How the Interstellar Medium Moves: Testing Simulations

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ABSTRACT

Recently, it has become technically feasible to carry out large (>256^3 pixels) numerical simulations of the interstellar medium and to make very large (>10,000 positions) maps of interstellar gas and dust. However, we do not yet have a deep understanding of how well the simulations model the "real" interstellar medium in detail. This proposal offers to develop new quantitative methods for analyzing both numerical simulations and observed data cubes, and to use these methods, in tandem with existing ones, to bridge the gap in our physical understanding of the relationship between numerical simulations and the ISM. When the project is complete, we will be able to offer the astronomical community an optimal set of physically-motivated statistical diagnostics that best capture the properties of a position-position-velocity map of interstellar material, either simulated or observed. These statistical diagnostics will be critically important in probing the physical properties of the star-forming regions, supernova, remnants, large galactic clouds, and diffuse clouds observed from IRAS, ISO, and HST, and soon from SOFIA and SIRTF.

TABLE OF CONTENTS

Introduction & Background

In 1964, it was considered a great achievement to measure the spectral profile of a single radio-frequency transition emanating from molecular gas in the interstellar medium (e.g. Barrett et al. 1964). Little more than a decade later, receiver sensitivity increased to the point where "mapping" large portions of the molecular ISM using spectral lines became a booming cottage industry. And in the most recent decade, technological improvements have allowed for spatial and spectral resolution which routinely produce spectral-line maps of the ISM whose detailed features *cannot be appreciated by "inspection" or global statistics alone*. Similarly, in the theory domain, modern numerical models of the ISM are producing synthetic spectral-line maps nearly as extensive as those observed. **It is the goal of the study proposed below to develop a suite of quantitative, statistical, tools for understanding the spatial-velocity structure of both the observed and the synthetic spectral-line maps.**

Our ultimate aim is to use new and existing tools to sensitively discriminate among different realizations of theoretical models, so that we can best evaluate which set of physical inputs to a model best matches the observed properties of the ISM. The best-matching model "inputs" in particular types of regions (e.g. cold star-forming clouds, warm gas around clusters, high-latitude unbound clouds, and supernova remnants) will produce *both* a detailed description of the density, velocity, temperature, ionization and magnetic field structures in such regions *and* new insight into the physical origins of those structures.

The **key benefits** offered by the approach proposed below are:

1. *We have already begun developing the new tools proposed.* Specifically, we have developed an algorithm for measuring the "Spectral Correlation Function" [hereafter SCF] in maps, and we have shown that it is effective at quantifying map structure. The SCF is different from other diagnostics in that it uses, and preserves, spatial and spectral information simultaneously (see p. 9).

2. *We have access*, through our observational efforts and collaborations, *to a large number of observed data cubes*, all of which we have permission to analyze.

3. We have already discussed using our tools on the *synthetic data cubes* currently being produced by several theoretical groups' large existing simulations. In fact, we have already carried out a preliminary comparison of a C^{18}O map of Heiles' Cloud 2 and one of the Ostriker, Gammie & Stone (1996) MHD simulations (see p. 11).

4. We plan to *intercompare several* applicable existing statistical tools, as well as the new ones developed, to find an "optimal" set of spectral-line map descriptors. Many of the existing tools are highly developed (e.g. autocorrelation analyses, wavelet transforms, principal components analysis, clumpfinding algorithms), and a few have already been successfully applied to some of the data and simulations we plan to analyze.

Several of the simulations we plan to analyze have been funded by NASA grants (e.g. Ostriker et al. 1996), and the *creators of those simulations agree* that an effort dedicated to rigorously understanding how simulations relate to each other, input parameters, and real data is definitely needed at this time.

Existing Statistical Analyses of ISM Structure

Over the past fifteen years, as spectral line maps have grown in size, the number of attempts to model these maps has also risen rapidly. Existing analyses of ISM structure can be grouped into three general categories.

1. Analyses which **use spatial information but not velocity (spectral) information** (e.g. wavelets (Gill and Henriksen 1990, Langer et al. 1993); structure trees (Houlahan and Scalo 1990, Houlahan and Scalo 1992); pseudometric analysis (Wiseman and Adams 1994)). Using only spatial information, such as continuum dust emission or integrated spectral-line emission, has the advantage of reducing the amount of information one needs to analyze, but the disadvantage of losing a (potentially critically) important indicator of the physical state of the material under study--namely its velocity distribution. That said though, it is important to appreciate that any numerically-generated map which does not share at least its spatial properties with real maps is automatically, and easily, excluded from consideration as a realistic simulation. Therefore, in the proposed work, spatial-only analyses will be considered a *necessary, but not sufficient,* indicator of agreement between models and data.

2. Analyses which **assume a three-dimensional topology** (e.g. clump-like or fractal) in order to derive statistics from maps (e.g. GAUSSCLUMPS (Stutzki and Güsten 1990); CLUMPFIND (Williams et al. 1994); fractals (Elmegreen and Falgarone 1996)). Clumpfinding algorithms have proven tremendously useful for comparing the so-called "clump IMF" of the gas with the stellar IMF (e.g. Lada et al. 1991a,b; Lada 1992). The automated clumpfinding routine known as "CLUMPFIND" essentially contours a data cube in position-position-velocity space, in order to identify features which are localized in velocity space, as well as on the plane of the sky. Often, such procedures will produce different clump lists than the spatial-only analyses discussed in 1 above, and the lists produced by the routines which include velocity information are more likely to be physically meaningful. Fractal analyses (see Chappell and Scalo 1997, Elmegreen and Falgarone 1996, and references therein) impose a self-similar, rather than clump-like, topology on the ISM. While the fractal and clumpfinding approaches differ drastically in their morphological view of the ISM, they both offer a way to characterize an observed or simulated distribution of mass as a function of scale. In general, we expect that both clumpfinding and fractal analyses[1] provide more stringent tests of data/model agreement than spatial-only analyses.

3. Analyses which **use spectral information along with spatial information as a "scale" indicator** (e.g. autocorrelation and structure functions (Dickman and Kleiner 1985, Kitamura et al. 1993, Kleiner and Dickman 1987, Miesch and Bally 1994, Scalo 1984) ; principal component analysis (Heyer and Schloerb 1997); line width-size relations (Larson 1981, Goodman et al. 1997); centroid velocity probability density functions (Lis et al. 1996)). These methods are often used to derive a power-law index from a data cube. The specific index derived depends on the details of the analysis. For example, line width-size relations of the form (line width) ~ (size)^a, give an index, a, which is relatively easy to compare with similar indices used to describe theoretically understood processes such as incompressible (Kolmogorov) turbulence. Other procedures, such as the calculation of structure and autocorrelation functions, and principal component analysis, also produce statistics which describe the overall velocity structure of a cube as a function of scale. These analyses all share the property of utilizing both spatial and spectral information. However, the fact that spatial information is used as a "scale" indicator, rather than a "position" indicator in almost all the spatial/spectral combination analyses to date, restricts the level of detail these analyses can provide.

The new "Spectral Correlation Function" analysis we describe beginning on page 9 offers a new way to look at ISM structure, in that it utilizes all the available spectral and spatial information simultaneously. We are guessing that the fully-developed SCF will provide *a more detailed description*

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[1] Note that fractal analyses can compute either a *volume* fractal dimension by including information on three dimensions *or* a projected (area) fractal dimension, by including only spatial information. The latter method is essentially another form of "spatial-only" analysis (see 1 above). Elmegreen and Falgarone (1996) claim to find the volume fractal dimension, by analyzing the observed *mass* spectrum in spectral line maps, which ultimately depends on the three dimensional distribution of gas.

of data cube structure than any of the techniques listed above, and thus ultimately provide one of the most stringent tests for models to pass when being compared with data. Nonetheless, our plan is to use several of the other methods described in 1-3 in tandem with the SCF and other new procedures under development, in order to actually test which of these statistical techniques actually offers the most detailed (i.e. hardest to match by accident) description of a data cube.

Existing Numerical Simulations of ISM Structure

Recent advances in computing power have led to a wealth of new simulations of interstellar structure. Eariler calculations (e.g. Field and Saslaw 1965) were not intended to produce models of interstellar structure that would match observations in great detail, but the new ones are. No one, though, has yet produced a simulation that includes *all* of the physical processes creating the "real" ISM.

In order not to exceed the page limit, or--worse yet--try your patience, we have created Table 1, found on page 7, which summarizes the properties of many recently published and in-progress numerical simulations. We have tried to include at least one recent paper from each group currently working on large numerical simulations of the ISM. All of the models have their most basic outline in common: each one assumes a set of initial conditions, inputs a power spectrum of fluctuations, and follows what happens. While Table 1 certainly does not describe the details of each simulation, we offer it as a convenient summary of the physics included and excluded in each calculation. One important point to note is that none of the published simulations includes ambipolar diffusion.

We fully appreciate that the "details" of the inputs to these simulations will eventually become critical to discriminating among them, and we have found that in most cases those details are included in the text of the published paper describing the simulation. In cases where the details are unclear, it is our intention to directly contact the authors.

Table 1: Recent Simulations of the ISM

	2D or 3D?	Radiative Transfer	Self-gravity	Compressible	Heating & Cooling	Large-scale shear	Pressure/Heating due to Star-Form.	Magnetic Fields	Ambipolar Diffusion	Periodic Boundary Conditions	Synthetic (Parameter) Maps	Synthetic Spectra Generated	Comments
Porter, Pouquet & Woodward 1994/Falgarone et al. 1994	3D			●						●	●	●	Falgarone et al paper computes synthetic spectra & compares w/data
Vázquez-Semadeni, Passot & Pouquet 1995	2D		●	●	●	●	●			●	●		unrealistically high cloud temperatures and too low density contrast result; cooling only radiative, low τ assumed, virial clouds long-lasting, *relevant to 100-1000 pc scales*
Passot, Vázquez-Semadeni & Pouquet 1995	2D		●	●	●	●	●	●		●	●		realistic B-fields & magnetic/kinetic equipartition result; rotation of galactic disk included (extension of Vázquez-Semadeni et al. 1995)
Vázquez-Semadeni, Passot & Pouquet 1996	2D		●	●	●	●	●	●		●	●		experiments with turning "on and off" various features, and varying parameters of Passot et al. 1995 runs
Dubinski, Narayan & Phillips 1995	3D									●	●	●	purely Kolmogorov turbulence; Gaussian-Hermite polynomials used similar to SCF; spectra "similar" to real clouds
Ostriker, Gammie & Stone 1996	3D	●	●	●	●			●		●	●	●	*relavant to 1-10 pc scales*
Padoan et al 97	3D	●		●				●		●	●	●	3D staggered mesh; spectral maps "look" realistic

Existing Comparisons of Spectral-Line Maps and Numerical Simulations

This category is rather sparsely populated, and that is the motivation of our proposal. One of the first, and only, detailed simulation-data comparisons was carried out by Falgarone and collaborators (Falgarone et al. 1994), who compared the non-magnetic, non-self-gravitating turbulence simulations of Porter, Pouquet & Woodward (1994) to a ^{12}CO(2-1) map of a piece of a high-latitude cloud. Portions of the synthetic spectral-line data cubes presented by Falgarone et al. are shown in Figure 1, below. The left panel shows a cube at an early time, just after the power spectrum of fluctuations is injected, and the right panel shows the cube at a later, more “relaxed,” epoch.

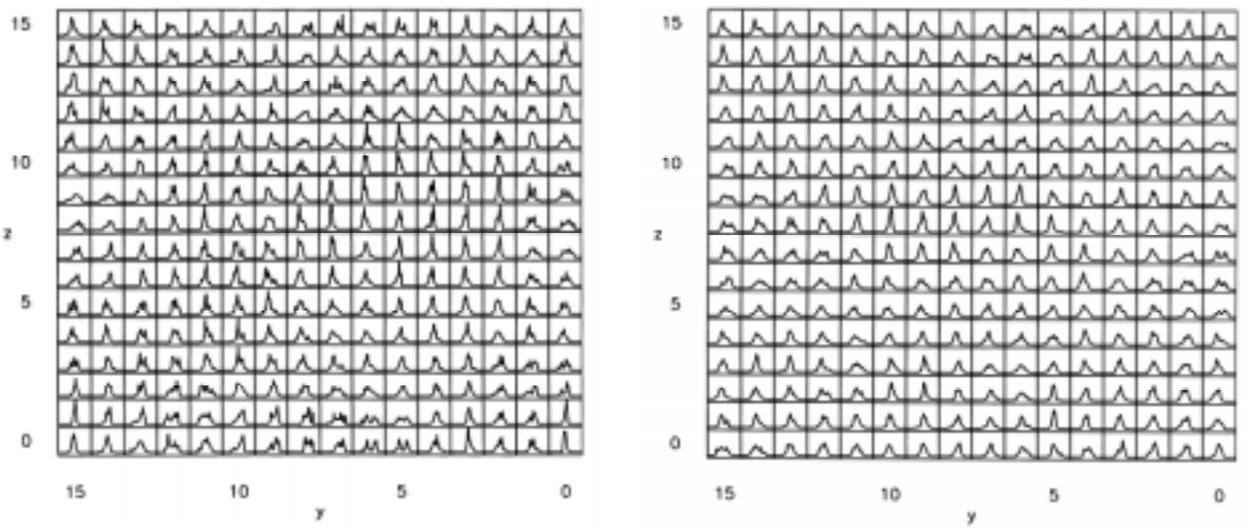

Figure 1: Numerical simulation of turbulence in the ISM, from Falgarone et al. 1994. The left panel shows synthesized spectra shortly after the initial energy injection. The right panel, shows a later time in the simulation, which has relaxed to more of a Kolmogorov-like cascade. Notice that the line profiles become generally smoother at later times.

The synthetic spectra in Falgarone et al. are produced assuming that the emission is optically thin, so no explicit radiative transfer is included. Nonetheless, Falgarone et al. show that the overall distributions of spectral properties (e.g. width, skewness, kurtosis, etc.) in the right-hand panel of Figure 1 is similar to the distributions measured in high-latitude clouds. However, Falgarone et al. do not quantitatively address the issue of *whether or not neighboring spectra vary in their properties the way neighboring spectra would in a real map*. This is a subtle but very important point. It is possible to produce simulations where the distribution of spectral properites will match observations--even though the point-to-point variations in spectra do not resemble real maps at all.[2] For example, both maps might have the same fraction of double-peaked profiles, but if those profiles are scattered randomly in the simulation, and grouped in real data, then the simulation should not be said to "match" the data. Figure 3, discussed on page 11, uses the SCF to vividly demonstrate this point.

In 1994, Tom Phillips gave a colloquium at the Center for Astrophysics on the Falgarone et al. work. As the story goes, Ramesh Narayan was in the audience, and wondered, upon seeing figures like Figure 1, how much of the spatial-velocity structure in these simulations could be produced by purely incompressible turbulence. Along with John Dubinski and Tom Phillips, Narayan set out to make some simple simulations of incompressible turbulence to answer this question. The result was Dubinski, Narayan & Phillips (1995), which clearly shows that the "evolved" phase of the Falgarone et al. simulations (right panel of Figure 1) is very similar to simple compressible turbulence. Dubinski et al. explain that the main difference between their incompressible simulations and the Falgarone et al. simulations is the absence of the "intermittency" effects found in the compressible simulations, but that it is, of course, not possible to simulate this highly non-Gaussian behavior in an incompressible, Kolmogorov-like, cascade. Furthermore, Dubinski et al. use Gaussian-Hermite polynomials to model each spectrum in their simulations, and then map out the terms in the polynomial, in order to investigate the "spatial correlations of profile distortions" (see their Figure 3). This analysis, which is a parameterized form of the more general SCF (described in the next section) leads Dubinski et al. to the conclusion that the spatial distribution of

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[2] For the record, it was just this worry that inspired the P.I. to develop a routine like the SCF, when Edith Falgarone first showed her these simulations, in 1993.

profile types is well-visualized in this way, and that this kind of structural breakdown should be applied to real data. We agree!

Ostriker, Gammie & Stone (1996) have placed great emphasis on creating realistic synthetic spectral line maps from their new 3D, compressible, self-gravitating, MHD simulations. These maps are produced in a "numerical observatory" program, developed by Charles Gammie, and *do* include radiative transfer effects. So far, Ostriker et al. have not compared their maps in detail with real data cubes, but they would like to do so. The P.I. and her student, Erik Rosolowsky, have recently informally collaborated with Gammie, in using the newly developed SCF to compare the Ostriker et al. simulations with data. The results of this comparison are shown in Figure 4, below.

Methods

As described above, we plan to utilize several existing statistical analysis techniques (e.g. structure and autocorrelation functions, clumpfinding algorithms, etc.) to compare simulated and observed data cubes, but we also plan to develop *new* techniques which may be superior to the existing ones in their ability to quantify the detailed spatial variations in spectral properties. We have spent the last few months developing one of these new techniques, which we call the "Spectral Correlation Function," or "SCF." We have made rapid progress in this endeavor, thanks in large part to the efforts of a student, Erik Rosolowsky. Below, we will briefly outline the SCF in words, but we refer the interested reviewer to http://cfa-www.harvard.edu/~agoodman/scf/velocity_methods.html, where a paper by Mr. Rosolowsky summarizing his algorithms and their applications is posted. (The detailed equations used in the SCF, and their justification, can be found at that site as well.)

The Spectral Correlation Function

The goal of the SCF is to produce a description of how the velocity structure of a data cube varies as a function of position, rather than just as a function of scale. This goal is accomplished by assessing the similarity (i.e. "correlation") of a spectrum and its neighbors for every observed spectrum in a map. The SCF has value unity when a spectrum and its neighbors within a resolution element are identical, and the SCF is zero when there is no measurable resemblance of a spectrum and its neighbors. Specifically, the key steps used in calculating the SCF are as follows:

1. **A resolution for the SCF is chosen.** Only the spectra within the resolution element are considered when calculating the value of the SCF at each position. Currently, the finest resolution we can use is a 3-by-3 pixel box, which includes just the eight immediate neighbors of each spectrum in the calculation of the SCF. (The example of the SCF shown in Figure 2 uses a coarser resolution, corresponding to a five-by-five spectrum box.)

2. **The (square of the) difference, as a function of velocity, between each spectrum and its neighbors within the resolution element is minimized and recorded.** This minimization is calculated under a variety of conditions: an adjustable lag between the spectra can be on or off, and a scaling parameter can be on or off. Ultimately, these adjustments lead to four possible values for the SCF, corresponding to "lag off, scaling off;" "lag off, scaling on;" "lag on, scaling off;" and "lag on, scaling on."

3. The difference calculated in 2 is **integrated over velocity**.

4. The velocity-integrated minimized difference calculated in 3 **is averaged over all the spectra in the resolution element**.

5. The **SCF is calculated as a normalized version** of the velocity-integrated minimized average difference calculated in 4.

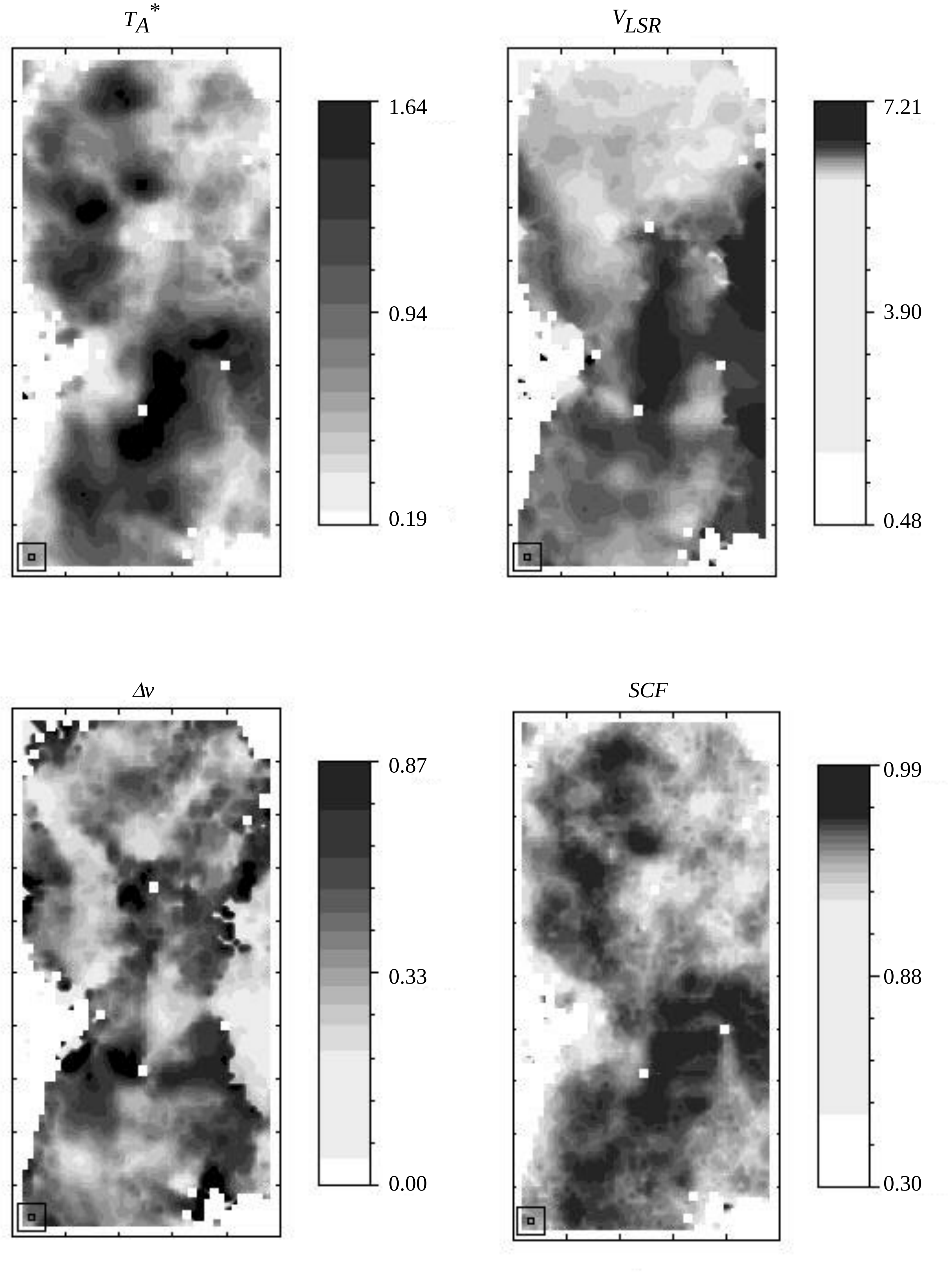

Figure 2: The Spectral Correlation Function as applied to a $C^{18}O$ map of Heiles Cloud 2 (data courtesy of M. Heyer). The greyscale plots show, clockwise from the top left, antenna temperature (in K), LSR velocity (in km s^{-1}), FWHM line width (in km s^{-1}), and the Spectral Correlation Function (range 0:1).

Figure 2 presents a sample map of the SCF, for a $C^{18}O$ map of Heiles Cloud 2 constructed by Mark Heyer and his collaborators. For reference, the typical gas density traced by the $C^{18}O$ line observed is of order 10^3-10^4 cm^{-3}. The figure shows greyscale maps of antenna temperature (line intensity), LSR centroid velocity, and FWHM line width, all determined from Gaussian fits to the spectra, along with the SCF. A cursory inspection of the figure shows that the SCF appears, in general, to be high where the line intensity is high. We have performed tests to see whether this effect is caused by the spatial concentration of higher signal-to-noise spectra at map peaks, but the effect does not seem explicable by this selection effect alone. (Note that low signal-to-noise spectra are eliminated early on from the analysis, in a step preceding #1 above, and that isolated white pixels in Figure 2 mark the location of such excluded spectra.)

At present, mostly because the procedure is so new, and we have applied it only to a handful of data cubes, we are not yet expert at interpreting “raw” maps of the SCF. Instead, we are developing quantitative measures of the distribution of the SCF within a map. The simplest statistic to consider is the frequency distribution of the SCF. Below, in Figures 3 and 4, we show some of these SCF distributions whose implications are clear. In Figure 3, we compare the true SCF distribution for the HCl 2 map shown in Figure 2 with an SCF distribution for a data cube constructed by randomizing the positions of the spectra in the HCl 2 cube. Notice how much higher the mean value of the SCF is for the “real” cube than for the randomized one. Also, the width of the distribution is markedly narrower for the real cube.

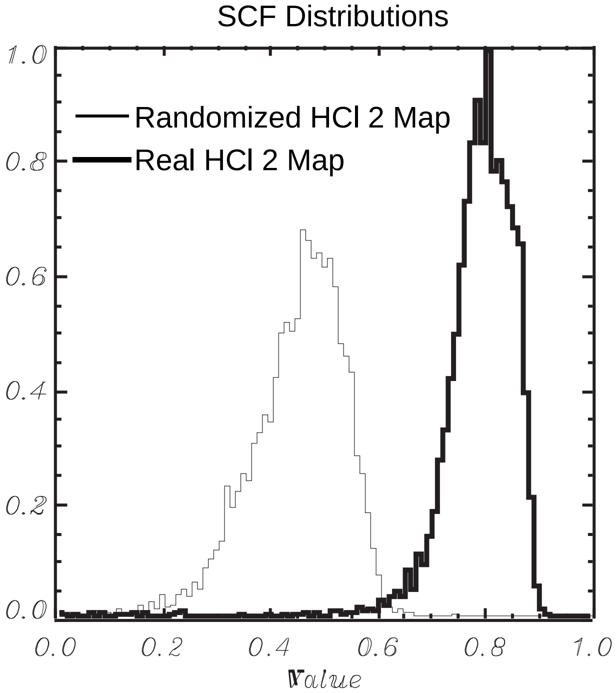

Figure 3: Comparison of the SCF distributions calculated for the “real” Heiles Cloud 2 map shown in Figure 2, and a map created by randomizing the positions of the spectra in the Heiles Cloud 2 map.

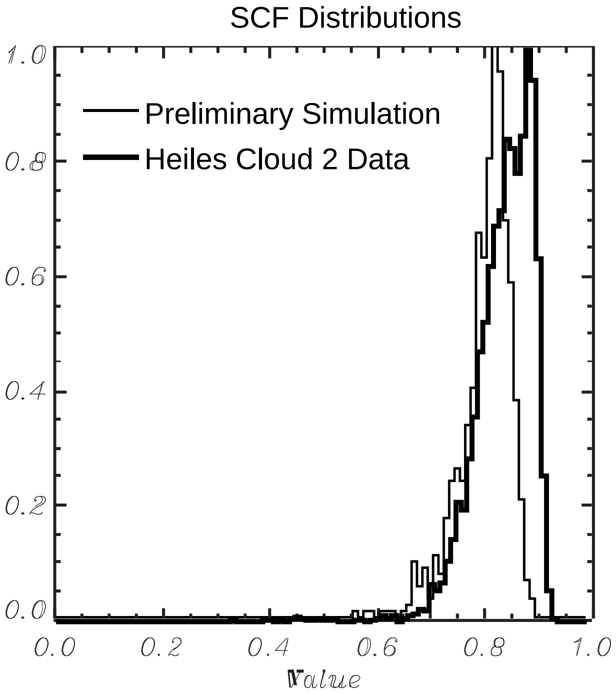

Figure 4: Comparison of the SCF distributions calculated for the “real” Heiles Cloud 2 map and a synthetic data cube resulting from a 3D compressible MHD simulation (courtesy of C. Gammie).

In Figure 4, we compare the SCF distribution for HCl 2 with the results of a 3D numerical MHD simulation of self-gravitating gas of roughly the density traced in the HCl 2 map. Considering the magnitude of the difference between randomized and real data shown in Figure 3, the similarity of the SCF distributions for the data and simulations in Figure 4 is remarkable. However, there are obvious differences between the "real" and "simulated" distributions in Figure 4, and these differences are exactly what we seek to study.

Highly discriminatory statistics derived from measures like the SCF will be used in our analysis to compare numerical simulations of specific conditions with observations relevant to the same conditions. The simulations whose statistics best "match" the observed statistics will be deemed closest to representing the real ISM.

Objectives and Expected Results

Our objective is to provide a systematic comparison of existing and in-progress theoretical simulations with relevant existing and in-progress spectral-line data cubes. Our analysis will be designed to address the following questions, whose answers should have the impact discussed after each group of questions:

1. Are there regions where turbulence theory is descriptive enough? If not, what features in observed spectral-line cubes cannot be explained by a turbulent velocity field alone? How much realism does **compressibility** in a turbulence simulation add: specifically, does compressibility matter less as a function of time, as non-linear features such as shocks dissipate?

> Obvious departures from Kolmogorov-like incompressible turbulence will be quantitatively identifiable, and their causes may be understood. Compressibility in the ISM may be found responsible for more of these departures at "early" times (as suggested by Falgarone et al. 1994), and the age of certain regions may be established by analyzing these departures (see 4, below).

2. Are there **differences between regions where self-gravity is important and where it is not**--for example, between high-latitude clouds and the dense interiors of star-forming clouds?

> Claims have been made (e.g. Williams and Blitz 1993), and unmade (e.g. Williams et al. 1994), that the clump mass spectrum differs in high-density (strongly self-gravitating) regions and low-density (marginally- or non-self-gravitating) regions. Simulations found to be good representations of self-gravitating and non-self-gravitating gas can be utilized to extract, and compare, theoretical clump mass functions. Knowledge of these clump mass functions are **critical for models of star-formation, and models of the stellar IMF**.
>
> It is known observationally that magnetic and kinetic energy are comparable in *both* self-gravitating and non-self-gravitating regions (Goodman and Heiles 1994, Myers et al. 1995), and gravitational energy is also typically comparable in self-gravitating regions (Myers and Goodman 1988). Magnetic-kinetic equipartition has also been found in some recent numerical simulations (Ostriker et al. 1996, Passot et al. 1995). Our analysis should facilitate a better **understanding of the specific conditions which produce** this **magnetic-kinetic equipartition**.

3. Are there substantial, discernible**, differences in the predicted spectral-line cubes of non-magnetic and magnetic simulations**? If so, what magnetic field structures are predicted by the simulations under specific conditions? What are the effects of **including ambipolar diffusion** (non-ideal MHD)?

> Tests of the magnetic field's influence under a variety of conditions will be facilitated by our analysis. For example, it is possible that we will find that magnetic effects are critical in high-latitude (unbound) cloud dynamics, but not in very dense regions. Such differences may only become apparent when ambipolar diffusion is explicitly included in the simulations. Current simulations all assume ideal MHD, despite low observed and predicted ion fractions in dense regions (see Myers and Khersonsky 1995 and references therein).

> Magnetic fields are often divided into two components in models of the ISM: the "uniform" (straightish on large scales) component is thought to produce asymmetric structure (e.g. oblateness in collapsing clouds), and the "non-uniform" component is given credit for isotropic support and an important role in mediating and maintaining turbulence. Observational evaluations of the relative amounts of uniform and non-uniform field (Jones et al. 1992, Myers and Goodman 1991) in the cold ISM indicate roughly equal energy in each component. And, observations do not indicate obvious correlations between the orientation of dense filamentary clouds and the ambient magnetic field (Goodman et al. 1990, 1992, 1995). However, these conclusions are based on background starlight polarization observations, which *do not reliably trace field structure in dense regions*, where grains polarize background starlight inefficiently (Goodman et al. 1995, Lazarian et al. 1997). Identification of relevant numerical simulations will produce **physical insight into field structure in dense star-forming gas** that is **currently unattainable** without thermal emission polarimetric observations (Goodman 1996), and will offer predictions for future (NASA-sponsored) sub-mm and far-infrared polarimetric measurements of the field.[3]

4. How do the **properties** of a spectral-line cube **depend on the observed region's age**, where "age" measures time elapsed since the gas gathered into approximately its current form? Specifically, are line profiles more "jagged" or different in another way in young regions, such as supernova remnants, supershells, swept-up gas near H II regions and/or outflows?

> Dubinski, Narayan & Phillips (1995) point out that all but the initial phases of the Falgarone et al. (1994) turbulence simulations' (see Figure 1) look very similar to their own purely incompressible simulations. Falgarone et al. also point out this same similarity to incompressible turbulence, and both groups suggest that the **effects of compressibility may diminish over time**.
>
> Utilizing our newfound understanding of the simulations, we may be able to **identify "evolved" regions by the smoothness of their profiles**, or at least see transitions from more recently shocked/disturbed gas to older "ambient" gas in spectral-line maps. Pound & Goodman (1997) recently carried out an extensive IRAS-CO-HI study of the Ursa Major molecular cloud complex, which can be used to demonstrate this idea. Large-scale IRAS maps suggest that the Ursa Major complex "hangs down" toward the Galactic plane from the large supershell known as the NCP Loop. When the spectral line data maps of the regions are folded into the analysis, a spatial transition along the filament from "swept-up shell" line profiles to smoother, more quiescent-looking profiles is evident. Independent observational evidence about the timescales relevant to the regions exhibiting the different kinds of profiles, combined with a theoretical understanding of how profiles evolve over time under different conditions in simulations would allow for a much more quantitative, time-stamped, picture of the Ursa Major complex's origin and evolution.

This is a long list of questions, but we believe that the methods outlined in the previous section will provide the theoretical insights necessary to answer many of them. The time is ripe for this analysis, in that only recently have both the simulations and data attained the spectral resolution necessary to allow for detailed comparisons.

Finally, a reviewer may wonder why the P.I., who does more observation than theory, would want to do this project. The reason is simple--it is frustrating to read (and produce!) papers containing more and more spectral-line mapping data with less and less physical information extracted, per bit, from these data. And, it is similarly frustrating to read, and consult on, big numerical simulations which are seldom

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[3] Such polarimetric observations are currently proposed to NASA, in the form of a new far-infrared polarimeter for SOFIA (Hildebrand 1997) and a space-borne far infrared polarimeter known as M4 (see Clemens et al. 1997 and http://cfa-www.harvard.edu/~agoodman/m4/).

compared systematically with real data. Typically, every simulation has some feature which compares in an obviously favorable way with data, and some feature which does not, but we want to know *which* feature of which simulation *causes* which agreement, and which disagreement. The P.I. and her collaborators are sure that many others--maybe even you--share our frustration. No doubt too, that there is at least one frustrated, young, theoretically-minded, observationally experienced, talented Ph.D. out there who would love NASA to support a postdoc dedicated to an effort aimed at alleviating this frustration for us all!

Work Plan & Schedule

Year 1

The **postdoctoral position** will be advertised upon notice of acceptance of this proposal, and the position should be filled within six months. In the first year, the postdoc will be responsible for obtaining and cataloging both observed and synthesized data cubes in machine-readable format. Furthermore, the postdoc and P.I. will contact the authors of many of the previously published structural-analysis techniques discussed above, in order to request the code used to run these analyses. The new **workstation** listed in the budget will be purchased in Year 1, and it will be used to store data cubes and run code.

Erik Rosolowsky[4], a Senior Thesis student of the P.I.'s, has developed the SCF technique from an idea (see http://cfa-www.harvard.edu/~agoodman/scf/scf.pdf) to a working algorithm, during just this past Summer (see Rosolowsky 1997). Erik is a highly motivated and talented student, and for his Senior Thesis (to be submitted in May of 1998) he will continue to develop and test the SCF on the data cubes and simulations we already have in-hand (see below). Drs. **David Wilner** and **Jonathan Williams**, both of the CfA, have been collaborating with Mr. Rosolowsky and the P.I. on this project, and this group will *submit an initial publication* describing the SCF and its initial applications to the *Astrophysical Journal* in the first half of 1998.

Martin van Rappard, a visiting student from the Netherlands, has been working with the P.I. on developing an automated velocity gradient mapping and analysis routine for large data cubes. van Rappard's program employs the gradient-fitting routine VFIT, which was developed by the P.I. for measuring gradients in small individual clouds (see Goodman et al. 1993). This project is just getting underway (in collaboration with Dr. Jonathan Williams), but should produce a usable tool, to be used in tandem with the SCF, which will be incorporated into our analysis of the large observed and simulated cubes. This incorporation will be carried out primarily by E. Rosolowsky, J. Williams, the P.I. and/or the postdoctoral fellow.

Héctor Arce is a third-year Harvard graduate student who has just completed his qualifying-exam project with the P.I. Mr. Arce wants to continue working with the P.I., and with Dr. Charles Lada, on problems related to the structure of the ISM for his thesis. This means that he will play some--potentially large--role in the project described in this proposal, but because his thesis plans are still being made, that role is not yet well-defined enough to make any promises on his behalf here.

A partial list of the **data cubes** already in-hand includes: a ~40,000 spectrum CO map of the Ursa Major cloud complex (Pound & Goodman 1997); several 10,000+ spectrum maps of galactic zones courtesy of our collaborator, Dr. **Mark Heyer**; several higher-density tracer maps of star-forming regions

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[4] E. Rosolowsky is a student at Swarthmore, who began this project while an SAO Summer Intern with AG at the CfA in 1997. Arrangements have already been made with Mr. Rosolowsky's Swarthmore advisor, Dr. John Gaustad, for AG to advise Erik's thesis long-distance. Erik will make ~bi-monthly trips to Cambridge.

courtesy of Dr. Jonathan Williams; and maps of several regions, some including supernova shells, courtesy of Dr. David Wilner.

As for **simulations**, we are working closely with Dr. **Charles Gammie**, of the CfA, who has already created a synthesized preliminary map from one of the Ostriker, Gammie & Stone simulations in progress. (The P.I. has been a consultant on these simulations since their inception.) The synthesized map was created specifically to be used as a quick test for the SCF and is compared with real data in Figure 4. We plan to continue working in close cooperation with Charles Gammie, **Eve Ostriker**, and **Jim Stone**. Their ongoing MHD simulations are currently being funded by NASA ATP grant NRA-96-04-GSFC-063, and they are pleased with the prospect of our quantitatively comparing their results with observed data cubes. The P.I. has also had extensive discussions about this project with **Enrique Vázquez-Semadeni**, who can also provide simulations for our analysis. Lastly, the P.I. is on very good terms with **Edith Falgarone** and **Tom Phillips**, who can provide additional simulations, both published and ongoing.

Year 2

By the end of Year 1, we should have enough data, simulations, and code, in-hand to begin producing the first direct observed/simulated data cube comparisons. Most of the personnel and collaborators mentioned in Year 1 (with the possible exceptions of the undergraduates Rosolowsky and van Rappard), will continue to work on the project. We will *publish* our first comparisons rapidly, in order to make both the observational and modeling communities aware of our results--in the hope that our results might influence future observing and numerical programs. The first round of comparisons will not include every possible data cube, but instead focus on "representative" regions (e.g. at least one each: high-latitude cloud; star-forming cloud; supernova remnant).

Year 3

By the third year, we will have had the time to apply our comparison methods to a wider range of data cubes. We will be able to assess the universality of conclusions drawn from the analyses in Years 1 and 2. By the end of Year 3, we will *publish* our best estimate of which set of diagnostics best describes a data cube, where "best" means that two cubes would be least likely to accidentally be declared similar.

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[5] Note that the MHD simulations of Ostriker, Gammie & Stone are referred to in the text as "Ostriker et al. 1996," as a convenience. This reference, which technically is to their ATP proposal, in actuality refers to "personal communications" of the early results from that proposal, most notably by Charles Gammie, to whom we are very grateful.