well as a one or two other data viewers, currently make use of the VOTable protocol and can handle 3D data visualization. So, in addition to the custom visualization tools we will develop, and distribute through http://projects.iq.harvard.edu/seamlessastronomy/software/dendrograms, we can and will offer access to our results through more general VO-compliant interfaces like WWT.

Our colleagues at Microsoft Research have already built Robert Hurt's artist's rendition of the Milky Way model Bob Benjamin was so instrumental in creating into the 3D viewer in WWT (presently downloadable at worldwidetelescope.org). Those same MSR/WWT colleagues look eagerly forward to incorporating and distributing new views of the distribution of star-forming regions in the Milky Way, as do we.

4. Harvard Policies

Harvard has a university-wide policy addressing the required protections for intellectual property arising from research. These policies can be found at http://otd.harvard.edu/resources/policies/

Data will not be encumbered with intellectual property rights (including copyright, database rights, license restrictions, trade secret, patent or trademark) by any party (including the investigators, investigators' institutions, and data providers.); nor is it subject to any additional legal requirements.

Harvard University's policies on intellectual property may be found at http://vpr.harvard.edu/content/intellectual-property.

universität wien

Fakultät für Geowissenschaften, Geographie und Astronomie

Institut für Astronomie
Univ.-Prof. Dr. João Alves
Türkenschanzstraße 17 (Sternwarte)
A- 1180 Wien

T+43-1-4277-538 10
F+43-1-4277-9 538
joao.alves@univie.ac.at
http://astro.univie.ac.at

Alyssa Goodman NSF proposal

Wien, am 31 Oktober 2011

To whom it may concern

I acknowledge that I am identified by name as as Senior Personnel to the investigation, entitled, *The Hierarchical Structure of Star-Forming Regions in the Milky Way,* that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

With best regards,

João Alves

João Alves

UNIVERSITY OF WISCONSIN
WHITEWATER

Nov 1, 2011

I acknowledge that I am identified by name as a CoI to the investigation, entitled *The Hierarchical Structure of Star-Forming Regions in the Milky Way* that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

Sincerely,

Robert A. Benjamin
Associate Professor of Physics
U. of Wisconsin-Whitewater

Harvard-Smithsonian Center for Astrophysics

60 Garden Street, Cambridge, MA 02138

October 26, 2011

To Whom it May Concern:

I acknowledge that I am identified by name as a CoI to the investigation, entitled "The Hierarchical Structure of Star-Forming Regions in the Milky Way" that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

Sincerely,

Thomas M. Dame

Thomas M. Dame

Stella Offner
Institute for Theory & Computation, MS-51, P-247
Harvard-Smithsonian Center for Astrophysics
60 Garden St.
Cambridge, MA 02138

Prof. Alyssa Goodman
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138

Dear Prof. Goodman,

I acknowledge that I am identified by name as a Collaborator to the investigation, entitled "The Hierarchical Structure of Star-Forming Regions in the Milky Way" that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation

Sincerely,

Stella Offner
NSF Postdoctoral Fellow

From: Mark Reid <reid@cfa.harvard.edu>
Subject: **Reid's letter**
Date: October 31, 2011 1:56:08 PM EDT
To: sblock@cfa.harvard.edu

Dear Prof. Goodman:

I acknowledge that I am identified by name as a CoI to the investigation, entitled "The Hierarchical Structure of Star-Forming Regions in the Milky Way" that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

Sincerely,

Mark Reid

Mark J. Reid Phone: 617-495-7470
Harvard-Smithsonian CfA Fax : 617-495-7345
60 Garden Street Email: reid@cfa.harvard.edu
Cambridge, MA 02138, USA Web : www.cfa.harvard.edu/~reid

Thomas Robitaille
Max Planck Institute for Astronomy
Königstuhl 17
D-69117 Heidelberg
Germany

Prof. Alyssa Goodman
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138

Dear Prof. Goodman,

I acknowledge that I am identified by name as Senior Personnel to the investigation, entitled "The Hierarchical Structure of Star-Forming Regions in the Milky Way" that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation

Sincerely,

Thomas Robitaille
Max Planck Research Group Leader

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

The University of British Columbia
Dr. Erik Rosolowsky
I.K. Barber School of Arts and Sciences -- Unit 5
Okanagan Campus
3333 University Way
Kelowna, BC V1V 1V7

Phone 250.575.6465
Fax 250.807.8004
erik.rosolowsky@ubc.ca
people.ok.ubc.ca/erosolo/

Dear Prof. Goodman:

I acknowledge that I am identified by name as a CoI to the investigation, entitled "The Hierarchical Structure of Star-Forming Regions in the Milky Way" that is submitted by Alyssa Goodman to the Research Announcement NSF 05-608, 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. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

Sincerely,

Erik Rosolowsky

Max-Planck-Institut für Astronomie

Prof. Dr. Thomas Henning
Direktor

Max-Planck-Institut für Astronomie · Königstuhl 17 · 69117 Heidelberg

November 7th, 2011 TH/jb

Prof. Alyssa Goodman
Harvard-Smithsonian Center for Astrophysics
60 Garden Street, MS 42
Cambridge, MA 02421

Dear Alyssa,

We at the MPIA are excited to host your team's "Year 3" meeting, and to hold a workshop on "The Structure of Milky Way Star-Forming Regions" at the new *Haus der Astronomie* in Heidelberg in conjunction with the team meeting. As you know, our new facility is shaped like the Milky Way, so I cannot think of a more appropriate venue for these activities. We also plan to focus on high-end visualization projects and outreach at the HdA, so the visualization challenges associated with your project make our facility, which has a beautiful projection system and a tilted dome auditorium, a perfect match as well.

I know that Dr. Thomas Robitaille of MPIA is named as a collaborator on your proposal, and he and I both look forward to working with you.

Best regards,

Prof. Dr. Thomas Henning
Director

Tel: +49-(0)6221-528-200
E-Mail: henning@mpia.de

Sekretariat: Maria Janssen-Bennynck Tel: +49-(0)6221-528-201
E-Mail: janssen@mpia.de Fax: +49-(0)6221-528-339

MAX-PLANCK-GESELLSCHAFT