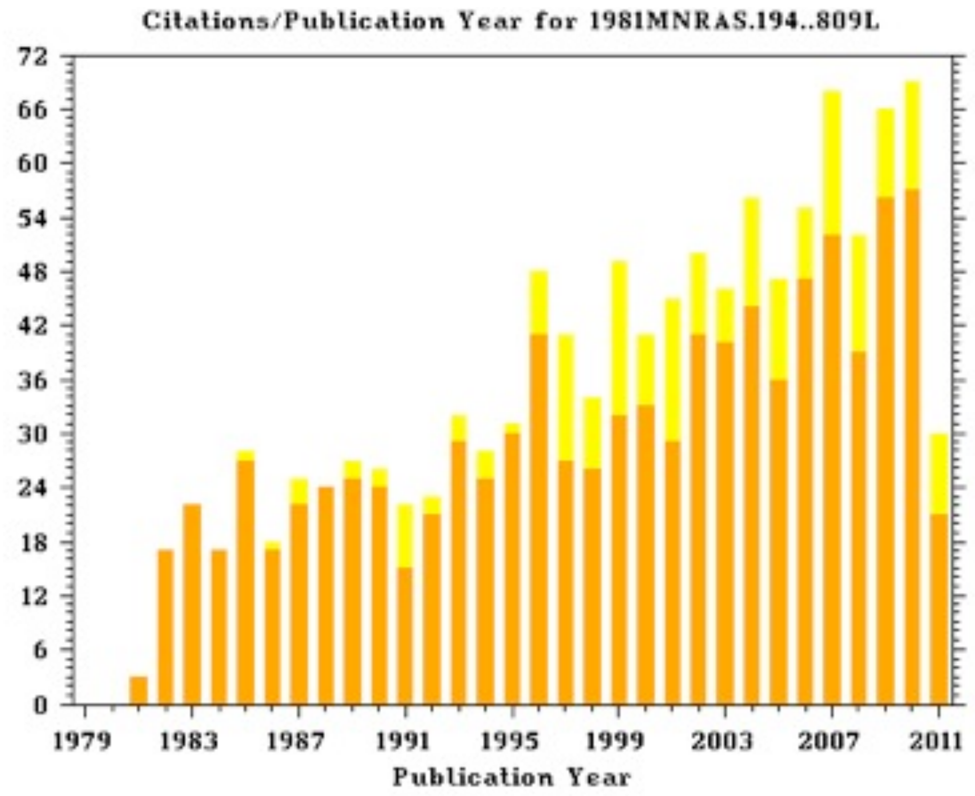
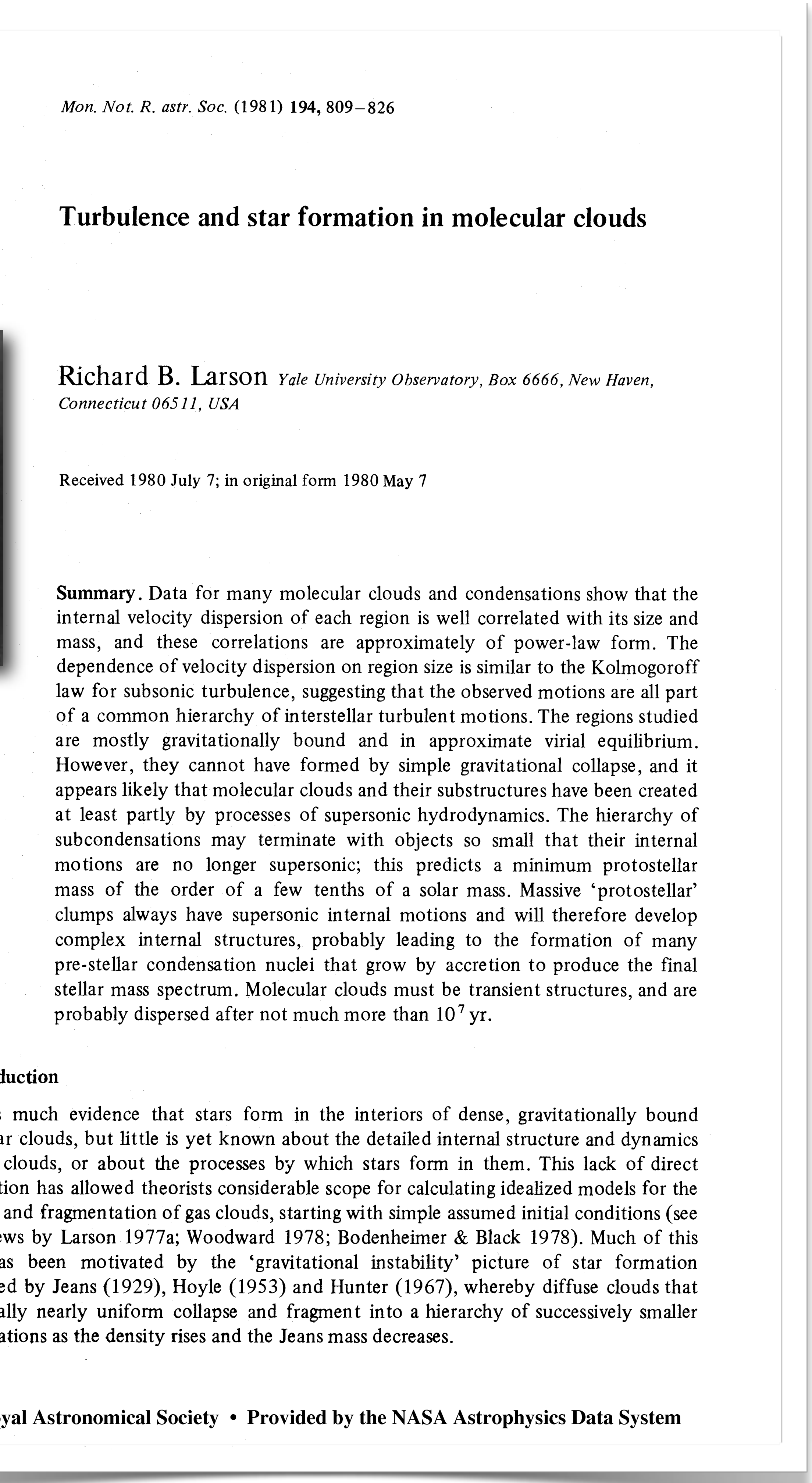
Larson's Legacy

The evolution of the ideas about turbulent molecular clouds first proposed by Richard Larson in his 1981 paper.





Mon. Not. R. astr. Soc. (1981) **194,** 809–826

Turbulence and star formation in molecular clouds

Richard B. Larson *Yale University Observatory, Box 6666, New Haven, Connecticut 06511, USA*

Received 1980 July 7; in original form 1980 May 7

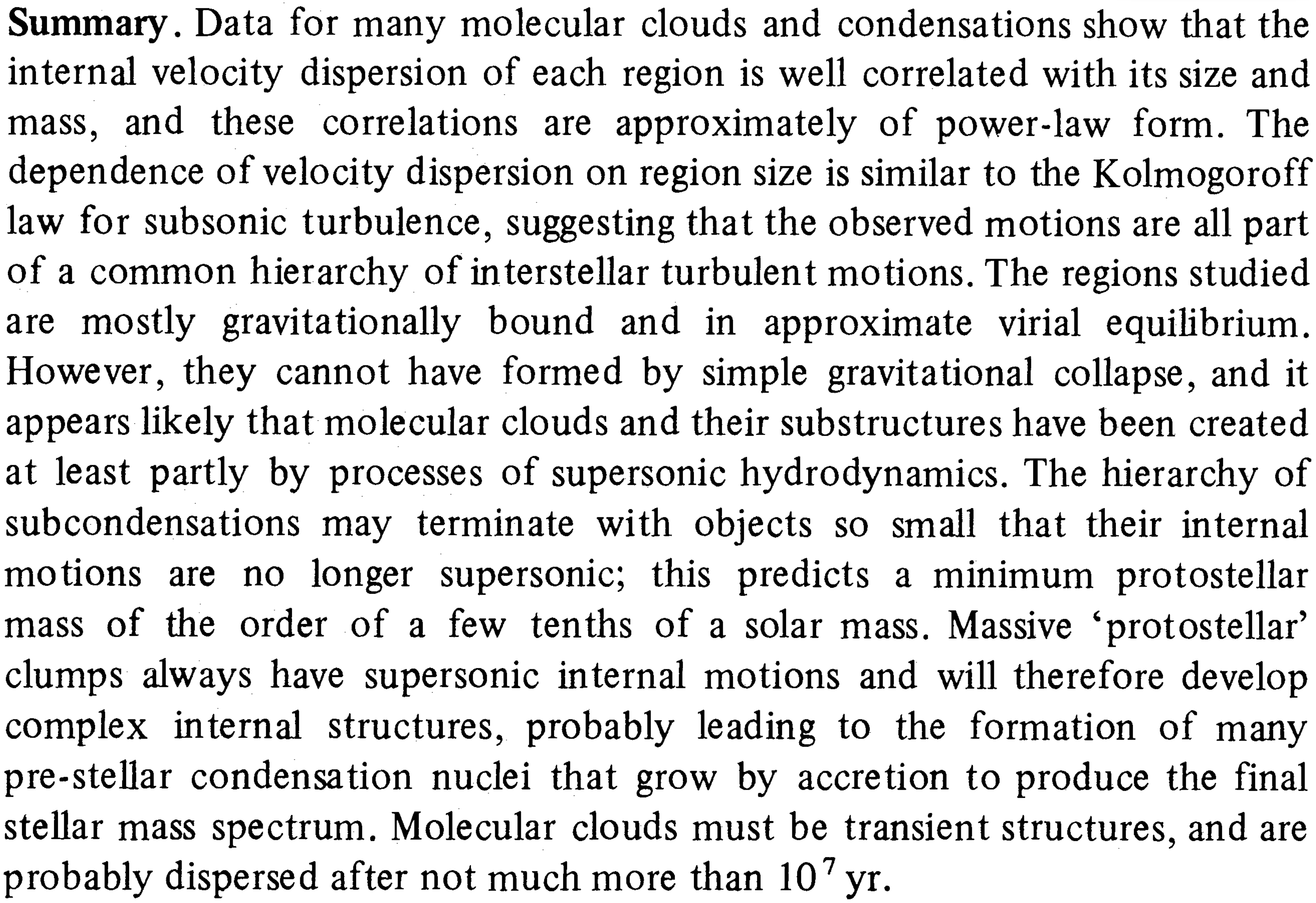
Summary. Data for many molecular clouds and condensations show that the internal velocity dispersion of each region is well correlated with its size and mass, and these correlations are approximately of power-law form. The dependence of velocity dispersion on region size is similar to the Kolmogoroff law for subsonic turbulence, suggesting that the observed motions are all part of a common hierarchy of interstellar turbulent motions. The regions studied are mostly gravitationally bound and in approximate virial equilibrium. However, they cannot have formed by simple gravitational collapse, and it appears likely that molecular clouds and their substructures have been created at least partly by processes of supersonic hydrodynamics. The hierarchy of subcondensations may terminate with objects so small that their internal motions are no longer supersonic; this predicts a minimum protostellar mass of the order of a few tenths of a solar mass. Massive 'protostellar' clumps always have supersonic internal motions and will therefore develop complex internal structures, probably leading to the formation of many pre-stellar condensation nuclei that grow by accretion to produce the final stellar mass spectrum. Molecular clouds must be transient structures, and are probably dispersed after not much more than 10^7 yr.

1 Introduction

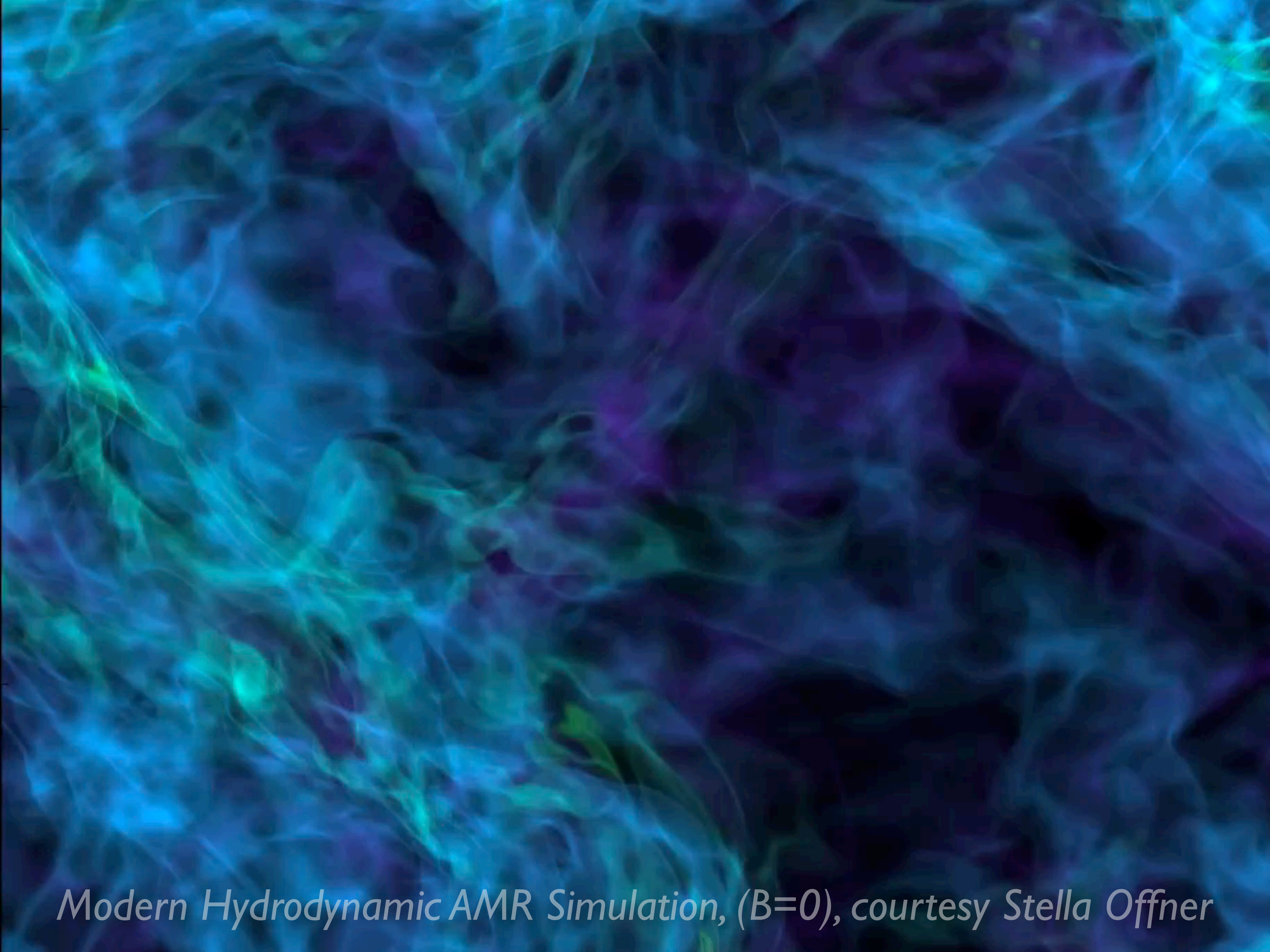
There is much evidence that stars form in the interiors of dense, gravitationally bound molecular clouds, but little is yet known about the detailed internal structure and dynamics of such clouds, or about the processes by which stars form in them. This lack of direct information has allowed theorists considerable scope for calculating idealized models for the collapse and fragmentation of gas clouds, starting with simple assumed initial conditions (see the reviews by Larson 1977a; Woodward 1978; Bodenheimer & Black 1978). Much of this work has been motivated by the 'gravitational instability' picture of star formation elaborated by Jeans (1929), Hoyle (1953) and Hunter (1967), whereby diffuse clouds that are initially nearly uniform collapse and fragment into a hierarchy of successively smaller condensations as the density rises and the Jeans mass decreases.

Slide set prepared by Alyssa Goodman, for Harvard Astronomy 201b, March 2011.

~100% Correct, but Details have Taken 30 Years (so far)

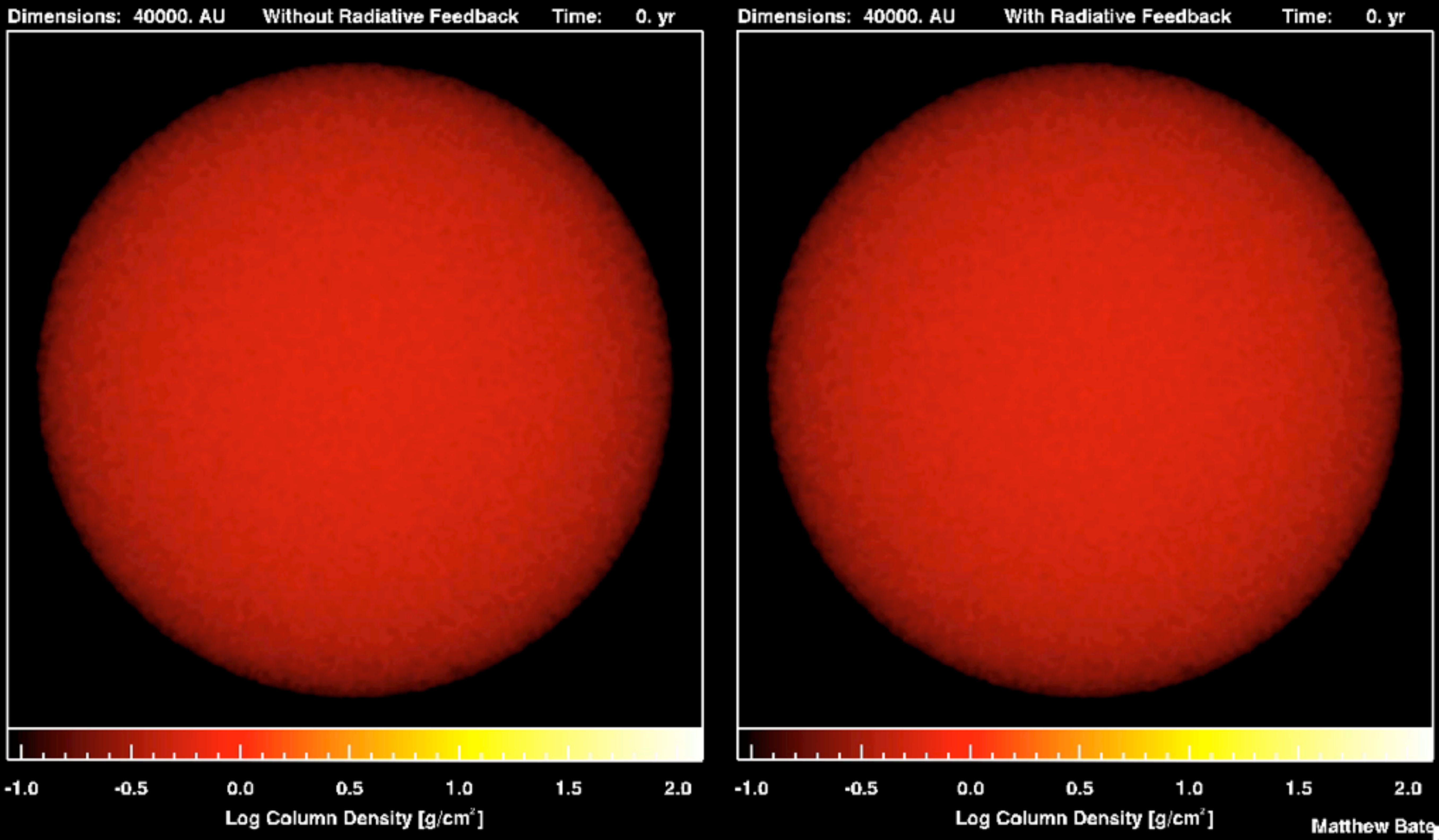


Summary. Data for many molecular clouds and condensations show that the internal velocity dispersion of each region is well correlated with its size and mass, and these correlations are approximately of power-law form. The dependence of velocity dispersion on region size is similar to the Kolmogoroff law for subsonic turbulence, suggesting that the observed motions are all part of a common hierarchy of interstellar turbulent motions. The regions studied are mostly gravitationally bound and in approximate virial equilibrium. However, they cannot have formed by simple gravitational collapse, and it appears likely that molecular clouds and their substructures have been created at least partly by processes of supersonic hydrodynamics. The hierarchy of subcondensations may terminate with objects so small that their internal motions are no longer supersonic; this predicts a minimum protostellar mass of the order of a few tenths of a solar mass. Massive ‘protostellar’ clumps always have supersonic internal motions and will therefore develop complex internal structures, probably leading to the formation of many pre-stellar condensation nuclei that grow by accretion to produce the final stellar mass spectrum. Molecular clouds must be transient structures, and are probably dispersed after not much more than 10^7 yr.



Modern Hydrodynamic AMR Simulation, (B=0), courtesy Stella Offner

+gravity +radiative feedback



Smoothed-Particle Hydrodynamics (B=0); Bate 2009

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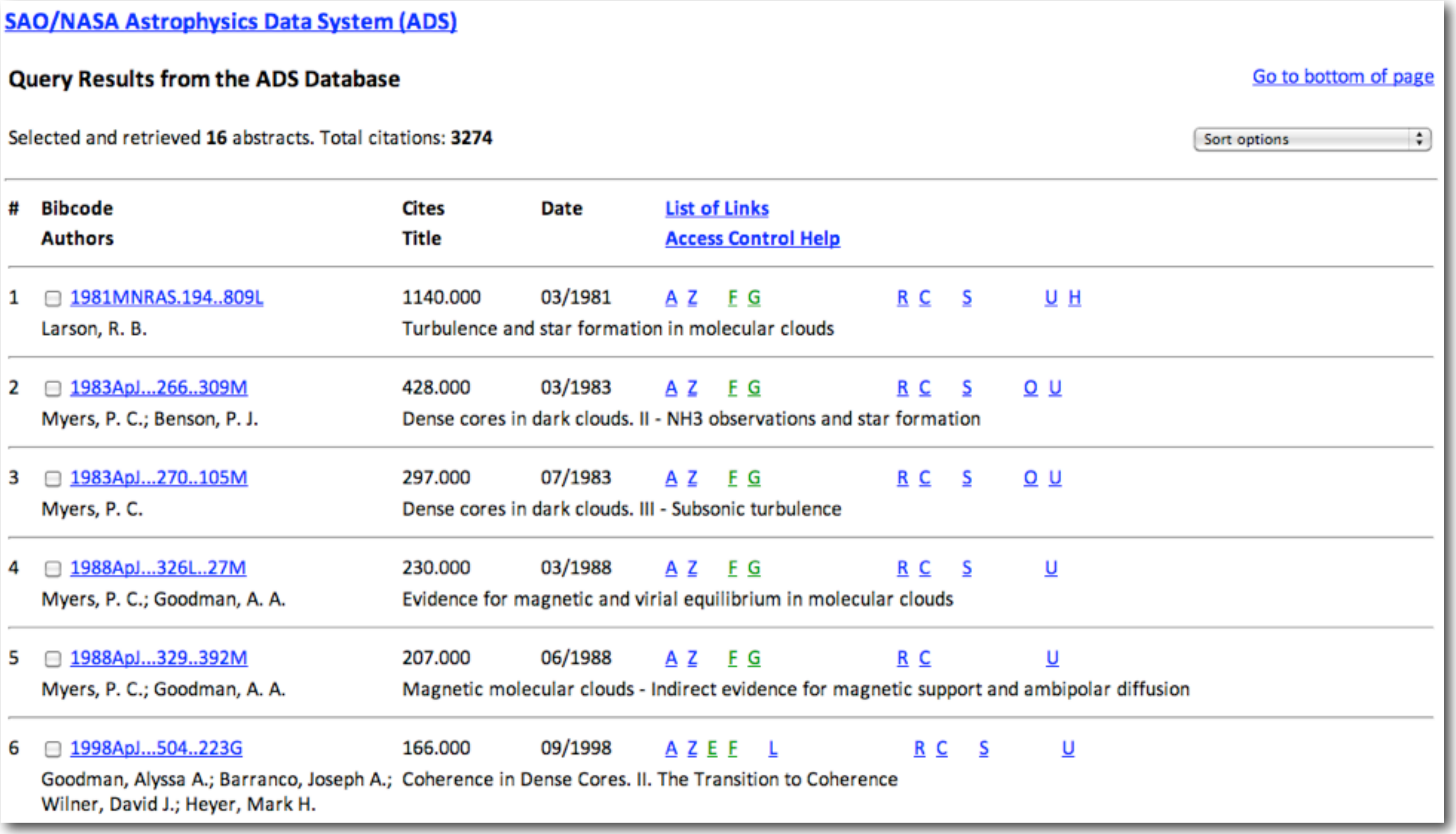

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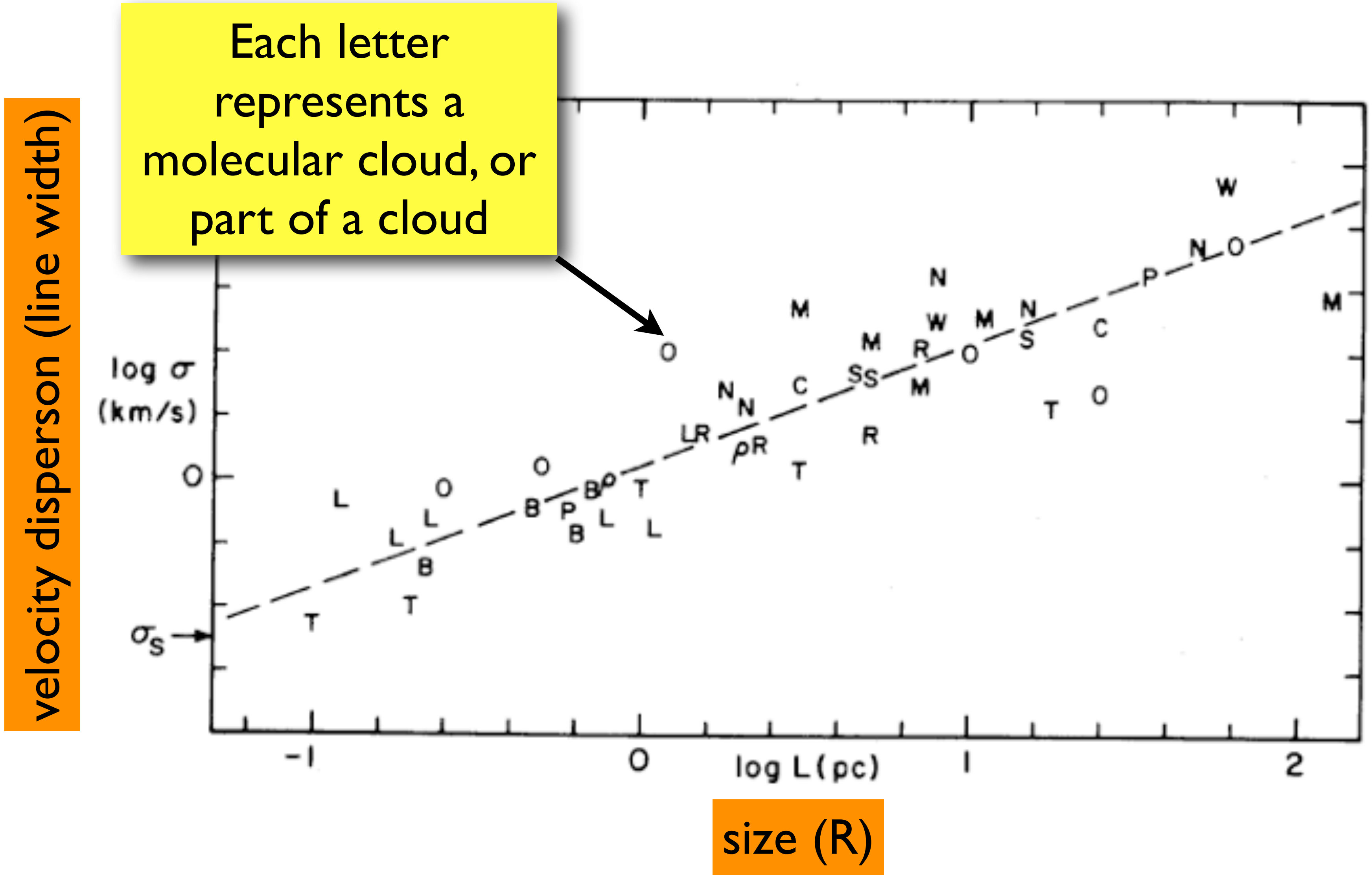
“Line width - size” $\sigma \sim R^{0.38}$



Each letter represents a molecular cloud, or part of a cloud

velocity disperson (line width)

size (R)

Figure 1. The three-dimensional internal velocity dispersion σ plotted versus the maximum linear dimension L of molecular clouds and condensations, based on data from Table 1; the symbols are identified in Table 1. The dashed line represents equation (1), and σ_S is the thermal velocity dispersion.

(More recently, 0.38 has become ~0.5. Larson liked 0.38 because Kolmogorov (incompressible) turbulence would give 0.33. A higher value is consistent with compressible (e.g. “Burger’s” turbulence.)

~Virial Equilibrium: Gravity Balanced by "Turbulent" Support

The dashed line in this figure is not fitted to the points, but represents the relation

$$\frac{2GM}{\sigma^2 L} = 0.92\, L\,(\mathrm{pc})^{0.14} \tag{4}$$

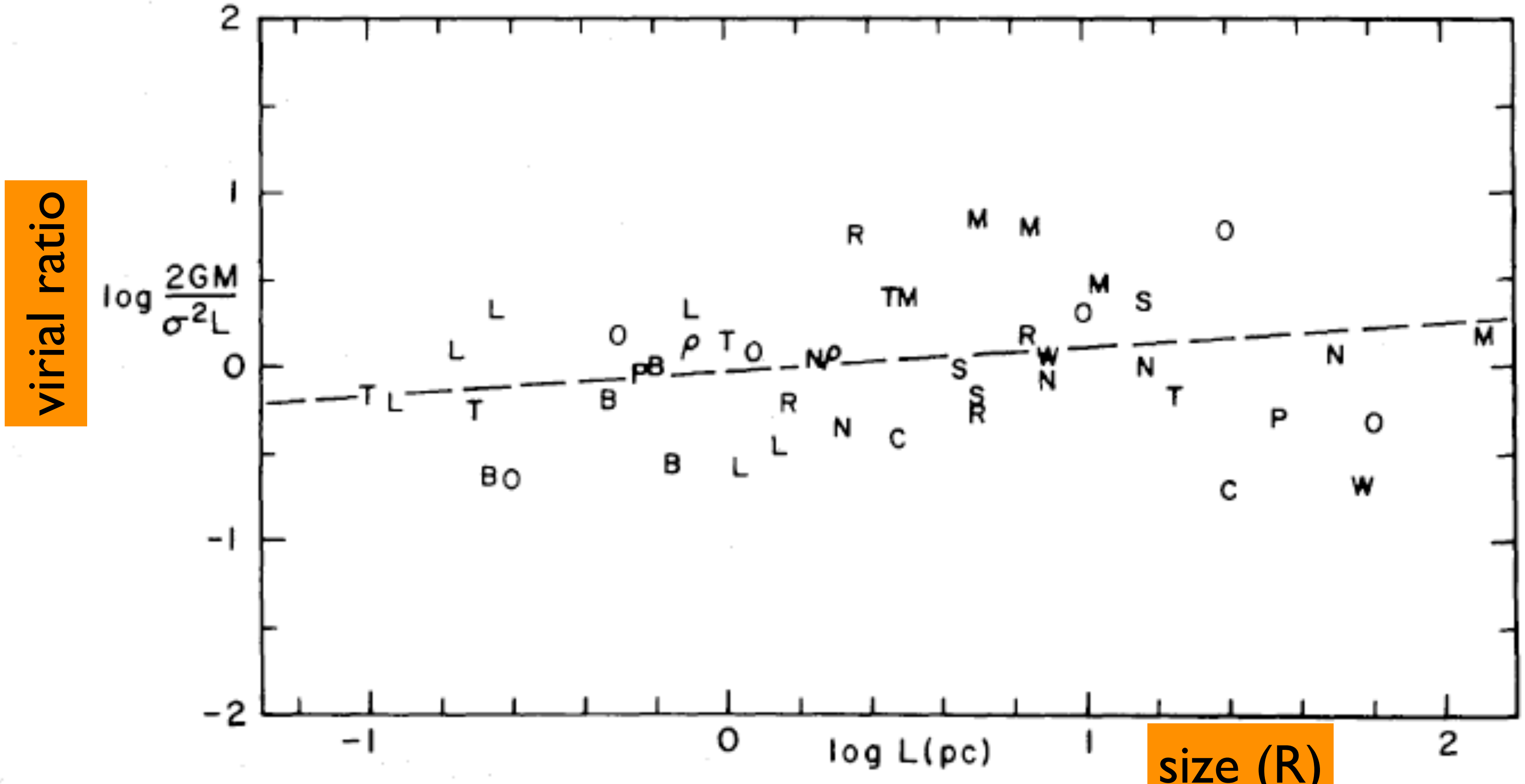


Figure 4. The virial ratio $2GM/\sigma^2 L$ plotted versus region size L for the same regions shown in Figs 1 and . The dashed line represents equation (4), and is derived from equations (1) and (2).

for exact virial equilibrium, $2GM/R^2\sigma^2=1$, and points above would be on horizontal line

“Density - size” $n \sim R^{-1.1}$

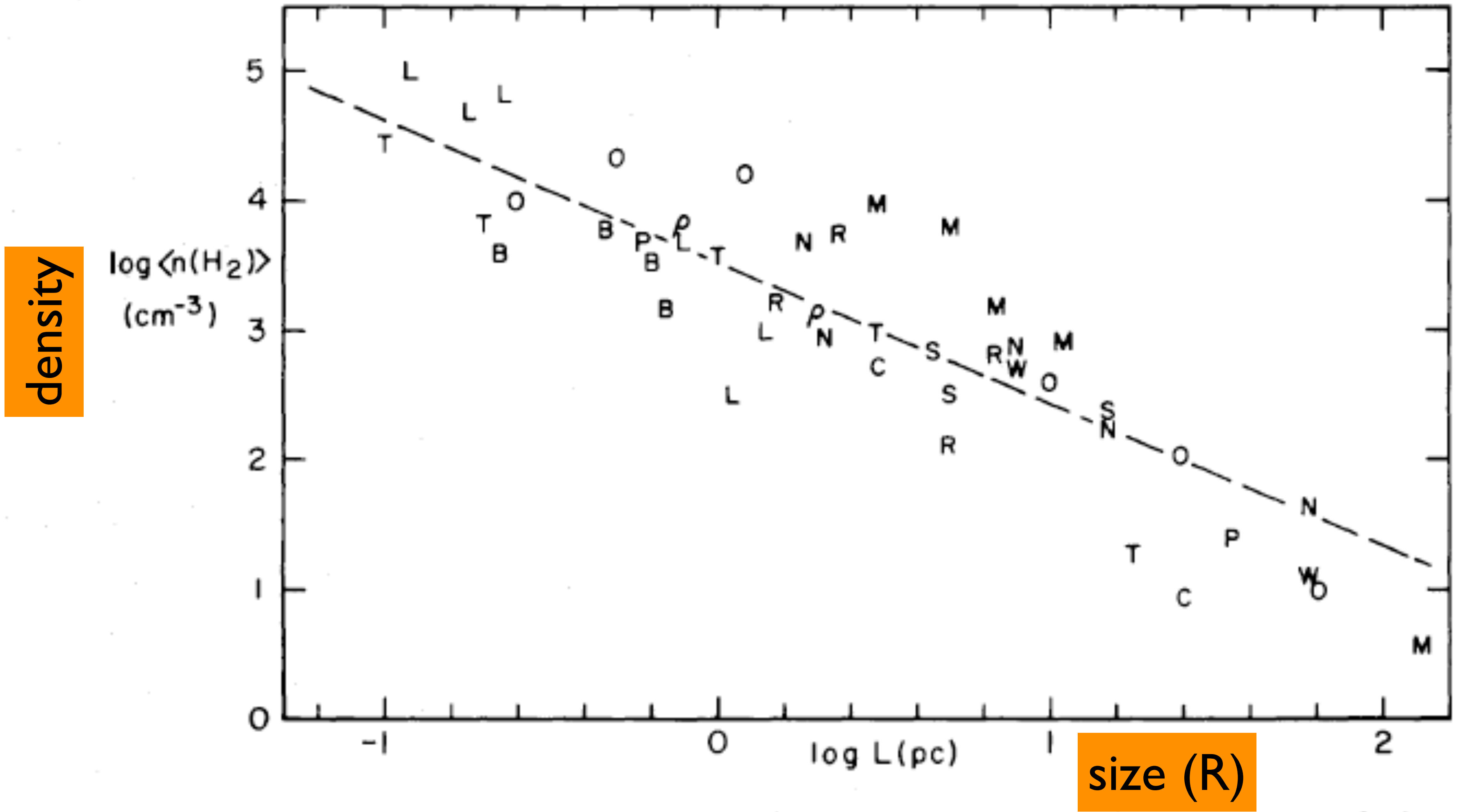
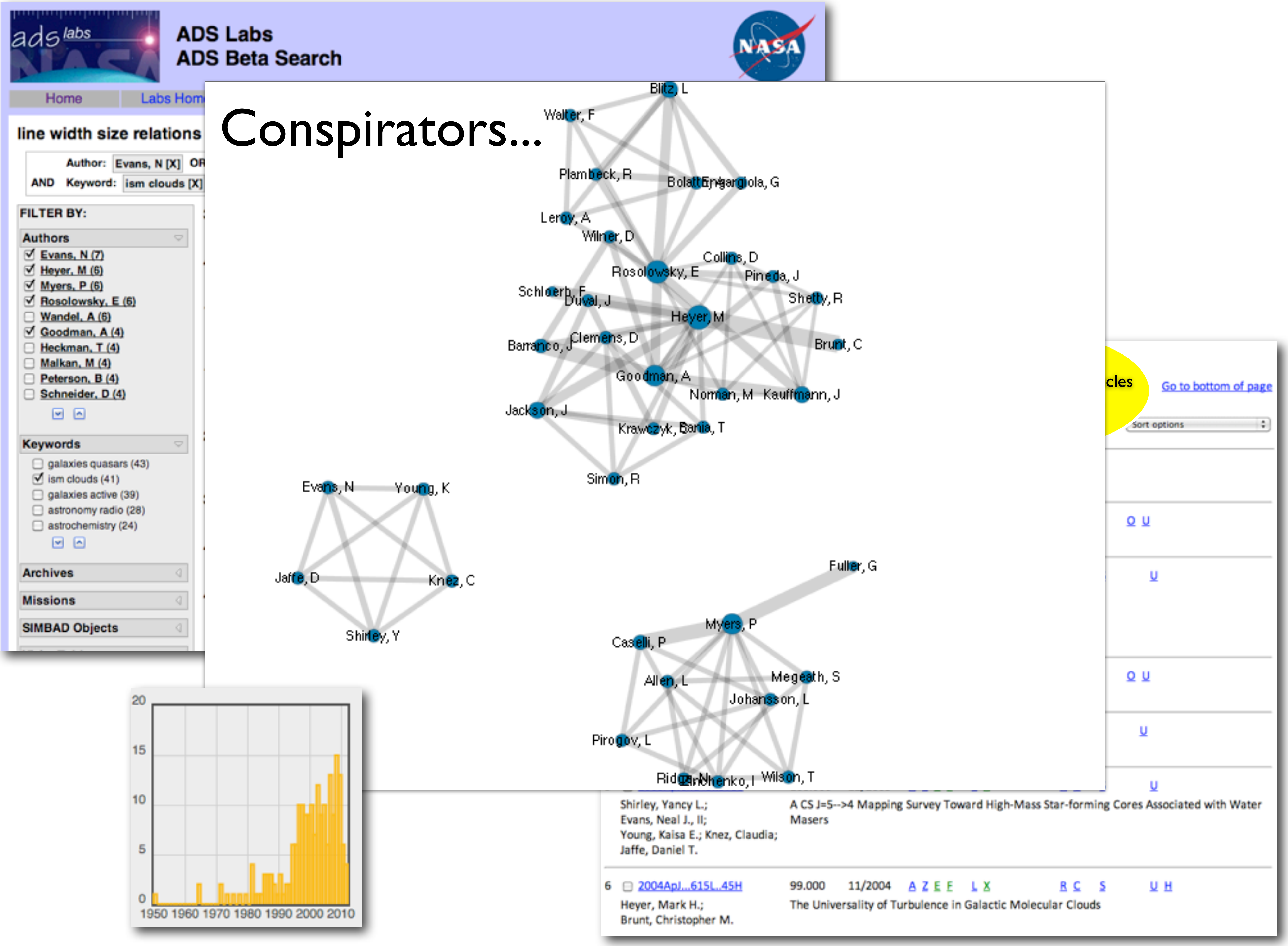


Figure 5. The average density, defined as the density of a sphere of mass *M* and diameter *L*, of all the regions shown in Figs 1 and 3 plotted versus region size *L*. The dashed line represents equation (5), and is derived from equations (1) and (2).

For $n \sim R^{-1}$, and $\sigma \sim R^{0.5}$, and $2GM/R^2\sigma^2 = 1$ (virial equilibrium) any one relation follows automatically from the other two

So, roughly speaking, Larson's "Laws" show that a *turbulent-like nature for the line width-size relation, plus virial equilibrium, gives the observed density-size relation.*

Conspirators...



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let’s look at magnetic fields...

Magnetic Origin of Supersonic Linewidths??

THE ASTROPHYSICAL JOURNAL, **329**:392–405, 1988 June 1

MAGNETIC MOLECULAR CLOUDS: INDIRECT EVIDENCE FOR MAGNETIC SUPPORT AND AMBIPOLAR DIFFUSION

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Received 1987 May 4; accepted 1987 December 17

ABSTRACT

Over 120 measurements of molecular cloud size R, velocity dispersion σ, and density n are compiled to investigate the well-known relations $\sigma \propto R^{1/2}$, $n \propto R^{-1}$, and $GM/R \approx \sigma^2$. For cloud sizes from 0.1 to 100 pc, a crude virial equilibrium model of thermal and magnetic support against gravity fits the observed trends, provided the one free parameter, magnetic field strength, is 15–40 μG. This range is comparable to that of available field strength measurements in self-gravitating clouds. Low-mass dense cores have a significantly smaller ratio of nonthermal kinetic energy to gravitational potential energy than do larger clouds. According to the equilibrium model these cores have substantially less magnetic support against gravity, and substantially smaller flux-to-mass ratio, than do the larger clouds. This relatively weak magnetic support may arise from ambipolar diffusion: for constant field strength, a model cloud with thermal and magnetic balance against gravity has a critical size for which ambipolar diffusion is fastest, and this size is close to that of typical low-mass cores, $\sim$0.1 pc. In contrast, more massive cores have equilibrium field strength 3–10 times greater than do their lower density surroundings. The model of magnetic and thermal support can be tested by new observations of the Zeeman effect in the centimeter-wavelength spectral lines of OH and H.

Subject headings: hydromagnetics — interstellar: magnetic fields — interstellar: molecules

I. INTRODUCTION

Spectral lines in molecular clouds have long been recognized to be supersonic (e.g., Barrett, Meeks, and Weinreb 1964), and the origin of these supersonic motions is a fundamental problem in molecular cloud physics. In the middle 1970s it was recognized that these motions are unlikely to arise from complete gravitational collapse of molecular clouds, because then the formation rate of stellar mass in the Galaxy would greatly exceed the few $M_\odot$ yr^{-1} deduced from stellar observations (Zuckerman and Palmer 1974). The line widths are usually attributed to chaotic "turbulent" motions, but the physical characteristics of this turbulence remain uncertain. It was also suggested that the supersonic line widths may arise from magnetic motions, such as Alfvén waves (Arons and Max 1975), or other hydromagnetic waves (Mouschovias 1975), but direct observational tests of this and similar proposals have not been possible.

Important clues were found when relationships among cloud mass M, velocity dispersion σ, cloud size R, and number density n were recognized in a set of molecular line data assembled from many diverse observational studies. Larson (1981) demonstrated power-law trends of the approximate form $\sigma \propto R^{0.5}$ and $n \propto R^{-1}$ over three decades in R, and showed that the clouds approximately satisfy virial equilibrium, $\sigma^2 \approx GM/R$. Similar power-law relations were also found for similar clouds, selected and observed more systematically than in Larson's sample; and for both smaller and larger clouds (Leung, Kutner, and Mead 1982; Myers 1983; Solomon and Sanders 1985; Dame *et al.* 1986). It is well established that these "Larson's Laws" represent a real and widespread phenomenon.

Only two of these three relations are independent: virial equilibrium and either the velocity dispersion–size law or the density–size law generates the other. Most attempts to account for these relations focus on the velocity dispersion–size law (Scalo 1987). Suggested explanations include the following: (1) mechanical "turbulence," possibly arising from a cascade of eddies as in Kolmogorov turbulence (Larson 1981), or from clump-clump collisions (Scalo and Pumphrey 1982)—the energy for these processes might originate from differential galactic rotation (Fleck 1983) or stellar winds (Silk 1985); (2) the clouds could typically lie at a point of critical equilibrium with a source of external pressure (Chieze 1987) or (3) could satisfy $\sigma \propto R^{1/2}$ by transporting angular momentum from smaller to larger scales, assuming constant torque density, or constant internal pressure, which could be magnetic (Henriksen and Turner 1984); (4) the clouds could typically harbor collisions among magnetically linked clumps (Elmegreen 1985; Falgarone and Puget 1986) or could generate nonthermal motions, including Alfvén waves, associated with substantial magnetic support (Franco, Tarsia, and Quiroga 1985; Mouschovias 1987*a*, *b*; Shu 1987).

In this paper we present an analysis which favors this last possibility (4) by comparing simple cloud models to more than 100 cloud observations. Preliminary versions of this work were presented by Goodman and Myers (1986) and by Myers (1987). For 14 clouds with magnetic field strength measured via the Zeeman effect, close agreement between observed field strengths and those predicted by the model in this paper was demonstrated by Myers and Goodman (1988). A closely related paper also appears in this volume (Fleck 1988).

The idea that interstellar magnetic fields may be coupled to gas motions was first discussed by Alfvén (1943) and Fermi (1949), and the pressure associated with cloud magnetic fields

THE ASTROPHYSICAL JOURNAL, **326**:L27–L30, 1988 March 1

EVIDENCE FOR MAGNETIC AND VIRIAL EQUILIBRIUM IN MOLECULAR CLOUDS

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A. A. GOODMAN
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Received 1987 October 8; accepted 1987 December 7

ABSTRACT

Recent measurements of the magnetic field strength, velocity dispersion, and size of 14 molecular clouds agree, within uncertainty of a factor of $\sim$2, with the predictions of a simple model in which the magnetic, kinetic, and gravitational energies are all equal. The clouds range from extended dark clouds to massive dense cores associated with OH masers and compact H II regions. Their field strengths range over a factor of $\sim 10^3$, from $\sim$10 μG to $\sim$10 mG. This result suggests that the magnetic contribution to the internal motions and energy of many molecular clouds is crucial for cloud dynamics, cloud evolution, and star formation.

Subject headings: interstellar: magnetic fields — interstellar: matter

I. INTRODUCTION

Recently, our knowledge of magnetic fields in molecular clouds has improved, in three ways. First, field strengths of order 10–100 μG have been determined from the Zeeman effect in lines of H I and OH in at least eight well-defined molecular clouds (see Table 1 for references). These include nearby dark clouds, and more massive clouds with H II regions. Second, molecular lines have been observed from about 10 dense cores associated with compact H II regions, where the field strength is known from the Zeeman effect in OH maser lines. In some cases, the pointlike OH masers coincide in position and velocity with the more extended, nonmaser, emission or absorption [e.g., W3(OH); Reid, Myers, and Bieging 1987]. This suggests that the field strength deduced from the masers can be associated with properties deduced from the nonmaser observations. Third, for more than 120 self-gravitating clouds, the two trends (1) between cloud velocity dispersion σ and size R, $\sigma \propto R^{1/2}$, and (2) between cloud density n and R, $n \propto R^{-1}$, both noted by Larson (1981), have been fitted by a magnetic virial equilibrium model, with magnetic field strength within a factor $\sim$2 of 30 μG (Henriksen and Turner 1984; Shu 1987; Myers 1987; Myers and Goodman 1988, hereafter MG). The success of this modeling constitutes indirect evidence that magnetic support may be a common feature of self-gravitating clouds.

The idea of magnetic support can now be tested directly for those clouds with measured field strengths. MG present two relations involving magnetic balance against gravity in a uniform, spherical cloud with negligible thermal support. For convenience we denote the magnetic, kinetic, and gravitational terms of the virial theorem by M, K, and G. The first relation, which is well known, requires only "magnetic" equilibrium ($\mathsf{M} \approx \mathsf{G}$; in this *Letter*, $\approx$ means equal within a factor of order 2):

$$B_{\rm eq} \approx 3\pi m \left(\frac{G}{5}\right)^{1/2} N\,, \qquad (1)$$

where m is the mean molecular mass, and N is the mean column density (Elmegreen 1978; Chandrasekhar and Fermi 1953). A second relation requires both "magnetic" and "virial" equilibrium ($\mathsf{M} \approx \mathsf{K} \approx \mathsf{G}$). It relates the field strength $B_{\rm eq}$ to the mean FWHM line width Δv and to the cloud size R over which B and Δv are mean values:

$$B_{\rm eq} \approx \frac{3}{8 \ln 2}\left(\frac{5}{G}\right)^{1/2} \frac{\Delta v^2}{R}\,. \qquad (2)$$

MG note that in many cases Δv and R can be measured with much greater accuracy than can N, so that equation (2) may offer a more practical test than equation (1).

In this *Letter* we compare equilibrium field strengths, calculated from equation (2), with measured values for 14 clouds—all clouds known to us with enough suitable data to make the comparison. Our main conclusion is that the equilibrium and measured field strengths generally agree within a factor of $\sim$2, for a wide range of clouds and field strengths.

II. DATA

The data on 14 clouds in Table 1 were selected from 25 clouds with known field strength $B_{\rm obs}$ deduced from Zeeman measurements. We searched the literature for data on FWHM line width Δv and FWHM cloud diameter R, so that Δv, R, and $B_{\rm obs}$ are as mutually consistent as possible. We used the following as guidelines:

1. The line width Δv should be observed with angular resolution fine enough to resolve the cloud, i.e., with linear resolution smaller than R.
2. The line width should be measured in a line that has negligible broadening due to optical depth effects, and it should tend to trace bound motions (NH_3, H_2CO) rather than outflows (^{12}CO, HCO^+).
3. Where possible, all three of Δv, R, and $B_{\rm obs}$ should be measured in the same emission line (as in the ρ Oph cloud).
4. Otherwise, both Δv and R should be measured in the same emission line [L204, L1641, S88B, W3, S106, Orion KL, W3(OH), W51e1].
5. Otherwise, Δv and R should pertain to the same region—as when an absorption line of width Δv is observed toward an angularly unresolved H II region. Then we take R from a con-

Myers & Goodman 1988a,b

“Indirect Evidence”

1988ApJ...329..392M

The Astrophysical Journal, **329**:392–405, 1988 June 1

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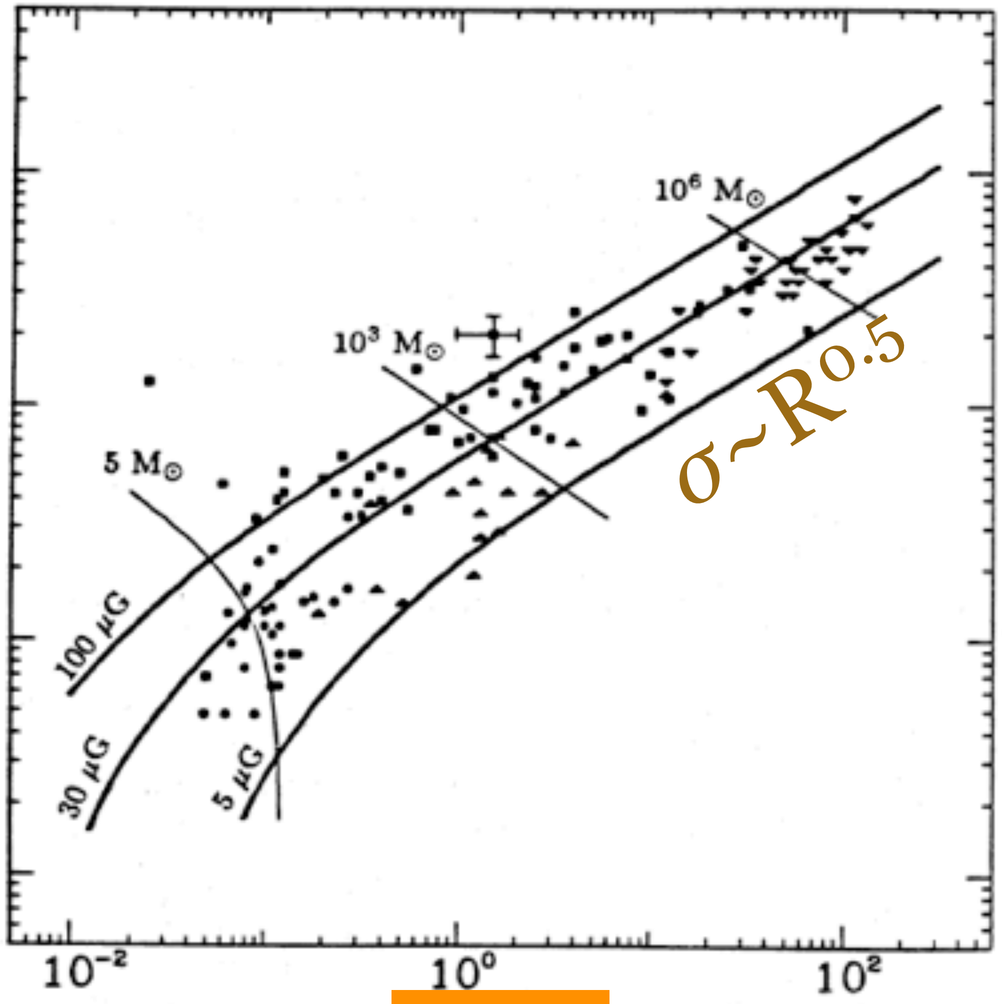
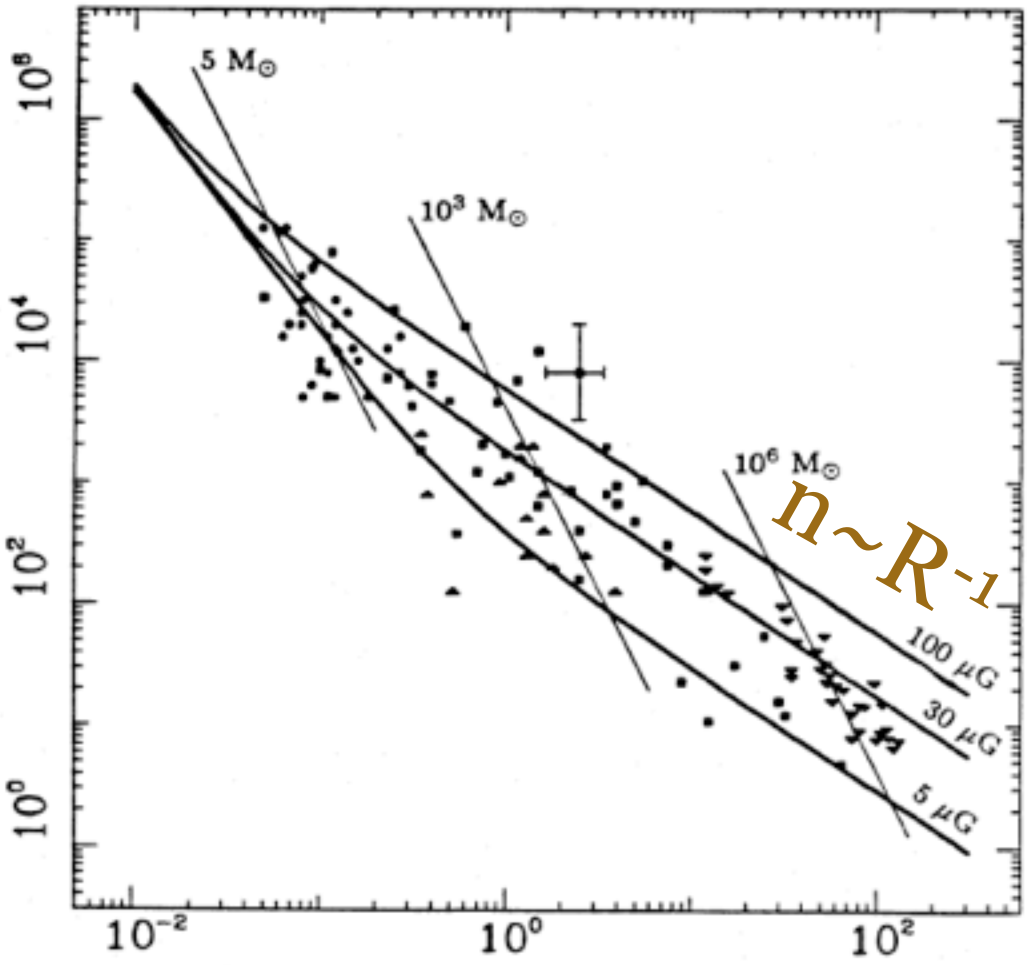
NON-THERMAL velocity disperson (line width)



$\sigma \sim R^{0.5}$

density



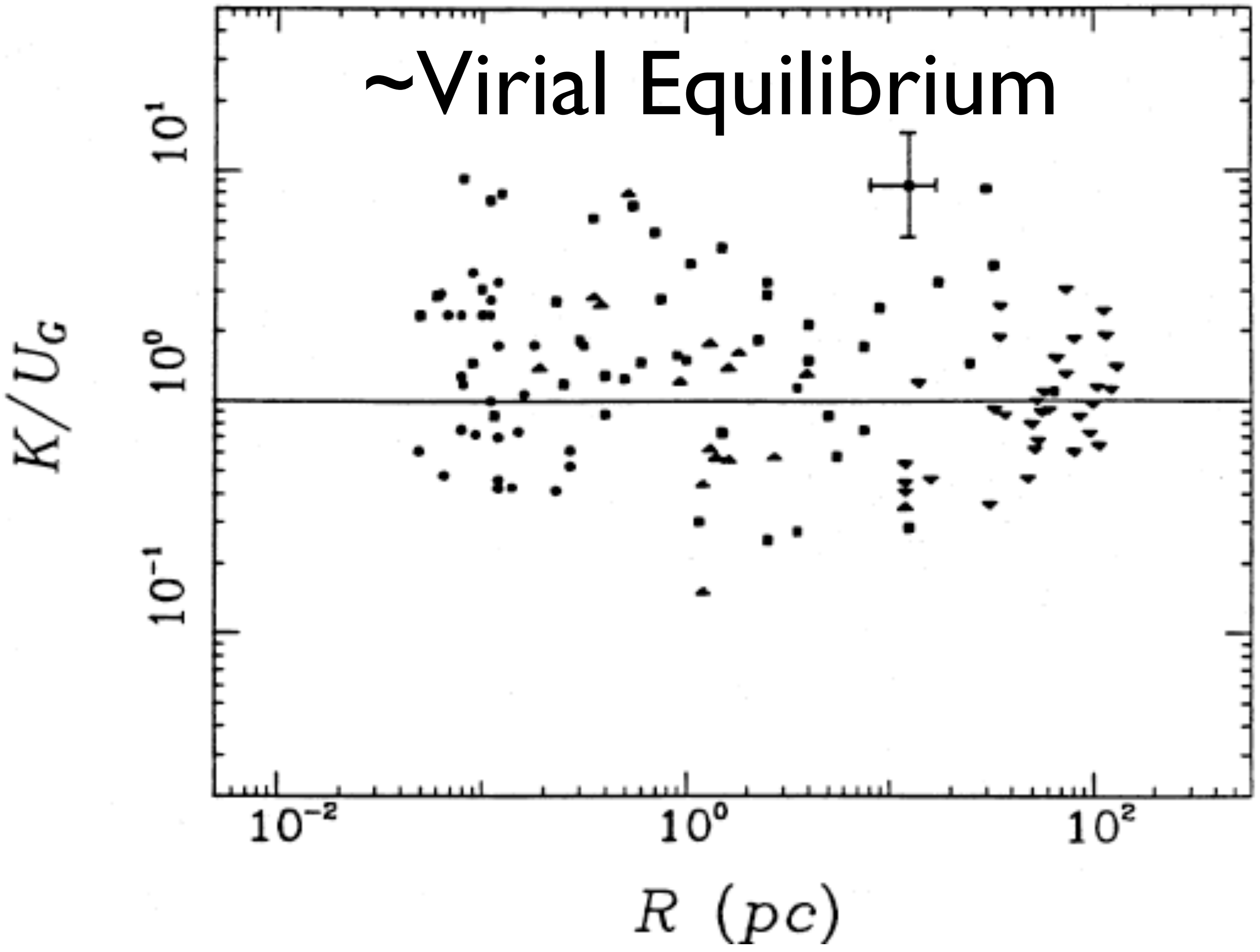
$n \sim R^{-1}$

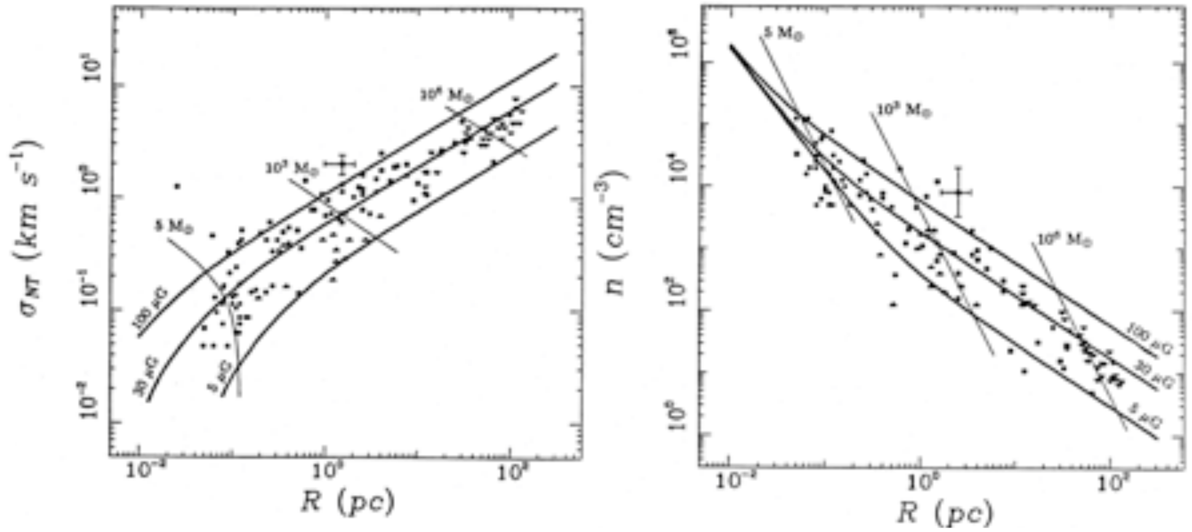
size (R)

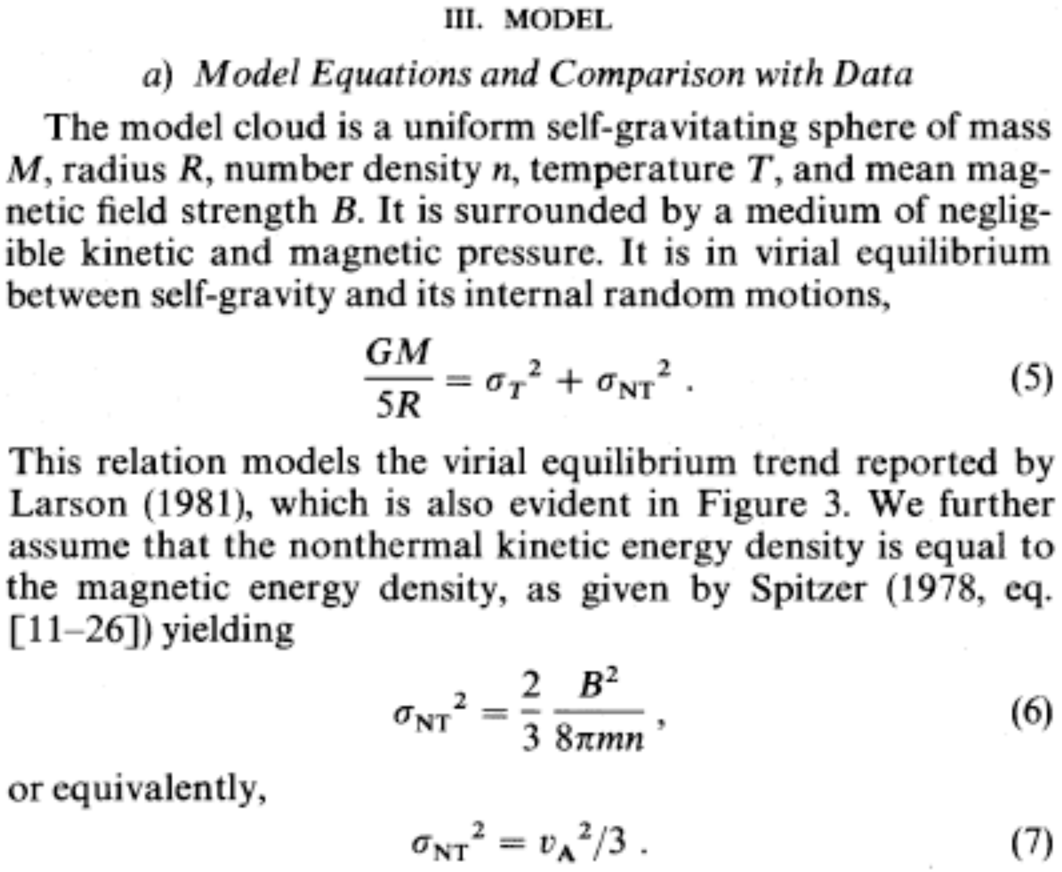
size (R)

lines assume various field strengths...

“Indirect Evidence”







III. MODEL

a) Model Equations and Comparison with Data

The model cloud is a uniform self-gravitating sphere of mass *M*, radius *R*, number density *n*, temperature *T*, and mean magnetic field strength *B*. It is surrounded by a medium of negligible kinetic and magnetic pressure. It is in virial equilibrium between self-gravity and its internal random motions,

$$\frac{GM}{5R} = \sigma_T{}^2 + \sigma_{\rm NT}{}^2 \ . \qquad (5)$$

This relation models the virial equilibrium trend reported by Larson (1981), which is also evident in Figure 3. We further assume that the nonthermal kinetic energy density is equal to the magnetic energy density, as given by Spitzer (1978, eq. [11–26]) yielding

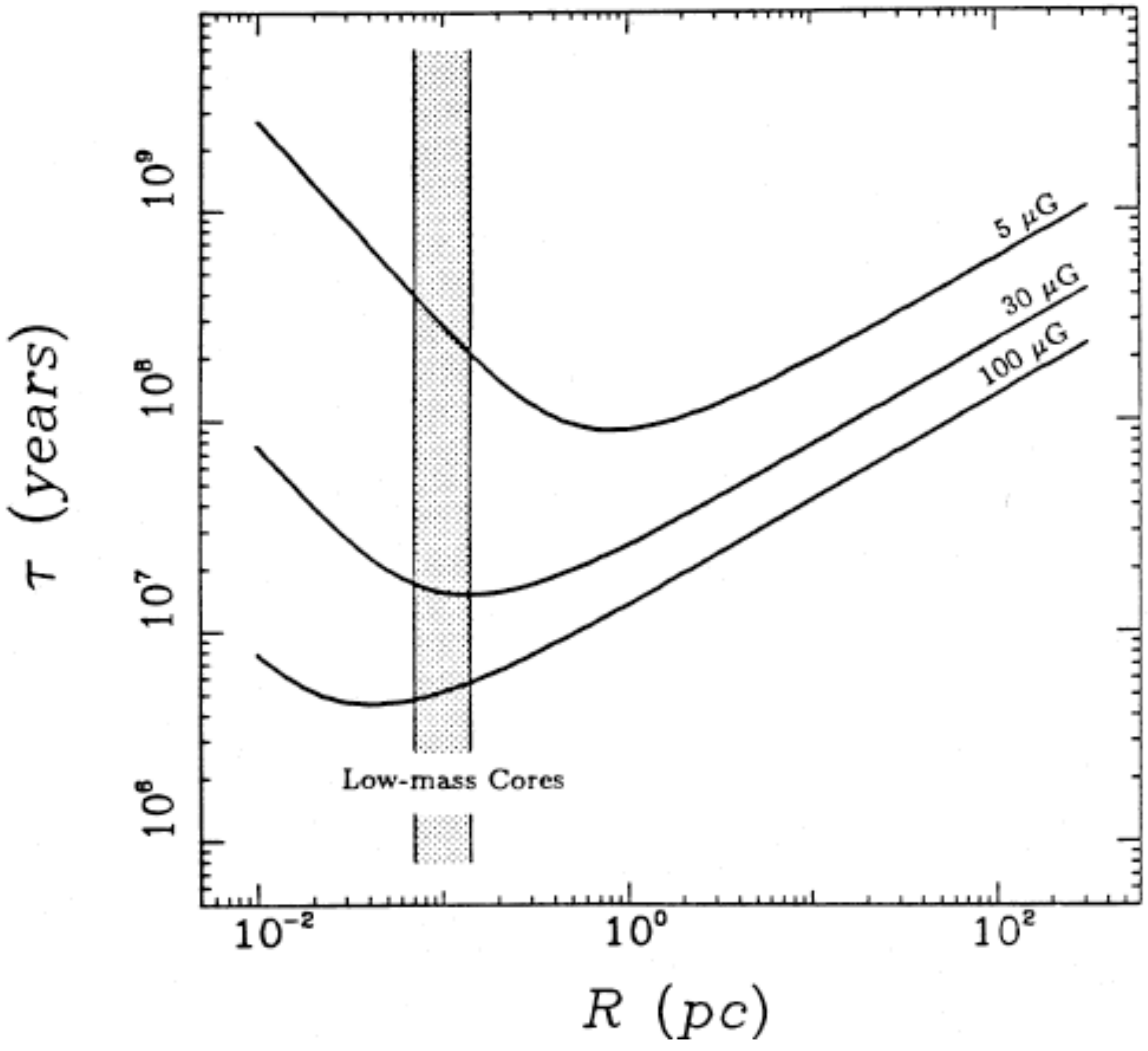
$$\sigma_{\rm NT}{}^2 = \frac{2}{3}\frac{B^2}{8\pi m n} \ , \qquad (6)$$

or equivalently,

$$\sigma_{\rm NT}{}^2 = v_{\rm A}{}^2/3 \ . \qquad (7)$$

MODEL: Assume non-thermal energy is magnetically controlled... ~replace “sound speed” with “Alfvén speed”

“Indirect Evidence”: Bonus Result



MODEL: Also predicts characteristic core sizes could be related to a minimum in the “ambipolar diffusion” time.

Magnetic Origin of Supersonic Linewidths??

THE ASTROPHYSICAL JOURNAL, **329**:392–405, 1988 June 1

MAGNETIC MOLECULAR CLOUDS: INDIRECT EVIDENCE FOR MAGNETIC SUPPORT AND AMBIPOLAR DIFFUSION

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ABSTRACT

Over 120 measurements of molecular cloud size R, velocity dispersion σ, and density n are compiled to investigate the well-known relations $\sigma \propto R^{1/2}$, $n \propto R^{-1}$, and $GM/R \approx \sigma^2$. For cloud sizes from 0.1 to 100 pc, a crude virial equilibrium model of thermal and magnetic support against gravity fits the observed trends, provided the one free parameter, magnetic field strength, is 15–40 μG. This range is comparable to that of available field strength measurements in self-gravitating clouds. Low-mass dense cores have a significantly smaller ratio of nonthermal kinetic energy to gravitational potential energy than do larger clouds. According to the equilibrium model these cores have substantially less magnetic support against gravity, and substantially smaller flux-to-mass ratio, than do the larger clouds. This relatively weak magnetic support may arise from ambipolar diffusion: for constant field strength, a model cloud with thermal and magnetic balance against gravity has a critical size for which ambipolar diffusion is fastest, and this size is close to that of typical low-mass cores, ~0.1 pc. In contrast, more massive cores have equilibrium field strength 3–10 times greater than do their lower density surroundings. The model of magnetic and thermal support can be tested by new observations of the Zeeman effect in the centimeter-wavelength spectral lines of OH and H.

Subject headings: hydromagnetics — interstellar: magnetic fields — interstellar: molecules

I. INTRODUCTION

Spectral lines in molecular clouds have long been recognized to be supersonic (e.g., Barrett, Meeks, and Weinreb 1964), and the origin of these supersonic motions is a fundamental problem in molecular cloud physics. In the middle 1970s it was recognized that these motions are unlikely to arise from complete gravitational collapse of molecular clouds, because then the formation rate of stellar mass in the Galaxy would greatly exceed the few $M_\odot$ yr^{-1} deduced from stellar observations (Zuckerman and Palmer 1974). The line widths are usually attributed to chaotic "turbulent" motions, but the physical characteristics of this turbulence remain uncertain. It was also suggested that the supersonic line widths may arise from magnetic motions, such as Alfvén waves (Arons and Max 1975), or other hydromagnetic waves (Mouschovias 1975), but direct observational tests of this and similar proposals have not been possible.

Important clues were found when relationships among cloud mass M, velocity dispersion σ, cloud size R, and number density n were recognized in a set of molecular line data assembled from many diverse observational studies. Larson (1981) demonstrated power-law trends of the approximate form $\sigma \propto R^{0.5}$ and $n \propto R^{-1}$ over three decades in R, and showed that the clouds approximately satisfy virial equilibrium, $\sigma^2 \approx GM/R$. Similar power-law relations were also found for similar clouds, selected and observed more systematically than in Larson's sample; and for both smaller and larger clouds (Leung, Kutner, and Mead 1982; Myers 1983; Solomon and Sanders 1985; Dame *et al.* 1986). It is well established that these "Larson's Laws" represent a real and widespread phenomenon.

Only two of these three relations are independent: virial equilibrium and either the velocity dispersion–size law or the density–size law generates the other. Most attempts to account for these relations focus on the velocity dispersion–size law (Scalo 1987). Suggested explanations include the following: (1) mechanical "turbulence," possibly arising from a cascade of eddies as in Kolmogorov turbulence (Larson 1981), or from clump-clump collisions (Scalo and Pumphrey 1982)—the energy for these processes might originate from differential galactic rotation (Fleck 1983) or stellar winds (Silk 1985); (2) the clouds could typically lie at a point of critical equilibrium with a source of external pressure (Chieze 1987) or (3) could satisfy $\sigma \propto R^{1/2}$ by transporting angular momentum from smaller to larger scales, assuming constant torque density, or constant internal pressure, which could be magnetic (Henriksen and Turner 1984); (4) the clouds could typically harbor collisions among magnetically linked clumps (Elmegreen 1985; Falgarone and Puget 1986) or could generate nonthermal motions, including Alfvén waves, associated with substantial magnetic support (Franco, Tarsia, and Quiroga 1985; Mouschovias 1987*a*, *b*; Shu 1987).

In this paper we present an analysis which favors this last possibility (4) by comparing simple cloud models to more than 100 cloud observations. Preliminary versions of this work were presented by Goodman and Myers (1986) and by Myers (1987). For 14 clouds with magnetic field strength measured via the Zeeman effect, close agreement between observed field strengths and those predicted by the model in this paper was demonstrated by Myers and Goodman (1988). A closely related paper also appears in this volume (Fleck 1988).

The idea that interstellar magnetic fields may be coupled to gas motions was first discussed by Alfvén (1943) and Fermi (1949), and the pressure associated with cloud magnetic fields

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EVIDENCE FOR MAGNETIC AND VIRIAL EQUILIBRIUM IN MOLECULAR CLOUDS

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ABSTRACT

Recent measurements of the magnetic field strength, velocity dispersion, and size of 14 molecular clouds agree, within uncertainty of a factor of ~2, with the predictions of a simple model in which the magnetic, kinetic, and gravitational energies are all equal. The clouds range from extended dark clouds to massive dense cores associated with OH masers and compact H II regions. Their field strengths range over a factor of $\sim 10^3$, from ~10 μG to ~10 mG. This result suggests that the magnetic contribution to the internal motions and energy of many molecular clouds is crucial for cloud dynamics, cloud evolution, and star formation.

Subject headings: interstellar: magnetic fields — interstellar: matter

I. INTRODUCTION

Recently, our knowledge of magnetic fields in molecular clouds has improved, in three ways. First, field strengths of order 10–100 μG have been determined from the Zeeman effect in lines of H I and OH in at least eight well-defined molecular clouds (see Table 1 for references). These include nearby dark clouds, and more massive clouds with H II regions. Second, molecular lines have been observed from about 10 dense cores associated with compact H II regions, where the field strength is known from the Zeeman effect in OH maser lines. In some cases, the pointlike OH masers coincide in position and velocity with the more extended, nonmaser, emission or absorption [e.g., W3(OH); Reid, Myers, and Bieging 1987]. This suggests that the field strength deduced from the masers can be associated with properties deduced from the nonmaser observations. Third, for more than 120 self-gravitating clouds, the two trends (1) between cloud velocity dispersion σ and size R, $\sigma \propto R^{1/2}$, and (2) between cloud density n and R, $n \propto R^{-1}$, both noted by Larson (1981), have been fitted by a magnetic virial equilibrium model, with magnetic field strength within a factor ~2 of 30 μG (Henriksen and Turner 1984; Shu 1987; Myers 1987; Myers and Goodman 1988, hereafter MG). The success of this modeling constitutes indirect evidence that magnetic support may be a common feature of self-gravitating clouds.

The idea of magnetic support can now be tested directly for those clouds with measured field strengths. MG present two relations involving magnetic balance against gravity in a uniform, spherical cloud with negligible thermal support. For convenience we denote the magnetic, kinetic, and gravitational terms of the virial theorem by M, K, and G. The first relation, which is well known, requires only "magnetic" equilibrium ($\mathsf{M} \approx \mathsf{G}$; in this *Letter*, $\approx$ means equal within a factor of order 2):

$$B_{\rm eq} \approx 3\pi m \left(\frac{G}{5}\right)^{1/2} N \,, \qquad (1)$$

where m is the mean molecular mass, and N is the mean column density (Elmegreen 1978; Chandrasekhar and Fermi 1953). A second relation requires both "magnetic" and "virial" equilibrium ($\mathsf{M} \approx \mathsf{K} \approx \mathsf{G}$). It relates the field strength $B_{\rm eq}$ to the mean FWHM line width Δv and to the cloud size R over which B and Δv are mean values:

$$B_{\rm eq} \approx \frac{3}{8 \ln 2}\left(\frac{5}{G}\right)^{1/2} \frac{\Delta v^2}{R} \,. \qquad (2)$$

MG note that in many cases Δv and R can be measured with much greater accuracy than can N, so that equation (2) may offer a more practical test than equation (1).

In this *Letter* we compare equilibrium field strengths, calculated from equation (2), with measured values for 14 clouds—all clouds known to us with enough suitable data to make the comparison. Our main conclusion is that the equilibrium and measured field strengths generally agree within a factor of ~2, for a wide range of clouds and field strengths.

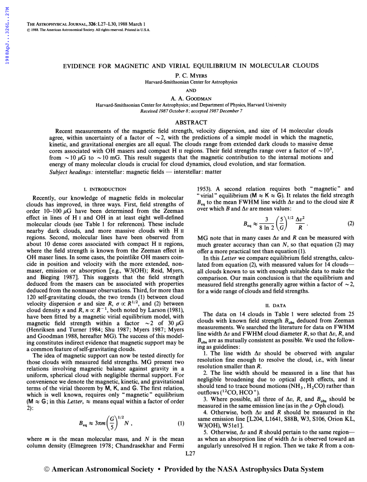
II. DATA

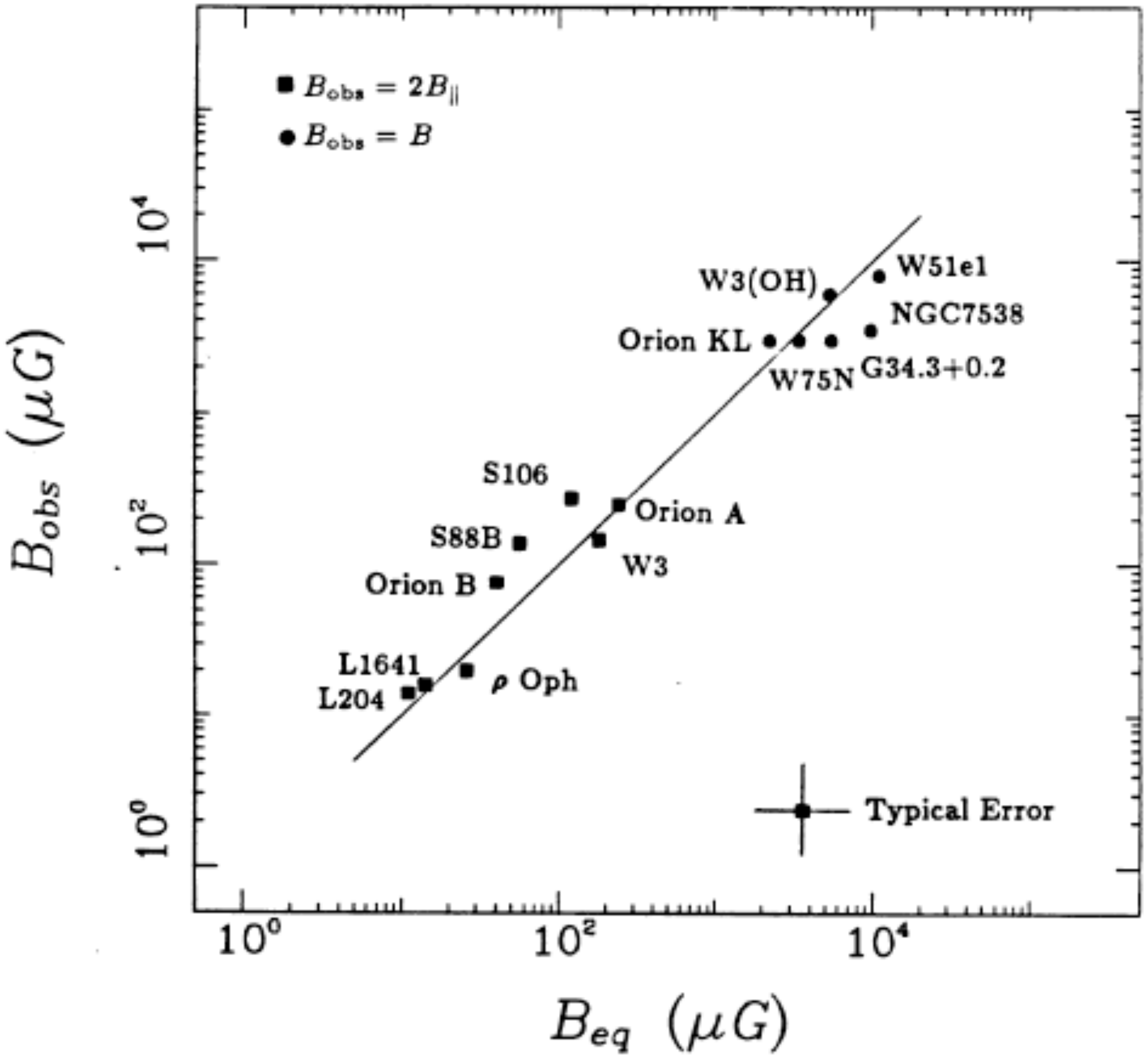
The data on 14 clouds in Table 1 were selected from 25 clouds with known field strength $B_{\rm obs}$ deduced from Zeeman measurements. We searched the literature for data on FWHM line width Δv and FWHM cloud diameter R, so that Δv, R, and $B_{\rm obs}$ are as mutually consistent as possible. We used the following as guidelines:

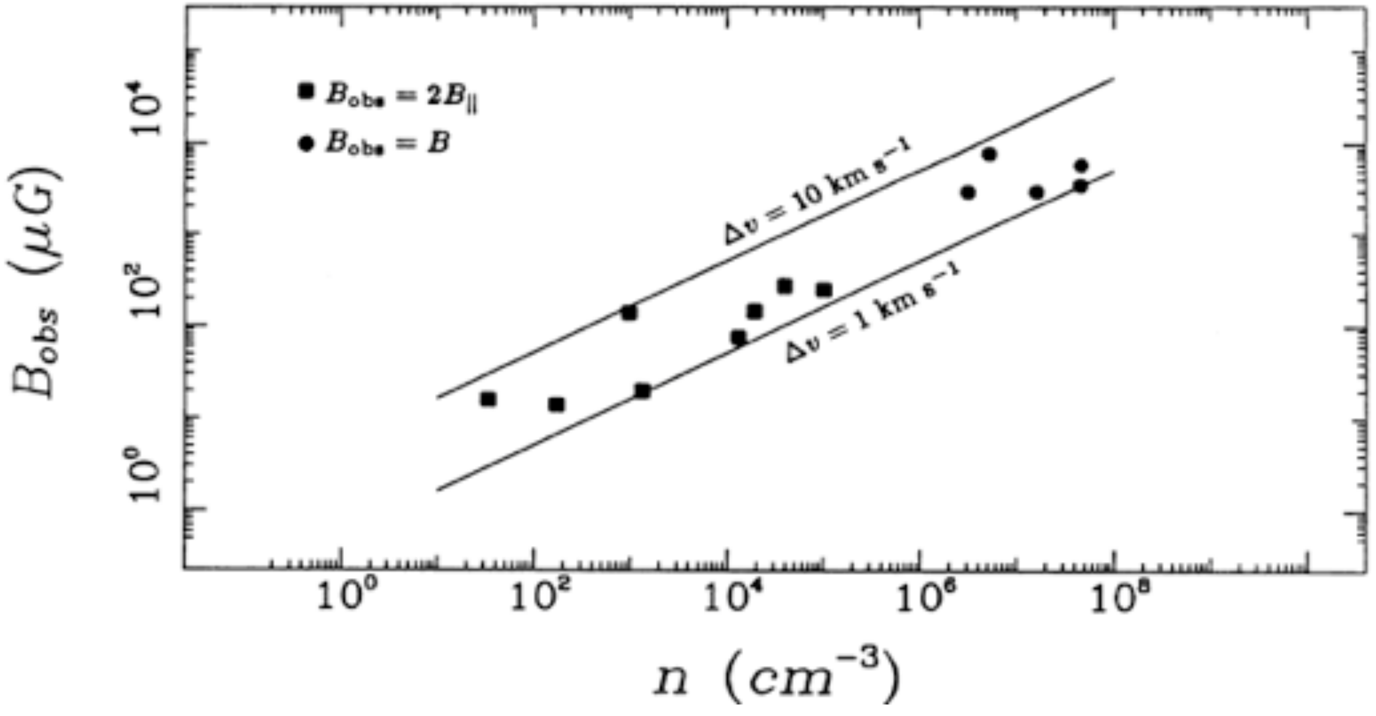
1. The line width Δv should be observed with angular resolution fine enough to resolve the cloud, i.e., with linear resolution smaller than R.
2. The line width should be measured in a line that has negligible broadening due to optical depth effects, and it should tend to trace bound motions (NH_3, H_2CO) rather than outflows (^{12}CO, HCO^+).
3. Where possible, all three of Δv, R, and $B_{\rm obs}$ should be measured in the same emission line (as in the ρ Oph cloud).
4. Otherwise, both Δv and R should be measured in the same emission line [L204, L1641, S88B, W3, S106, Orion KL, W3(OH), W51e1].
5. Otherwise, Δv and R should pertain to the same region—as when an absorption line of width Δv is observed toward an angularly unresolved H II region. Then we take R from a con-

Myers & Goodman 1988a,b

“Direct Evidence”



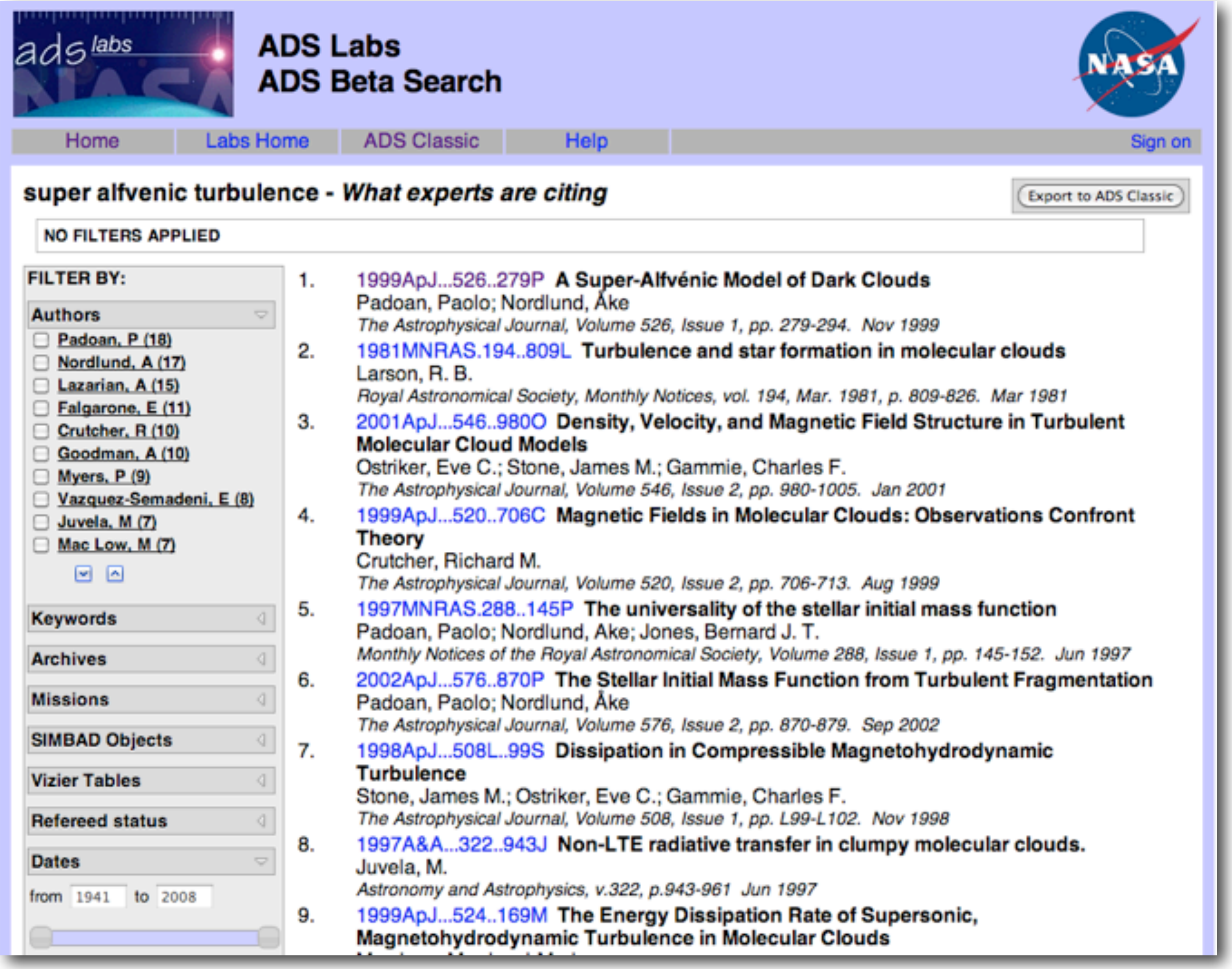




$$B_{eq} \approx \left(\frac{3\pi m}{2 \ln 2} \right)^{1/2} \Delta v \; n^{1/2}$$

1988 Magnetic field (Zeeman) observations were consistent with MODEL predictions. Modern results show that virial equipartition is actually an UPPER ENVELOPE on B-field values, and many regions are “super-Alfvénic” in that field is field is too weak to explain line width. (See Padoan et al.’s work on super-Alfvénic turbulence.)

For more on super-Alfvénic Turbulence go here...



super alfvenic turbulence - *What experts are citing*

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- ☐ Lazarian, A (15)
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- ☐ Crutcher, R (10)
- ☐ Goodman, A (10)
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Keywords

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Dates

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   Juvela, M.
   Astronomy and Astrophysics, v.322, p.943-961 Jun 1997
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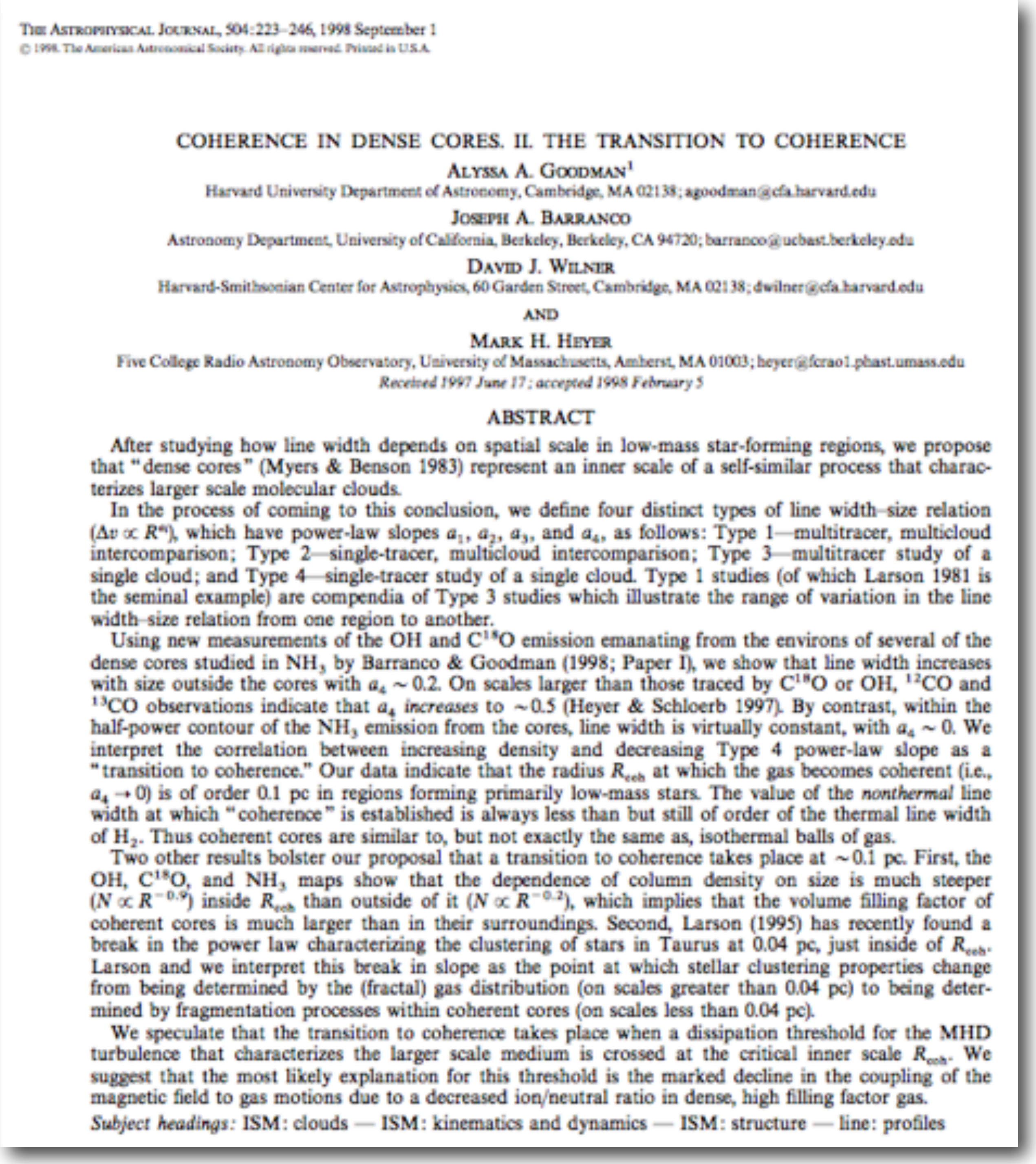
Is there a transition to a "thermal" regime? What happens there?



THE ASTROPHYSICAL JOURNAL, 504:223–246, 1998 September 1

COHERENCE IN DENSE CORES. II. THE TRANSITION TO COHERENCE

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ABSTRACT

After studying how line width depends on spatial scale in low-mass star-forming regions, we propose that "dense cores" (Myers & Benson 1983) represent an inner scale of a self-similar process that characterizes larger scale molecular clouds.

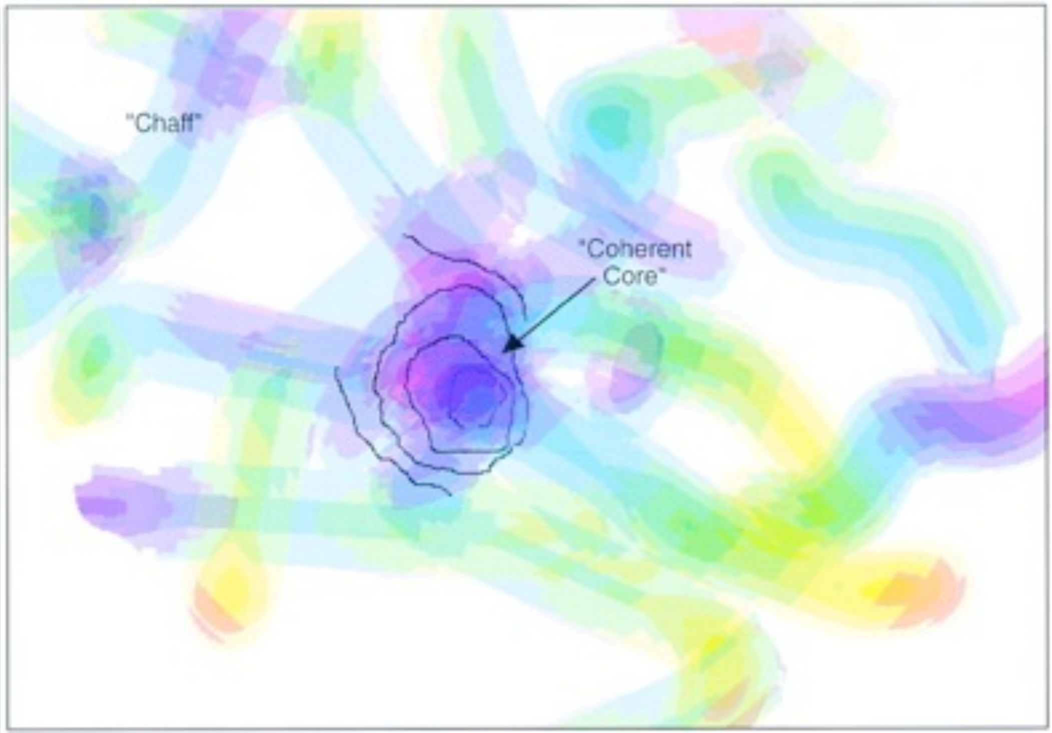
In the process of coming to this conclusion, we define four distinct types of line width–size relation ($\Delta v \propto R^{a}$), which have power-law slopes a_1, a_2, a_3, and a_4, as follows: Type 1—multitracer, multicloud intercomparison; Type 2—single-tracer, multicloud intercomparison; Type 3—multitracer study of a single cloud; and Type 4—single-tracer study of a single cloud. Type 1 studies (of which Larson 1981 is the seminal example) are compendia of Type 3 studies which illustrate the range of variation in the line width–size relation from one region to another.

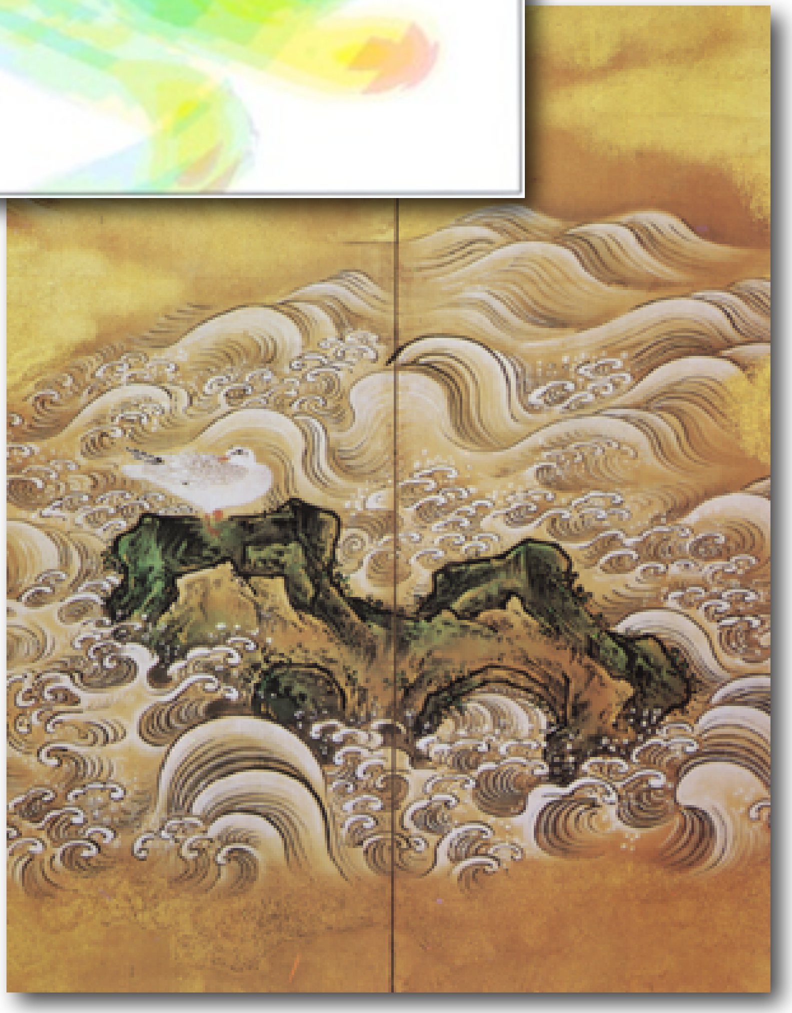
Using new measurements of the OH and $C^{18}O$ emission emanating from the environs of several of the dense cores studied in NH_3 by Barranco & Goodman (1998; Paper I), we show that line width increases with size outside the cores with $a_4 \sim 0.2$. On scales larger than those traced by $C^{18}O$ or OH, ^{12}CO and ^{13}CO observations indicate that a_4 *increases* to ~ 0.5 (Heyer & Schloerb 1997). By contrast, within the half-power contour of the NH_3 emission from the cores, line width is virtually constant, with $a_4 \sim 0$. We interpret the correlation between increasing density and decreasing Type 4 power-law slope as a "transition to coherence." Our data indicate that the radius R_{coh} at which the gas becomes coherent (i.e., $a_4 \rightarrow 0$) is of order 0.1 pc in regions forming primarily low-mass stars. The value of the *nonthermal* line width at which "coherence" is established is always less than but still of order of the thermal line width of H_2. Thus coherent cores are similar to, but not exactly the same as, isothermal balls of gas.

Two other results bolster our proposal that a transition to coherence takes place at ~ 0.1 pc. First, the OH, $C^{18}O$, and NH_3 maps show that the dependence of column density on size is much steeper ($N \propto R^{-0.9}$) inside R_{coh} than outside of it ($N \propto R^{-0.2}$), which implies that the volume filling factor of coherent cores is much larger than in their surroundings. Second, Larson (1995) has recently found a break in the power law characterizing the clustering of stars in Taurus at 0.04 pc, just inside of R_{coh}. Larson and we interpret this break in slope as the point at which stellar clustering properties change from being determined by the (fractal) gas distribution (on scales greater than 0.04 pc) to being determined by fragmentation processes within coherent cores (on scales less than 0.04 pc).

We speculate that the transition to coherence takes place when a dissipation threshold for the MHD turbulence that characterizes the larger scale medium is crossed at the critical inner scale R_{coh}. We suggest that the most likely explanation for this threshold is the marked decline in the coupling of the magnetic field to gas motions due to a decreased ion/neutral ratio in dense, high filling factor gas.

Subject headings: ISM: clouds — ISM: kinematics and dynamics — ISM: structure — line: profiles





"Coherent Cores" proposed in 1998

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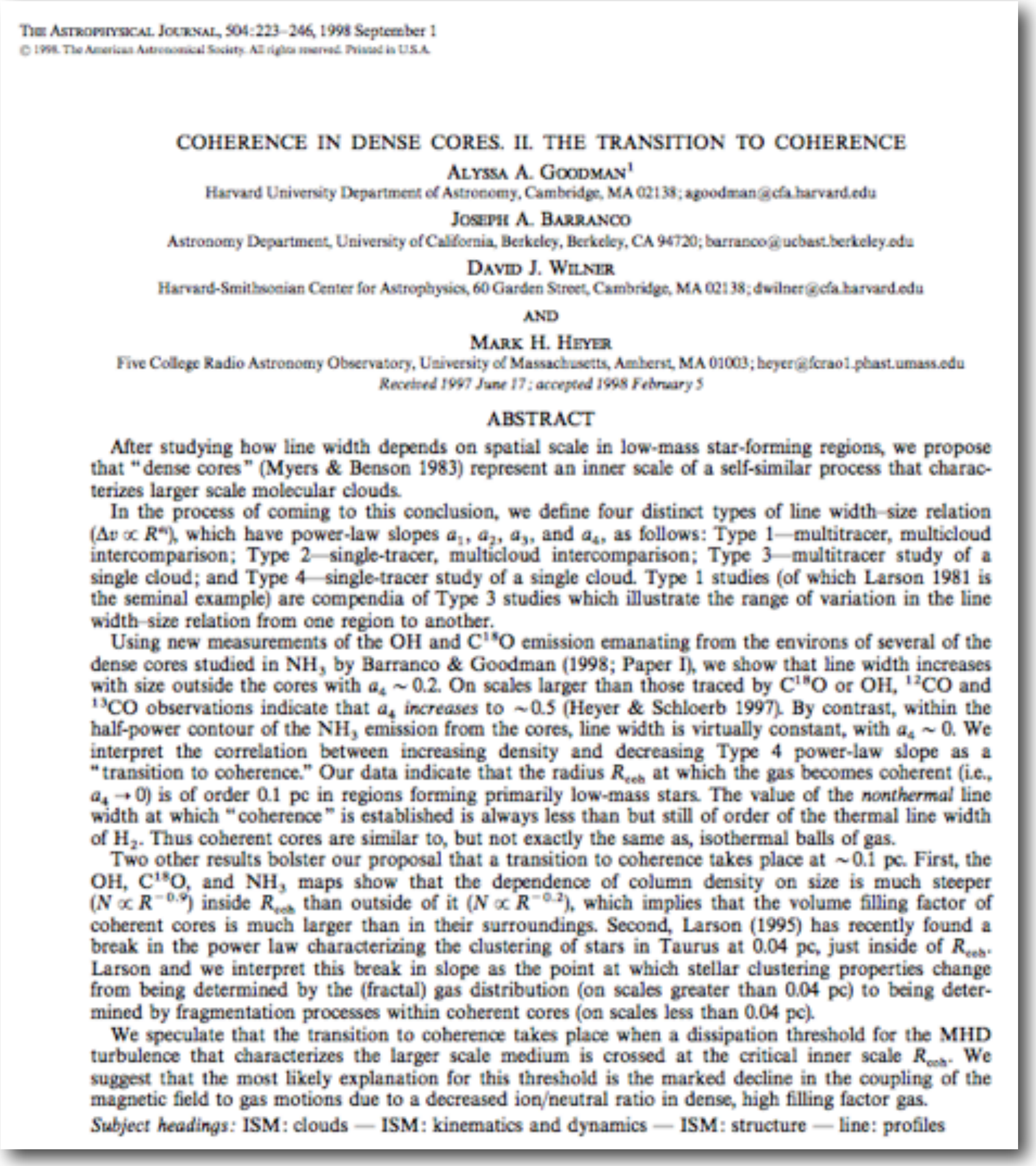

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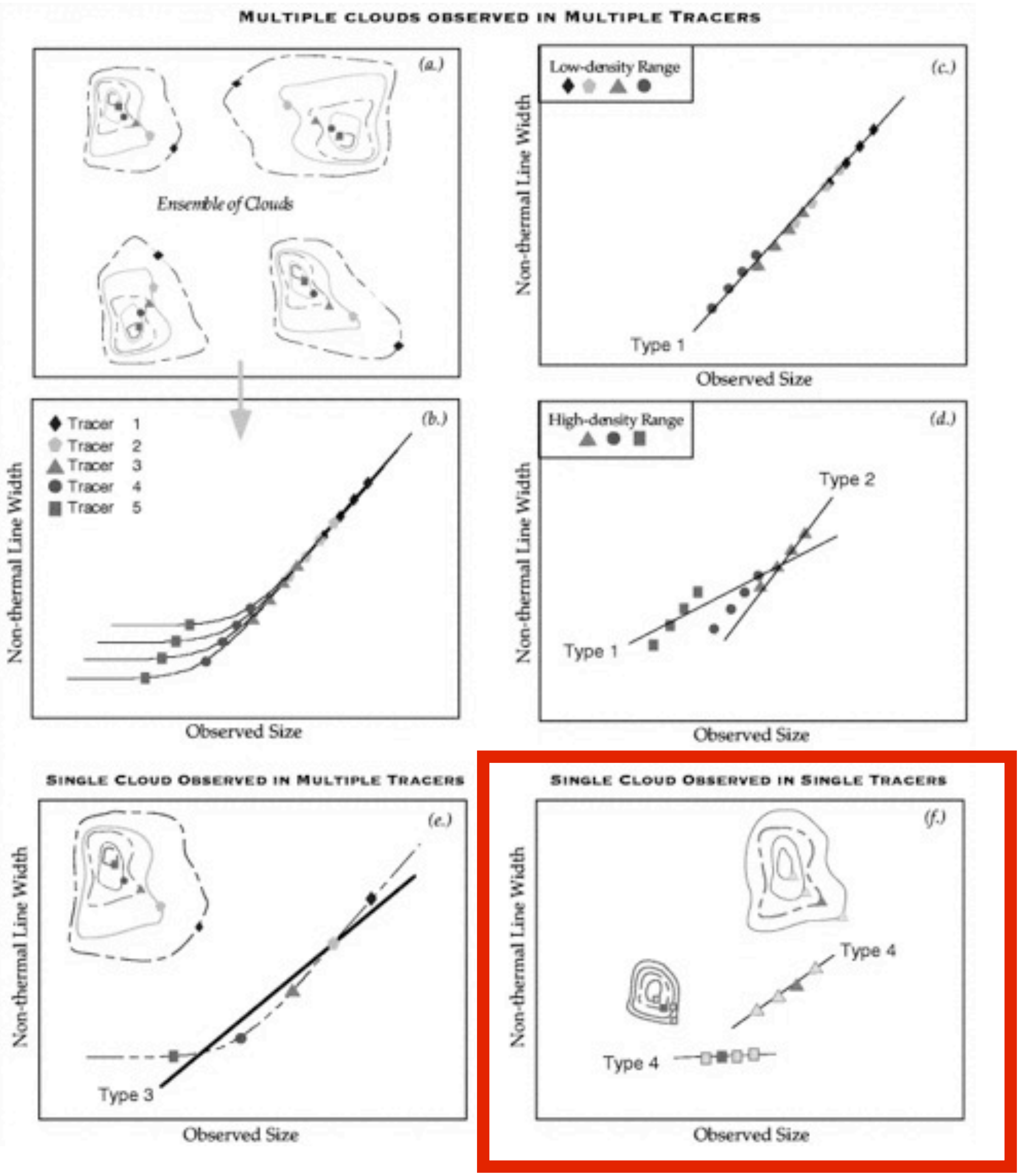
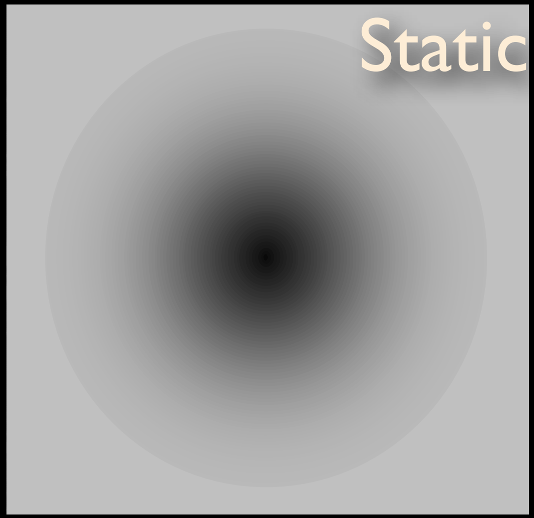
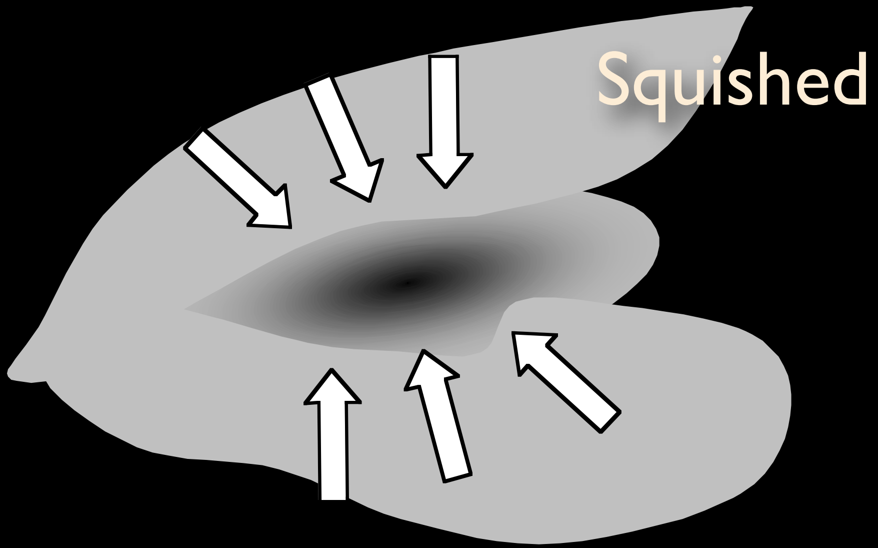
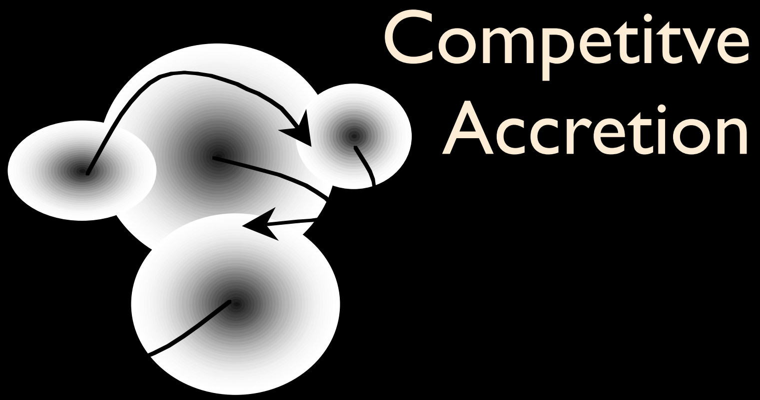


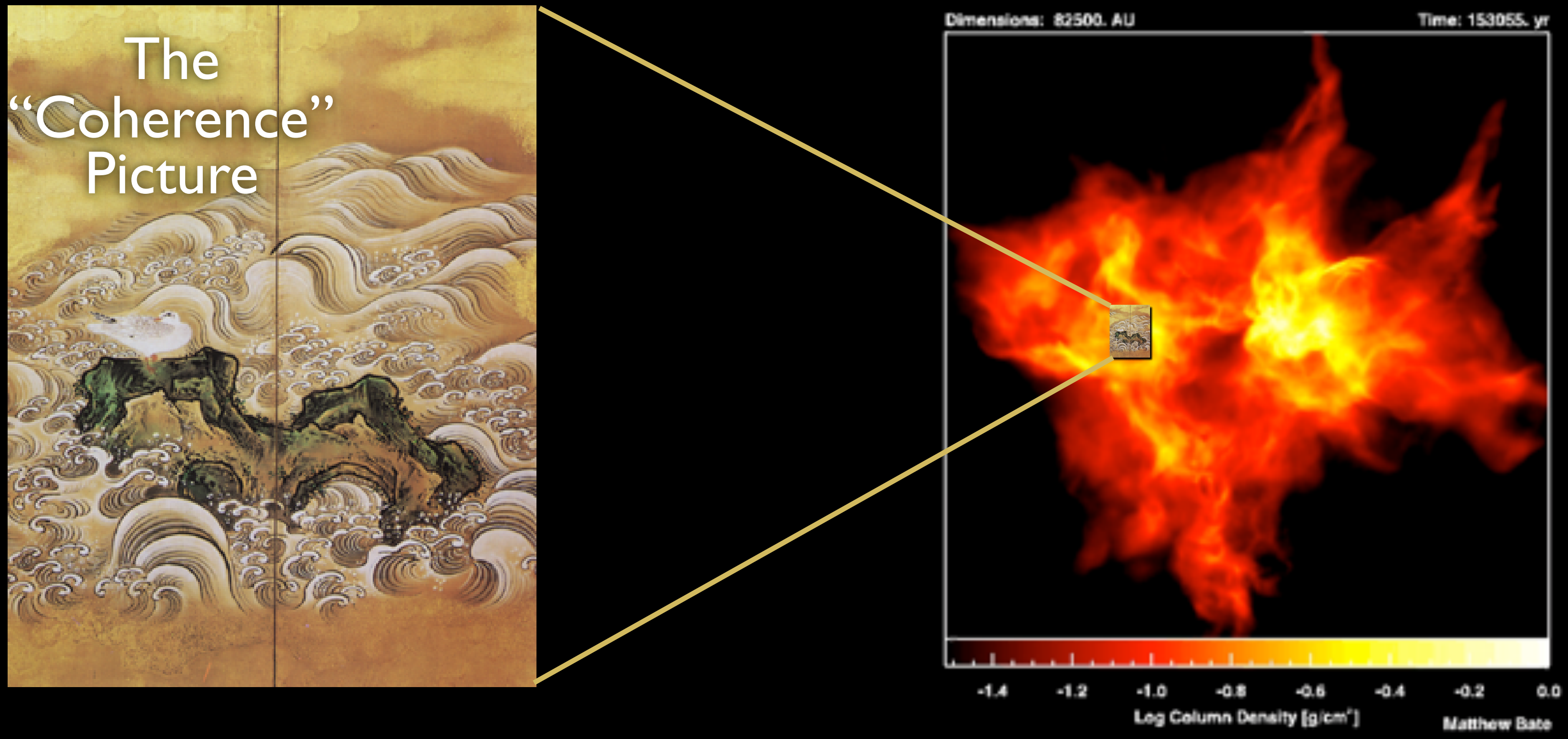
"Coherent Cores" proposed in 1998

“Modernist” Philosophy for non-Experts

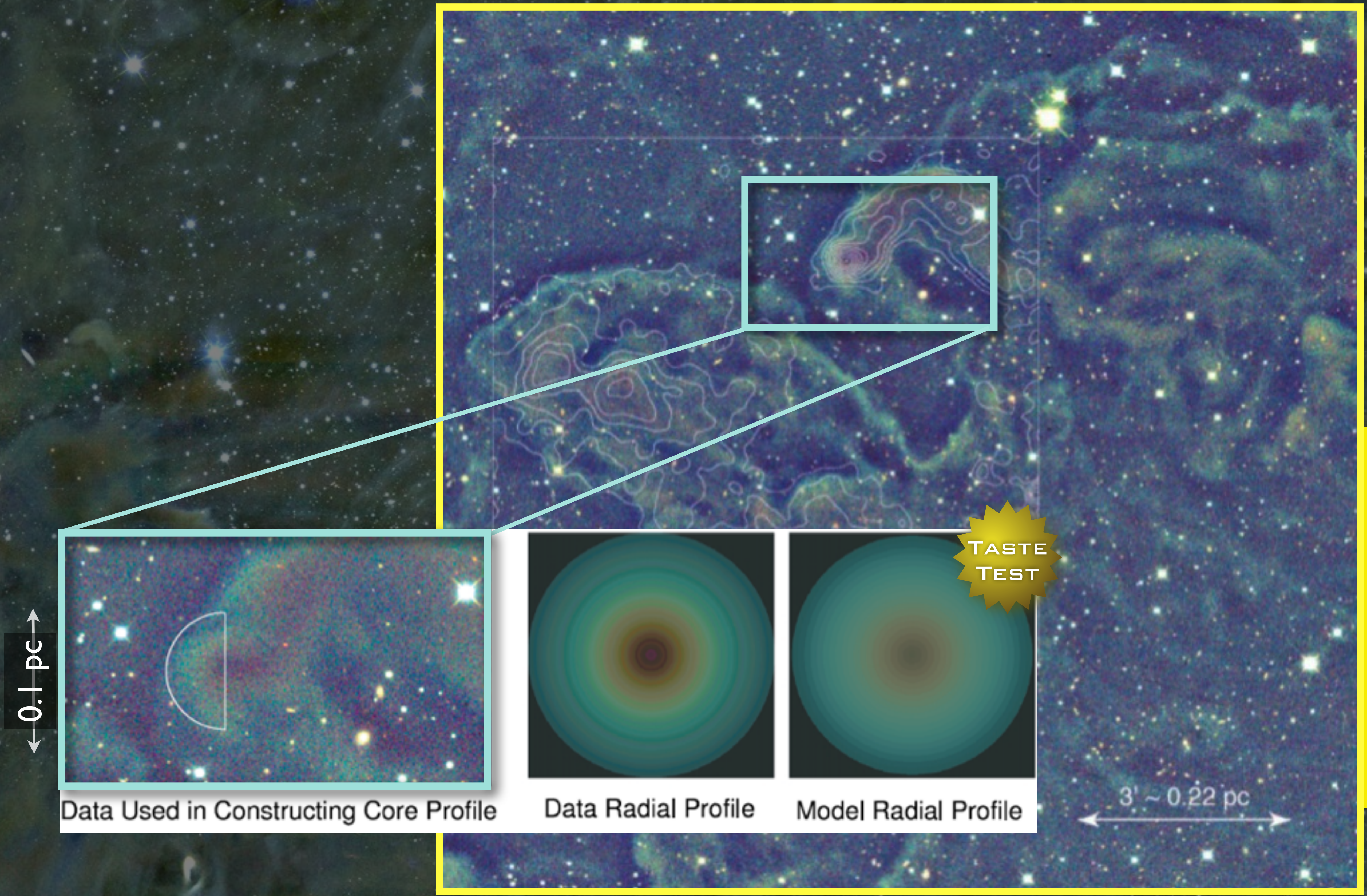




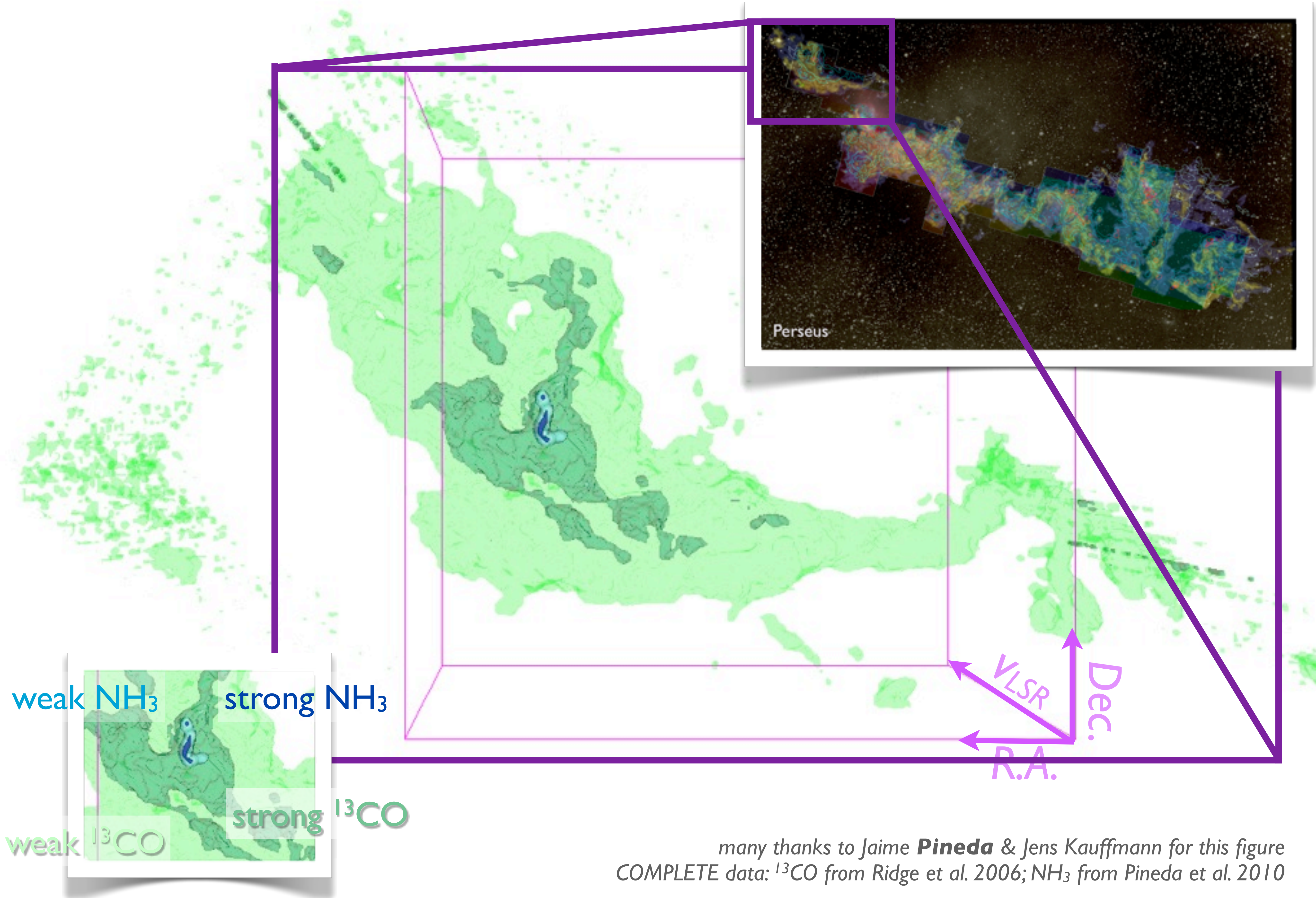




“Islands of Calm in a Turbulent Sea”

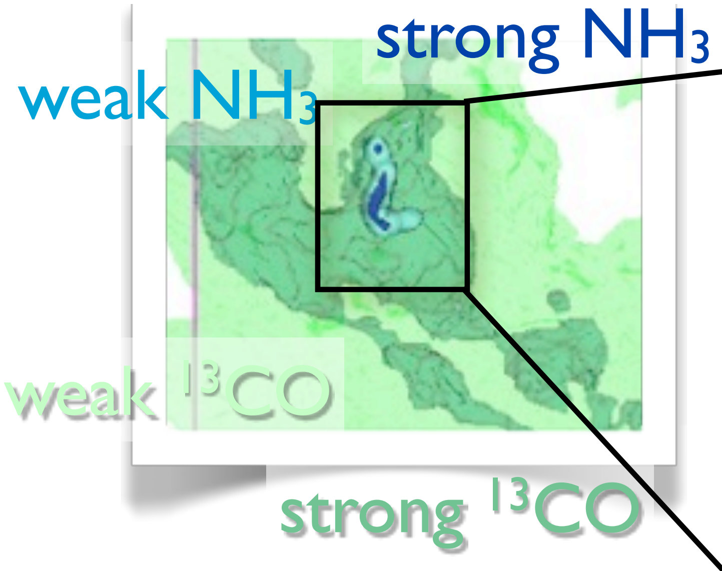


p-p-v structure of the B5 region in Perseus

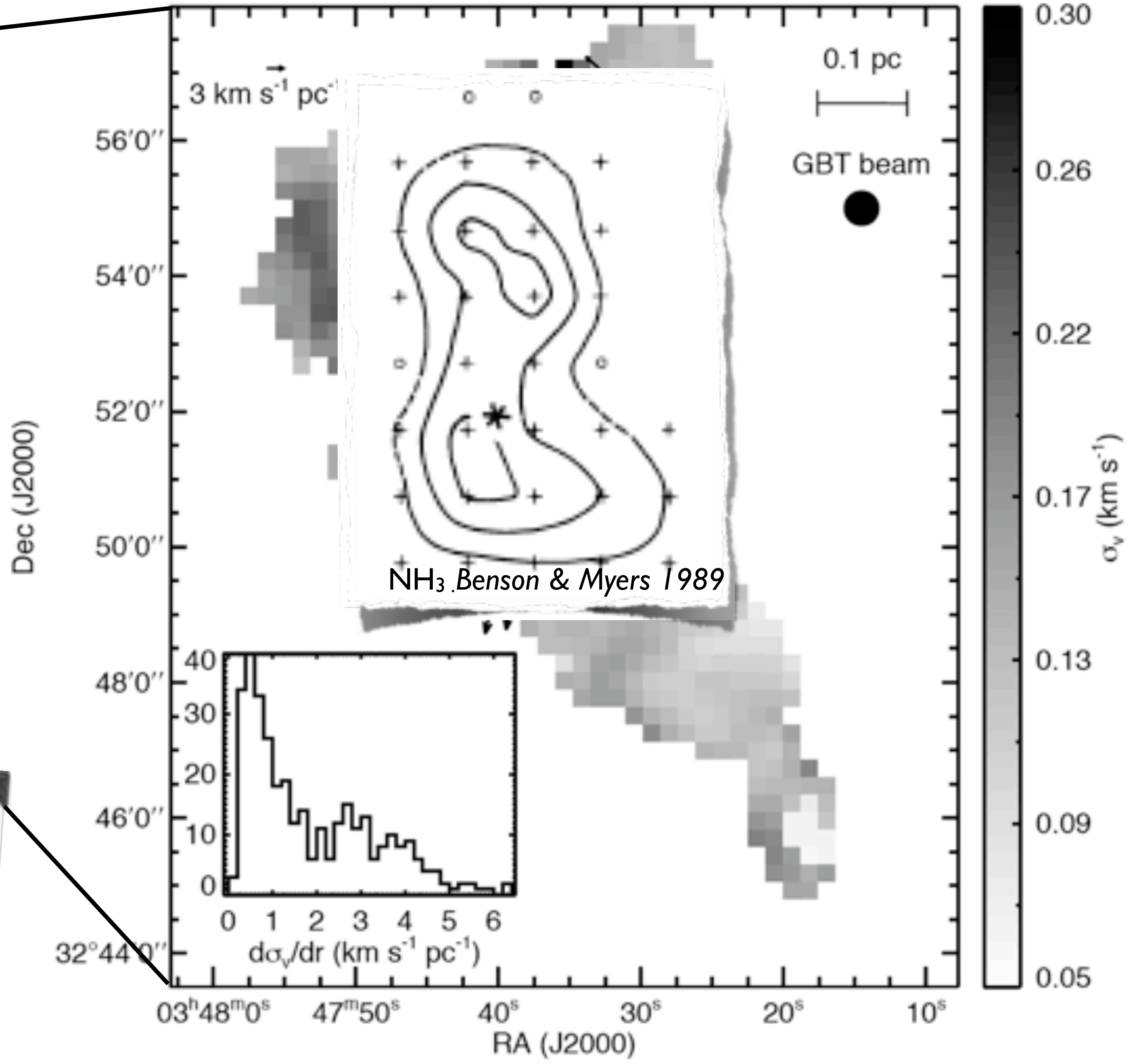


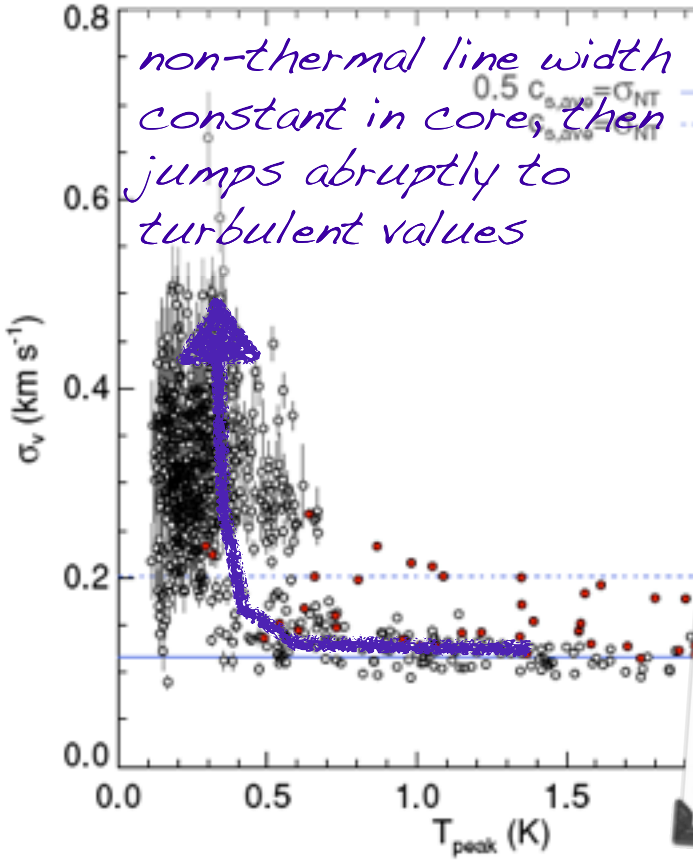
many thanks to Jaime ***Pineda*** *& Jens Kauffmann for this figure*
COMPLETE data: ^{13}CO from Ridge et al. 2006; NH$_3$ from Pineda et al. 2010

STRONG Evidence for Coherence in Dense Cores



greyscale shows NH_3 velocity dispersion, arrows show gradient in dispersion



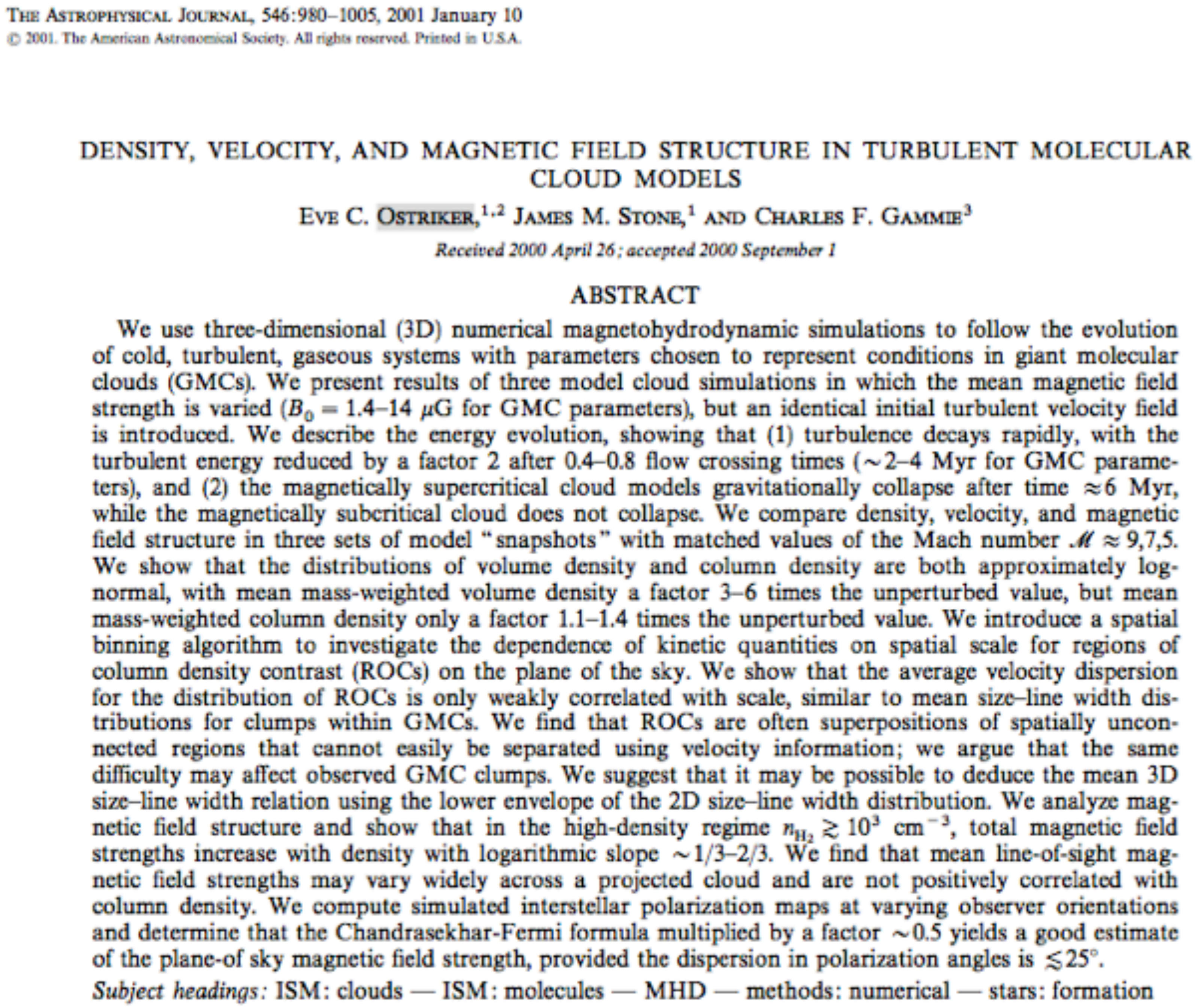


non-thermal line width constant in core, then jumps abruptly to turbulent values

GBT NH_3 observations of the B5 core (Pineda et al. 2010)

The rise of (MHD) simulations...

Around Y2K,
MHD Simulations Begin to Have Predictive Value…
Ostriker, Stone & Gammie 2001



The Astrophysical Journal, 546:980–1005, 2001 January 10

DENSITY, VELOCITY, AND MAGNETIC FIELD STRUCTURE IN TURBULENT MOLECULAR CLOUD MODELS

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ABSTRACT

We use three-dimensional (3D) numerical magnetohydrodynamic simulations to follow the evolution of cold, turbulent, gaseous systems with parameters chosen to represent conditions in giant molecular clouds (GMCs). We present results of three model cloud simulations in which the mean magnetic field strength is varied ($B_0 = 1.4$–$14\ \mu$G for GMC parameters), but an identical initial turbulent velocity field is introduced. We describe the energy evolution, showing that (1) turbulence decays rapidly, with the turbulent energy reduced by a factor 2 after 0.4–0.8 flow crossing times (∼2–4 Myr for GMC parameters), and (2) the magnetically supercritical cloud models gravitationally collapse after time ≈6 Myr, while the magnetically subcritical cloud does not collapse. We compare density, velocity, and magnetic field structure in three sets of model "snapshots" with matched values of the Mach number $\mathcal{M} \approx 9,7,5$. We show that the distributions of volume density and column density are both approximately log-normal, with mean mass-weighted volume density a factor 3–6 times the unperturbed value, but mean mass-weighted column density only a factor 1.1–1.4 times the unperturbed value. We introduce a spatial binning algorithm to investigate the dependence of kinetic quantities on spatial scale for regions of column density contrast (ROCs) on the plane of the sky. We show that the average velocity dispersion for the distribution of ROCs is only weakly correlated with scale, similar to mean size–line width distributions for clumps within GMCs. We find that ROCs are often superpositions of spatially unconnected regions that cannot easily be separated using velocity information; we argue that the same difficulty may affect observed GMC clumps. We suggest that it may be possible to deduce the mean 3D size–line width relation using the lower envelope of the 2D size–line width distribution. We analyze magnetic field structure and show that in the high-density regime $n_{\mathrm{H}_2} \gtrsim 10^3\ \mathrm{cm}^{-3}$, total magnetic field strengths increase with density with logarithmic slope ∼1/3–2/3. We find that mean line-of-sight magnetic field strengths may vary widely across a projected cloud and are not positively correlated with column density. We compute simulated interstellar polarization maps at varying observer orientations and determine that the Chandrasekhar-Fermi formula multiplied by a factor ∼0.5 yields a good estimate of the plane-of sky magnetic field strength, provided the dispersion in polarization angles is $\lesssim 25°$.

Subject headings: ISM: clouds — ISM: molecules — MHD — methods: numerical — stars: formation

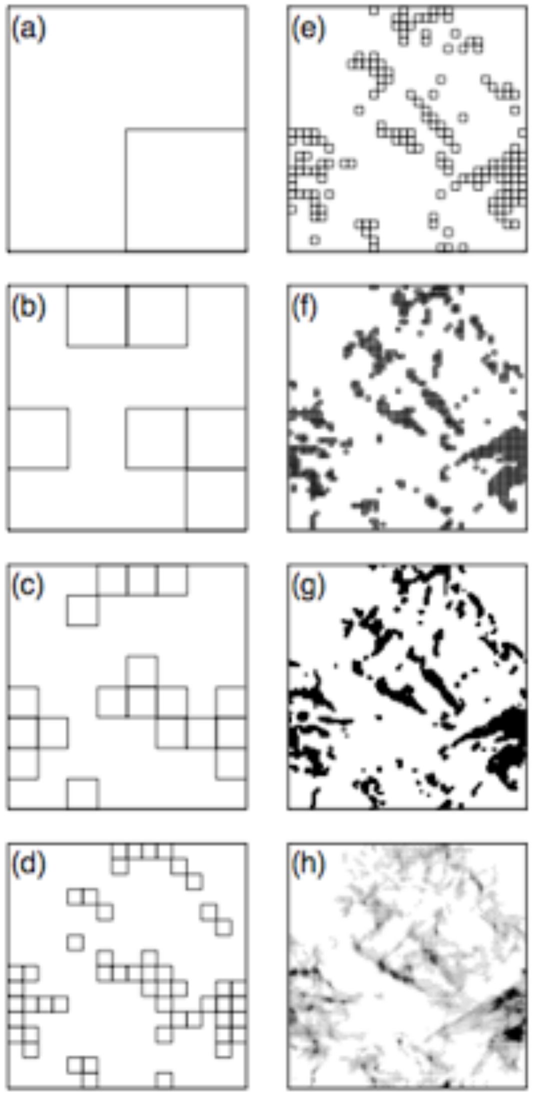

Fig. 9.—Identification of regions of contrast (ROCs) as a function of spatial scale for data from model snapshot B2. Figs. 1*a*–1*g* outline regions that meet the contrast criterion at increasingly fine spatial resolution. A gray-scale representation of the projected density is shown in Fig. 1*h* for comparison.

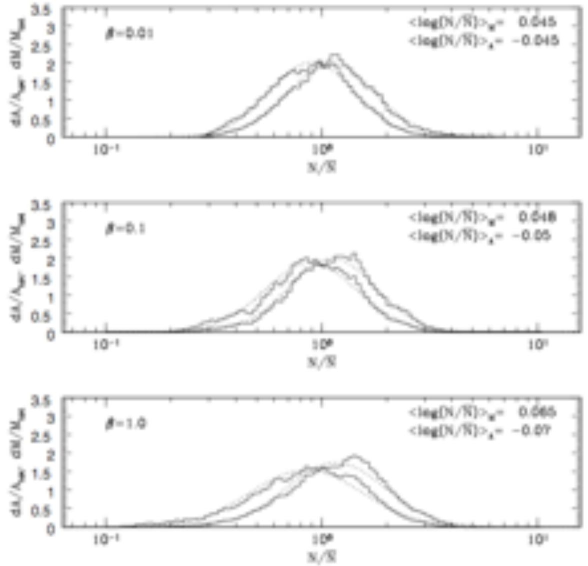

Fig. 5.—Comparative statistics of column density in three model snapshots (B2, C2, D2 from Table 2) with matched Mach numbers. Projection is along the $\hat{z}$ axis (perpendicular to the magnetic field). In each frame, left-displaced curves show *fraction of projected area* as a function of column density relative to the mean ($N/\bar{\rho}L \equiv N/\bar{N}$); right-displaced curves show *fraction of mass* as a function of $N/\bar{N}$. Dotted curves show lognormal distributions with the same mean and dispersion as in each model snapshot.

“Turbulent Fragmentation,” 2011

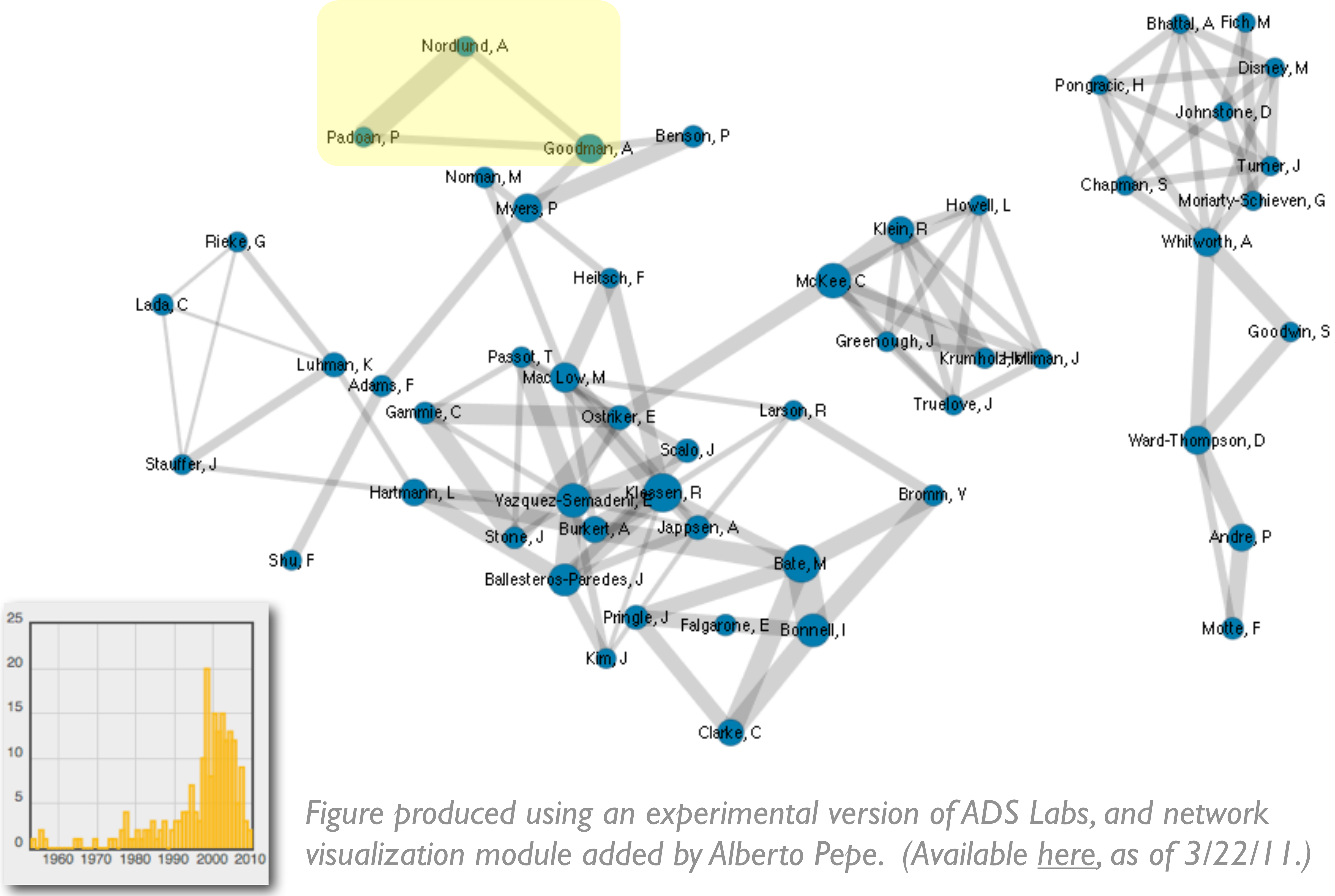

Figure produced using an experimental version of ADS Labs, and network visualization module added by Alberto Pepe. (Available here, as of 3/22/11.)

...and soon, you will hear how turbulent fragmentation can give the “IMF” through the “CMF”...
MAYBE!