From Filaments to Stars: a Theoretical Perspective

NRAO Filaments.

Oct. 10-11, 2014

Ralph E. Pudritz

Origins Institute, McMaster U.

Collaborators

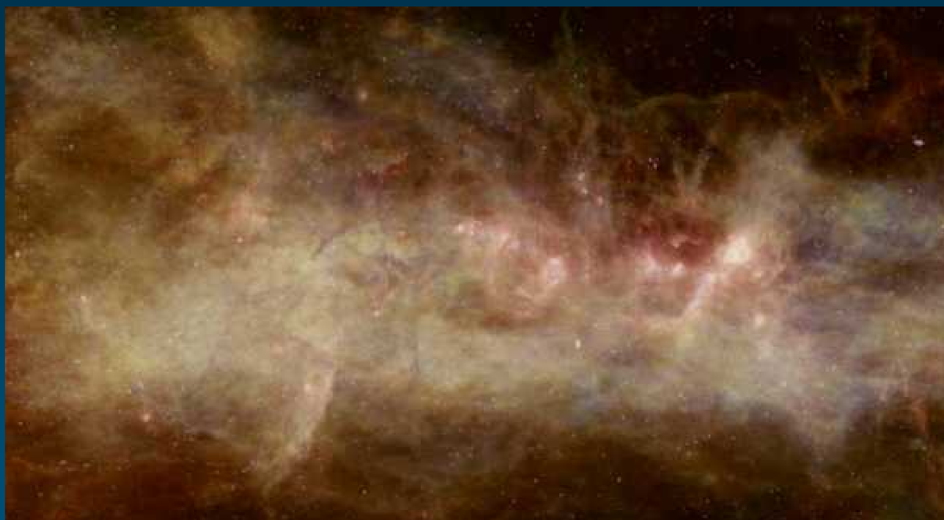
McMaster: Mikhail Klassen, Corey Howard, (Ph.D.s)
Helen Kirk (Banting Fellow), Bill Harris,
Samantha Pillsworth,

Hamburg/Heidelberg: Robi Banerjee, Daniel Seifried,
Ralf Klessen

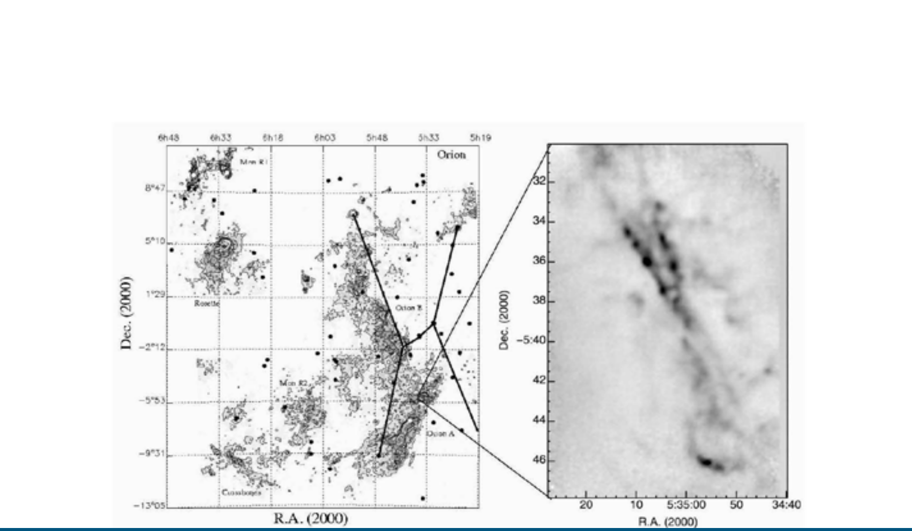
… and PPVI Andre et al team

The observations: several complex processes in play:

Turbulence controls structure formation ?



Diffuse Atomic Hydrogen in Milky Way (Canadian Galactic Plane Survey CGPS) near midplane towards Perseus.



Extinction map of Orion and Mon clouds (Cambresy 1998); right - Scuba continuum 850 micron map of 10 pc portion of cloud (Johnstone & Bally 2006)

Shocks and filaments on many scales, in diffuse and self-gravitating gas

Linked ?

Gravitational instability and star formation?

Herschel observations: clouds are filamentary

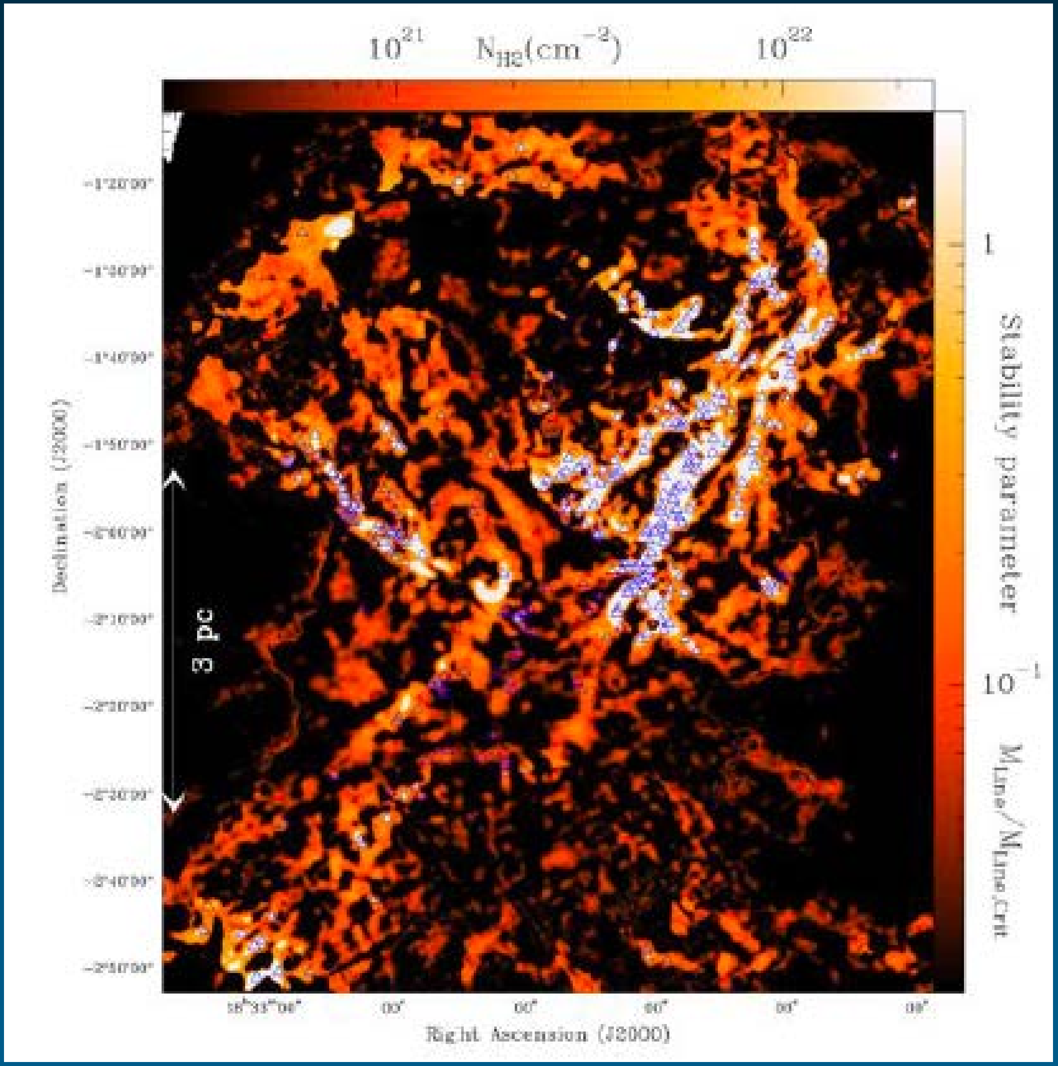
(Andre et al 2010, 2014 (PPVI) Menshchikov et al 2011, Henning et al 2010..)

- Cores are strongly associated with filaments

(> 70%; Polychroni et al 2013)

where

$$m > m_{crit} = 2\, c_s^2 / G$$

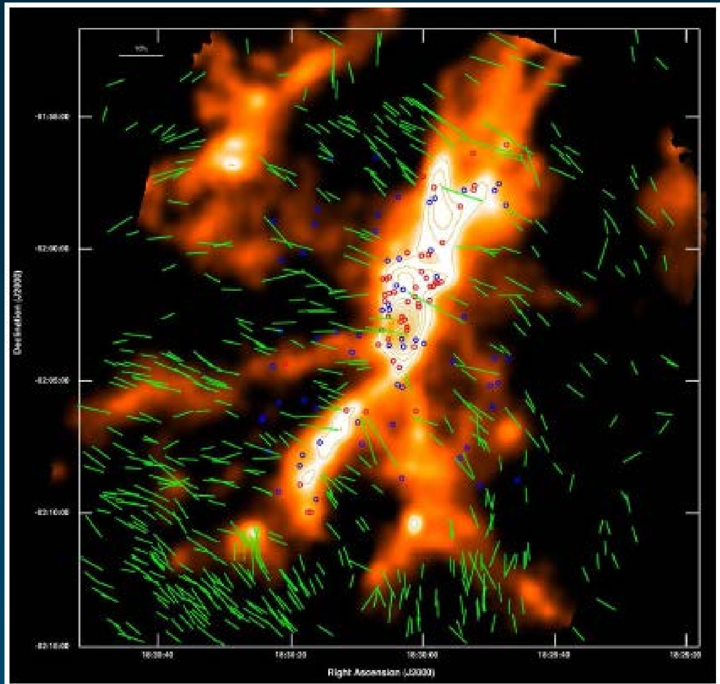


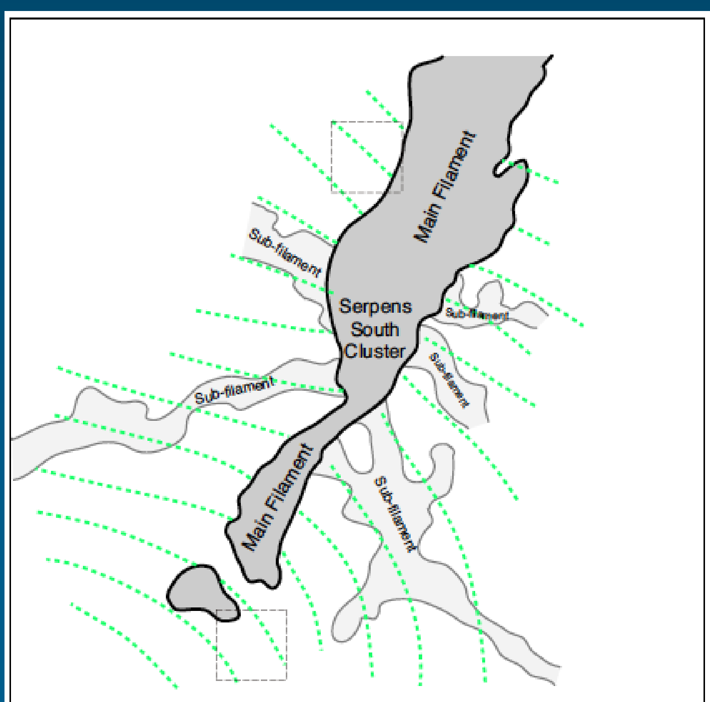
Aquila star forming cloud: Andre et al 2010

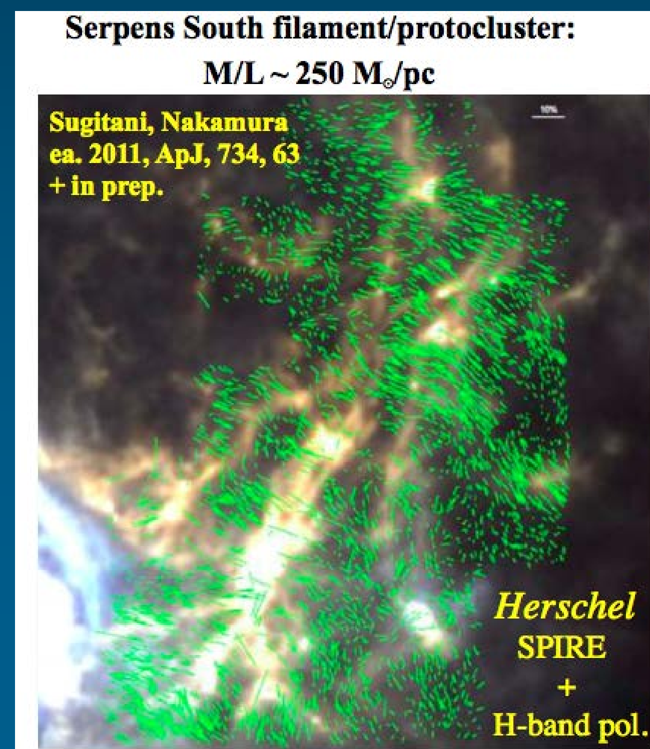
B fields - channel accretion flows or infall?

Infrared (H band) polarization overlaid on column density map + young stellar cluster

- Orientation – often perp to filament?
- Field strength ~ 100 μG





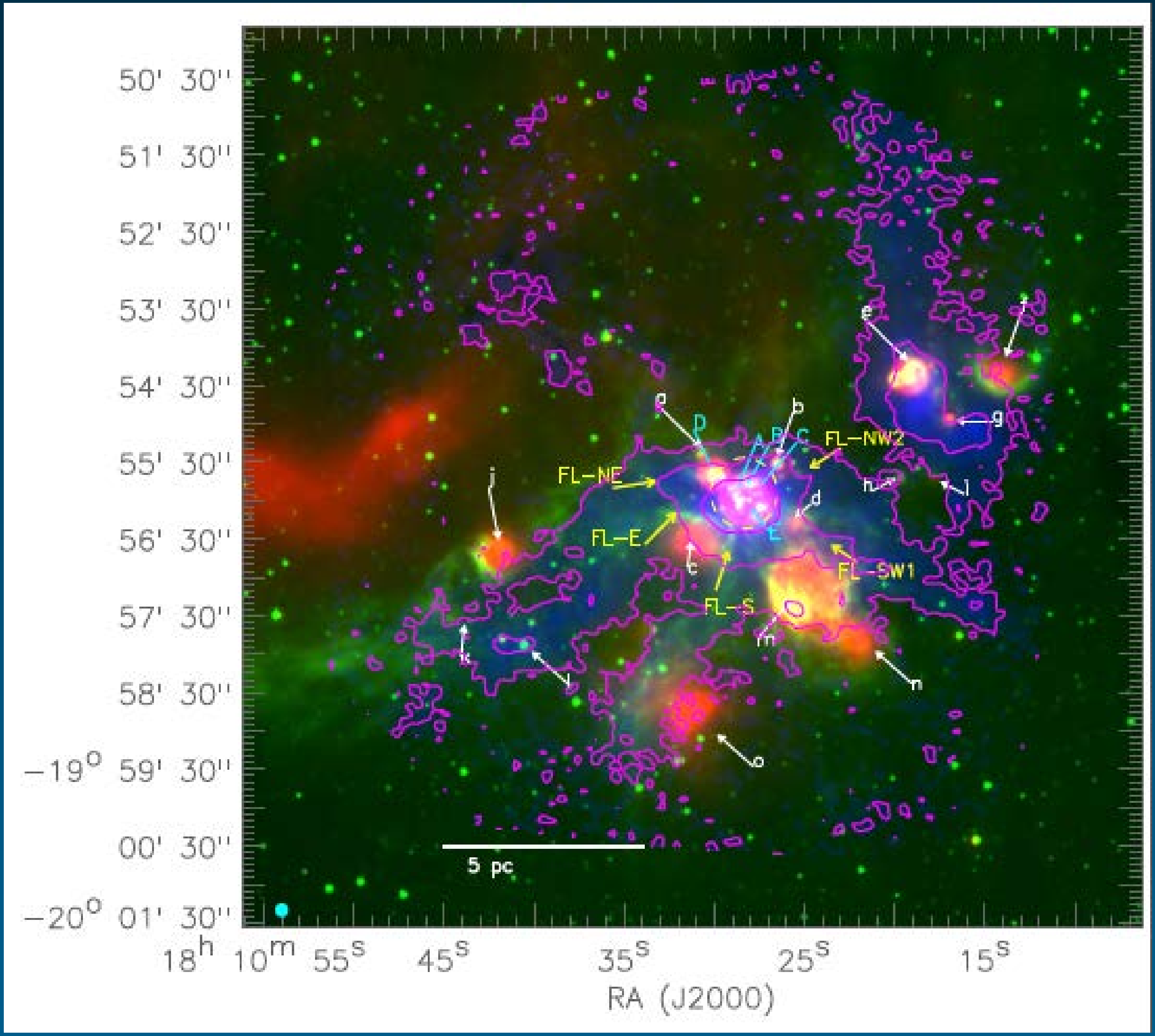


Radiative feedback from massive stars in young clusters – affect filaments? IMF?

Filaments and OB clusters, and HII regions in G10.6-0.4

(IRAM 30m MAMBO-2 bolometer array + SMA)

- 200 $M_{\odot}$ OB cluster
- Ultracompact HII regions: A-E



H.B. Liu et al 2011

I Equilibria and Their Fragmentation

Radial force balance for infinite cylinders with constant line mass

$$m \sim \rho\, r^{-2} \sim const \quad :$$

The gravitational force: $F_g = 2Gm / r \sim r^{-1}$

Balance with pure radial (thermal) pressure gradient for polytropic gas (index γ)

$$F_p = \rho^{-1}\, dP/dr \sim r^{1-2\gamma}$$

So: radial pressure / gravitational force ~ $r^{2(1-\gamma)}$

POINT: $\gamma > 1$ stable (pressure wins for small r)

Y<1 unstable (pressure loses to gravity ultimately)

Thermal gas properties, filaments, and fragmentation

Fitting polytropic equation of state to different parts of the cooling curve: 2 states, low and high density

(Larson 1985, 2005; Koyama & Inutsuka 2000; low density – Benson & Myers 1989, Evans 1999)…

$$T \propto \rho^{-0.27} \quad \rho < 10^{-18} gcm^{-3} \quad (\gamma = 0.73)$$

$$\propto \rho^{+007} \quad \rho > 10^{-18} \quad (\gamma = 1.03)$$

Fragmentation depends on polytropic index:

$P \sim \rho^{\gamma}$ implies scaling $T \sim \rho^{(\gamma-1)}$

Cools as gas gets denser for $\gamma < 1$: Prone to fragmentation

Heats as gas gets denser for $\gamma > 1$: Stable to fragmentation

Consequences for molecular clouds:

Critical indices:	Geometry	γ_{crit}
	Sphere	4/3
	Sheet	0
	Filament	1

$\gamma = 1$ isothermal case: Can define critical mass per unit length for hydrostatic equilibrium:

$$m_{crit} = 2c_s^2 / G = 16\ (T/10\ K)\quad M_\odot\ pc^{-1}$$

(Stodolkiewicz 1963; Ostriker 1964, Inutsuka &Miyama 1997, Fiege & Pudritz 2000a,),

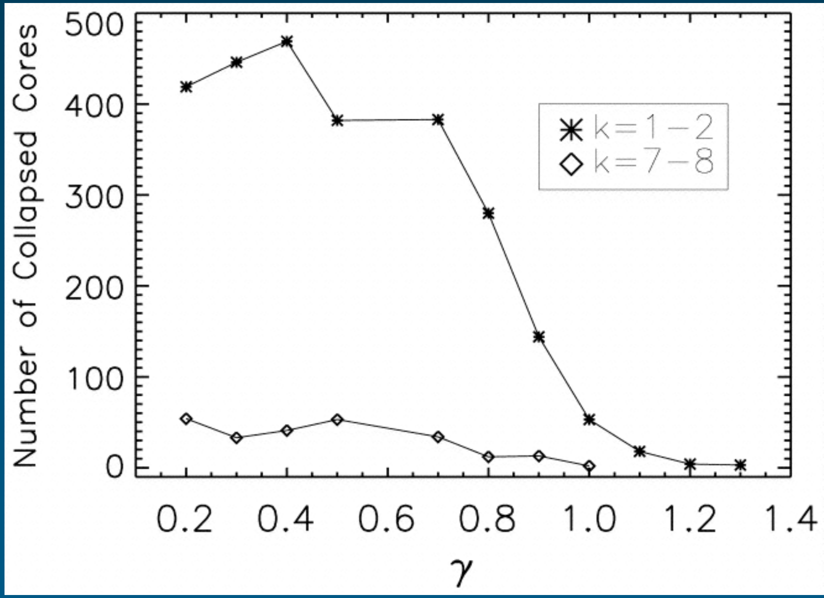
Highly filamentary molecular clouds – consequence of

$\gamma_{effective} < 1$?

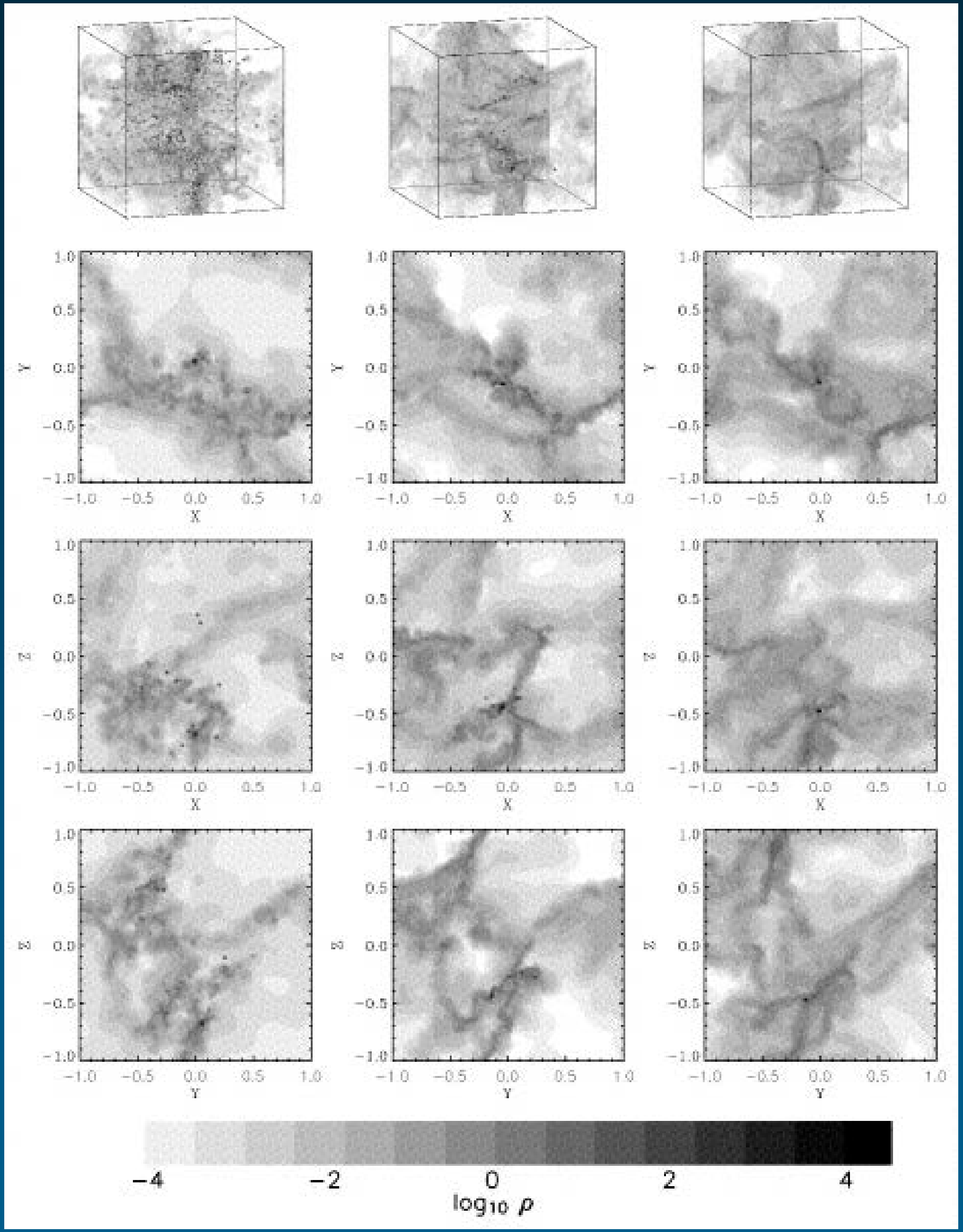
(Koyama & Inutsuka 2000, Larson 2005, Andre et al PPVI review,…)

Fragmentation and Equations of State

- Strong fragmentation γ≤1
- Suppressed for γ>1, and ceases for γ>1.4



Result of thermodynamics + stability properties of filaments (Larson 2005)



Li, Klessen, & MacLow (2003)

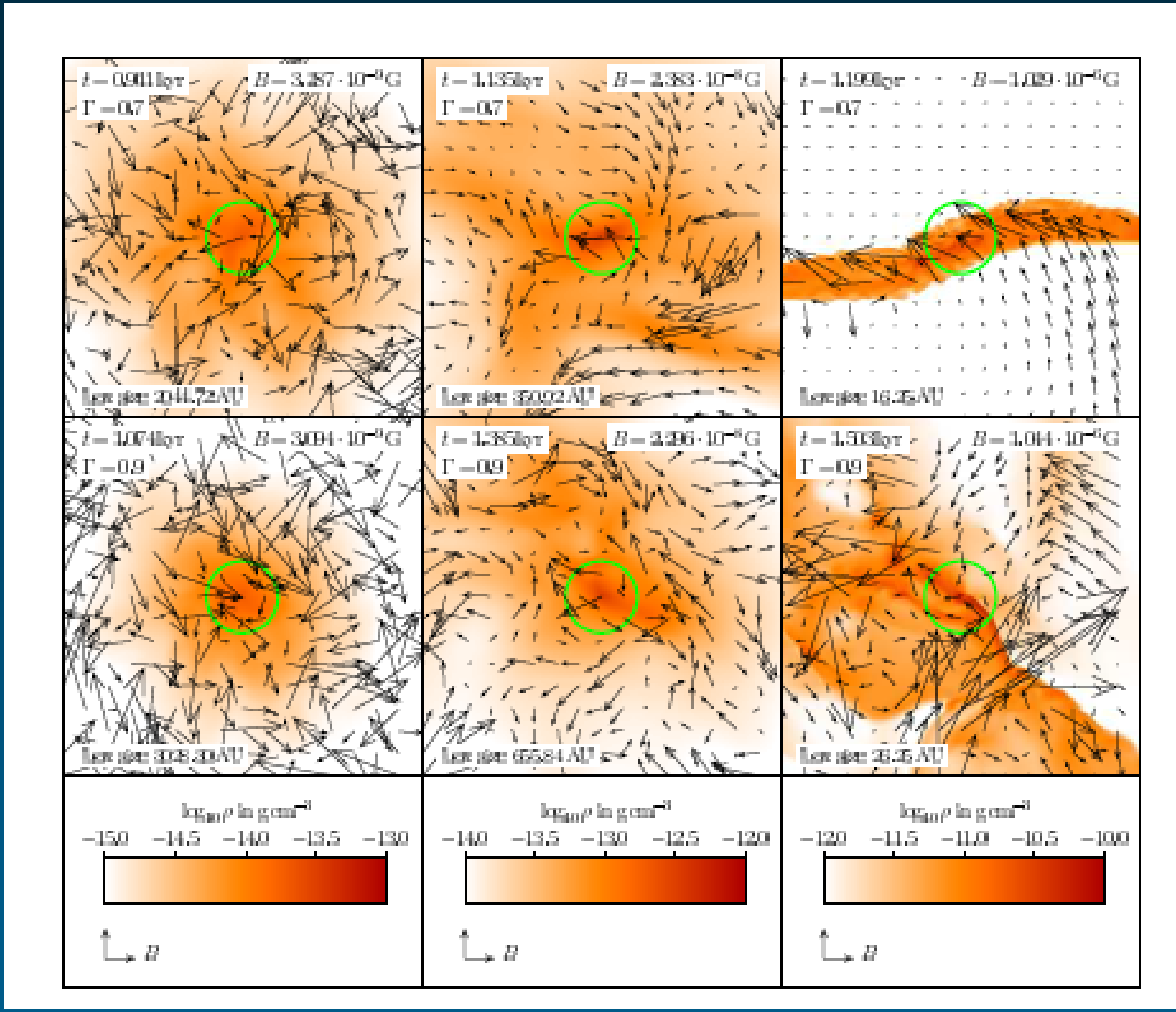
Filament formation: γ < 1

Top = 0.7

Bottom = 0.9

Filament forms more clearly for lower value

- Flow has strong shocks, intersecting sheets, and filaments
- B more ordered,
- More turbulence



Peters et al 2012

Filaments for $\gamma > 1$?

Top = 1.1

Bottom = 1.2

Pressure gradients slow the contraction

- Produces virialized core
- B more tangled
- Less turbulent

Complications – other forces.

Radial density profiles do not follow isothermal filaments (r^{-4})

MHD: Poloidal field supports cylinder against collapse – but a toroidal component (wrapping filament) *squeezes it*. (Fiege & Pudritz 2000)

-> Net magnetic contribution could be positive, *or negative*

Radial density profiles: $r^{-1.5} - r^{-2}$

Accretion: Filaments result of shock intersection – dynamic accretion not static equilibria. Get r^{-2} (simulations, Fabian's talk)

Turbulence: Changes the critical mass to

$$m_{crit} = 2\sigma^2 / G \; ; \quad \sigma^2 = c_s^2 \, (1 + M^2/3)$$

-> LARGE critical line mass until turbulence damps

Cores and stars from GI?

Polytropes:

- Radial collapse wins

– halted as γ increases… then slower fragmentation

- Smaller than preferred mode in linear instability analysis.

(Inutsuka & Miyama 1992, 1997)

** What determines fragmentation spectrum? IMF? **

General B field; induce twisting motions as well (Fiege & Pudritz, 2000b)

Density + Poloidal velocity

Toroidal velocity

II Making filaments and clusters

Clouds are not likely to be equilibria.   Dynamical process:

- Gravitational instability
  (galactic dynamics, filaments (nonlinear evolution),….)
- Turbulence
- Shocks (compression, vorticity generation,…)
- Magnetic fields (channeling, squeezing,…)

Filaments (large scale) connected with GMC formation

- Colliding flows (Heitsch et al 2008, Banerjee et al 2009,..) produce highly turbulent, filamentary clouds

- GI via Toomre instability (Tasker 2011, Dobbs et al 2011, Bournaud et al 2010, Agertz et al 2009, Benincasa et al 2013);

Long filaments from shear + cloud-cloud tidal interaction

Benincasa, Tasker, Pudritz, & Wadsley 2013, ApJ : (No Feedback)

Super Nova driven structure and turbulence in the galactic disk

3D, SN driven shocks:

Simulations done for galactic disk with numerical resolution 1.25 pc

Broad range in density enhancements, several orders of magnitude

This image cannot currently be displayed.

Avillez & Breitschwerdt (2003) – density contrast

Turbulence

Turbulence, filaments, and turbulent fragmentation

-Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

-Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

- Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks dissipate turbulent support as t^{-1}

(eg. Ostriker 2001)

Gas flows along filaments into local potential minima – cluster formation regions

(eg. Banerjee et al 2006, R. Smith et al 2012, Kirk et al 2012,..)

This image cannot currently be displayed.

Bonnell et al (2003)

QUESTIONS:

Turbulent “fragmentation” drives CMF (eg. Padoan & Nordlund)
– or gravitational fragmentation of filaments?

Sources of “turbulence” in molecular gas

- galactic spiral shocks, supernovae, cosmic ray streaming, expanding HII regions, K-H and R-T instabilities, gravitational and thermal instabilities, … (eg. review Elmegreen & Scalo 2004)

Does the source of turbulence matter?

Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks:

Shock produced sheets fragment into filaments. -> Filament/ hub systems

and cluster formation

(Myers 2009)

Intersecting oblique shocks produce filaments, sheets (MacLow & Klessen review 2004)

Myers 2009

Pudritz & Kevlahan 2012

Initial conditions matter!

Different cloud density profiles are *most important factor*

TH = top hat: many sinks in filaments, subclusters and merging in outskirts, few high mass stars

PL15 = $r^{-1.5}$: one massive sink in centre in early stage, becomes most massive particle

BE= rescaled Bonner-Ebert – one central particle

This image cannot currently be displayed.

Initially: 100 $M_\odot$ of gas

Girihidis et al 2011

B and filaments

Look at B relative to filaments identified by DisPerse (Klassen, Pudritz, & Kirk, 2014) – 2 peaks, but broad band too…

Filaments as in Kirk et al 2014

Angles vs m/m_{crit}

Getting down to stellar scales – filamentary flow and disk formation

-large scale filamentary flow onto disk: links 0.1pc to sub AU scales (Banerjee, Pudritz, & Anderson 2006):

Multiple filaments and disk formation
(Seifried, Banerjee, Pudritz, & Klessen 2014, astro-ph)

1300 AU scale, 100 $M_{\odot}$, no initial rotation, velocity vectors, B (black lines), forming Keplerian disk (blue), filaments (green)

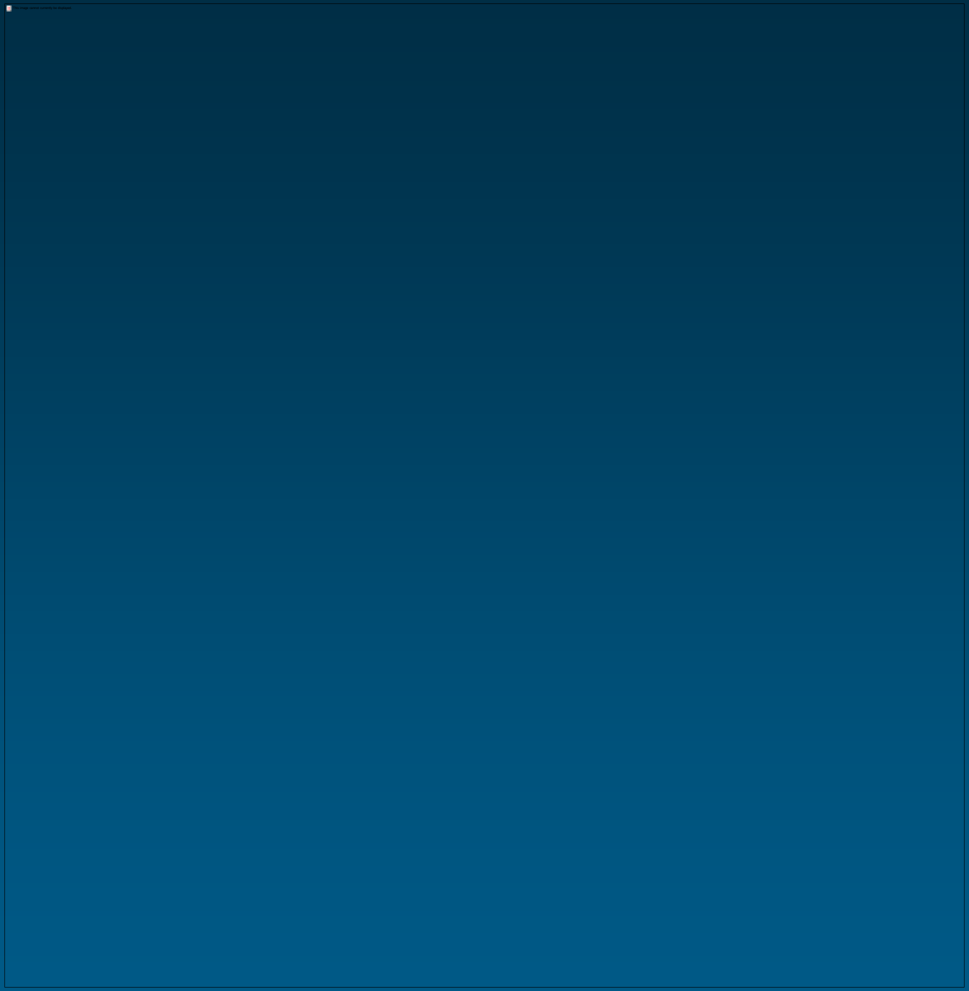
III. Radiative Feedback

Radiative effects in 2D; Yorke & Bodenheimer, 1999, Yorke & Sonnhalter (2003)

Need to prevent excessive fragmentation found in standard turbulence + cooling simulations (3D turbulent dynamics: Krumholz et al 2007)

- Important source of energy – accretion luminosity
- radiative feedback from massive stars: raises Jeans Mass

- filaments don’t fragment – gas drains into primary and its disk
- prevent fragmentation out to 1000 AU scales



Bate (2009)

Radiation heating in a cluster environment:

- Filaments drain material into central region
- Feedback from forming stars affects dense material in central region
- Suppression of objects by factor 4; produces stars/brown dwarfs = 5

Problem - ionization does not erode dense cold filaments (Dale & Bonnell, 2011)….. how does accretion stop?

Ionize diffuse gas in the voids instead – filamentary structure has major implications for efficiency of feedback, and therefore SFR

Break the filaments with outflows? (Wang et al 2010, poster paper yesterday by Adele Plunkett)

Cluster formation: stellar populations, star formation rates, and ionizing radiation

(Howard, Pudritz, & Harris 2013)

Subgrid model for cluster:
random sampling of IMF – in clumps (sinks) with initial mass, and ongoing accretion

This image cannot currently be displayed.

Columns (M_o yr^{-1})
Left = 0
Right = 2.8×10^{-2}

Rows, initial gas:
10^2, 10^3, 10^4 M_o

Cluster L, ionizing flux, and SFR

Columns: Initial masses of gas

10^2, 10^3, 10^4 M_o

Accretion rates (fixed) onto sinks:

(M_o yr^{-1})

Blue - 0

Red - 2.8 x 10^{-3}

Green - 2.8 x 10^{-2}

Cluster Formation and Feedback in a GMC - links to filaments

Radiative feedback from evolving IMF in cluster sink particles – using ray tracing from sources, not FLD…

-Cloud: virial parameter = 1, n=100 cm^{-3}, box 32 pc, profiles flattop, powerlaws; low rotation (2 %), mass 10^5 $M_{\odot}$

-Ionization, thermal heating, radiative momentum..

Howard, Pudritz, & Harris 2014, in prep

Density Temperature

3D Visualization: filaments, HII regions

This image cannot currently be displayed.

Heirarchical formation of larger clusters –

- many subclusters merge
- initial conditions matter (eg. flat topped vs power law)
- radiative feedback not sufficient to prevent high star formation efficiency..

Power-law (blue), flat top (cyan)

Summary

- How filaments change our ideas of star formation:

  - a physical mechanism for core formation (GI)
  - a new way of understanding accretion processes – large scales essential for the story
  - multiscale connectivity in density, velocity, B, – clouds to stars
  - challenge for feedback – how do you turnoff accretion? If by outflows – then B is fundamental since outflows are hydromagnetic.

- Filament formation: thermodynamics, turbulence, gravity, B, shocks - what is essential ?

-