School of Physics and Astronomy

FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

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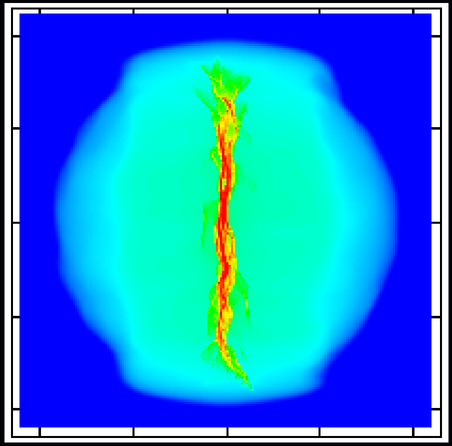
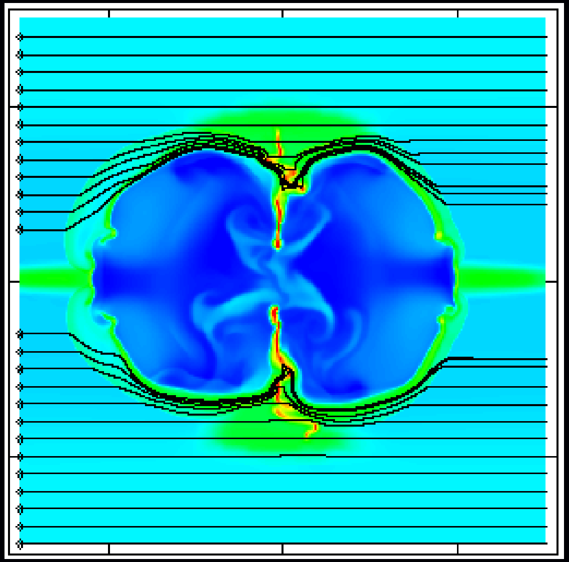
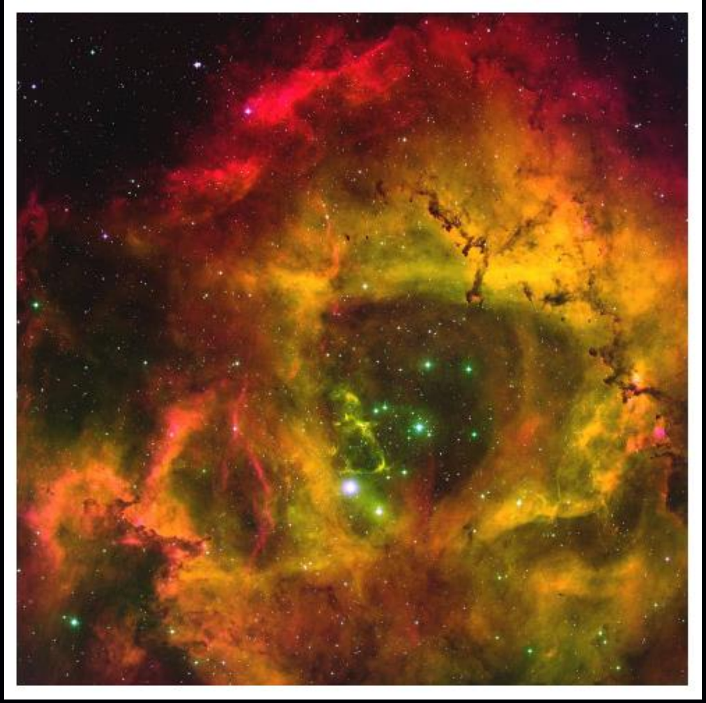
Filaments, feedback and forming the Rosette

MHD simulation of stellar feedback in a sheet-like molecular cloud formed by the thermal instability







Chris Wareing,
Astrophysics Group

J. Pittard, S. Falle, S. Van Loo (Leeds)
N. Wright (Keele)

Context & Aim

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- The radiative and mechanical energy injected by stars and supernovae (SNe) regulates the evolution of regions where stars and stellar clusters form.
- More specifically, the radiation fields, winds and SNe of massive stars destroy and disperse the molecular material of the natal molecular cloud in which they formed.
- This eventually ends star formation in clusters, though before that happens massive stars may trigger further star formation.

- Our aim is to perform simulations, including magnetic fields, self-gravity & photoionization to elucidate the effects of stellar radiation, stellar winds and SNe on the evolution of gas where stars and stellar clusters are born, with further regard to the study of triggered star formation.

Winds are important

CONTEXT & AIM

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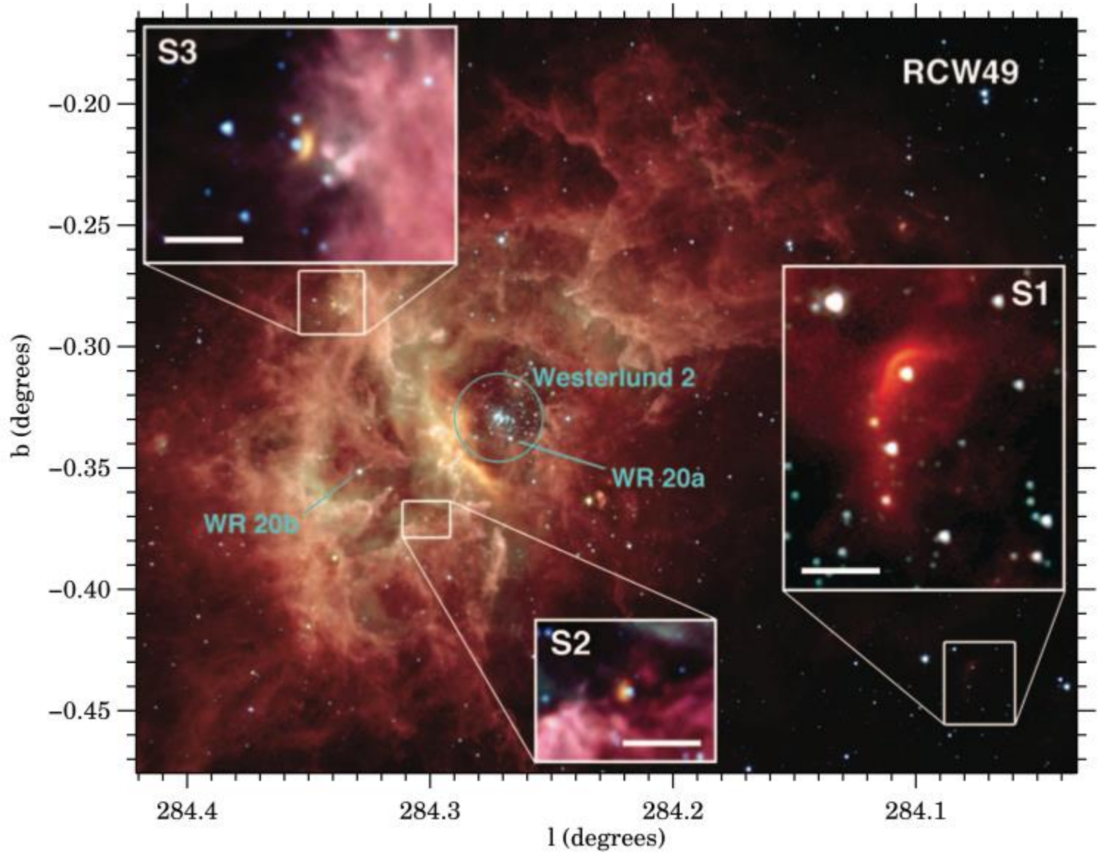
- Total energy injected is less than SNe, but in many clusters no SNe yet.
- Stellar winds create bow shocks around nearby stars, e.g. in RCW49.

- GLIMPSE full colour image of RCW49.
- The scale bars are 0.6 pc at 4.2 kpc.
- Bow shocks are indicated: S1, S2 & S3.
- Three energy sources that could drive large-scale interstellar flows are indicated.



Povich et al. 2008, ApJ, **689**, 242-248

Winds *can* disengage SN and cloud

CONTEXT & AIM

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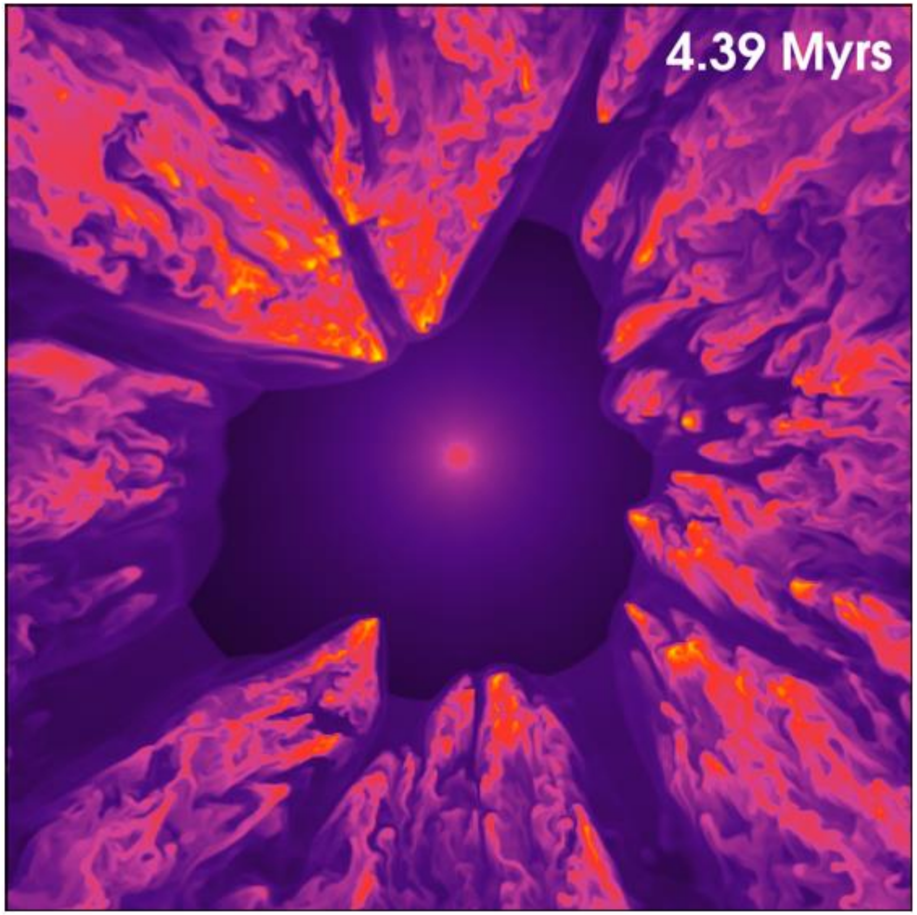
- Wind energy and momentum couple to the cluster gas and structure the stellar surroundings.
- SN mass and energy can leave the cloud along the channels formed by the winds.
- In some cases then, SN can *decouple* and have *less* effect.
- We began to explore this in previous works (albeit with simple cooling, no self-gravity & no magnetic field).



35, 32, 28$M_{\odot}$ cluster feedback, pre 35$M_{\odot}$ SN

Rogers & Pittard 2013, MNRAS **431**, 1337-1351

Rogers & Pittard 2014, MNRAS **441**, 964-982

Overview

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This seminar will concentrate on simulations including magnetic fields and self-gravity, examining the mass, momentum and energy effects of stellar winds and SNe.

- The physics we include in our models.
- The initial condition we have developed as a starting point.
- The stellar evolution models.
- Comparisons to previous work and observations.
- Serendipitous application to the Rosette Nebula.
- Revisiting the initial condition with high-resolution simulations.

In the future, we plan to implement a parallelised photoionization method in the numerical scheme and examine ionizing radiation fluxes.

Physical model

- We wish to start from the simplest set of self-consistent physics for the formation of a molecular cloud and examine what's possible from there, before adding further complexity.
  - 3D HD/MHD
  - Self-gravity
  - Multi-phase ISM, requiring a prescription for heating and cooling

- In future, extra additions may be explored:
  - Shear and pressure waves, imitating galactic evolution
  - Large-scale flows driven by e.g. shocks, cloud collision
  - "Turbulent" initial conditions applying randomised velocities

but if one can find a solution without recourse to extra complexity ...

lex parsimoniae / Occam's razor

The engine
Physical model

- Magnetohydrodynamic version of **MG** (*Morris Garages*) with self-gravity.
- Parallelised, upwind, conservative shock-capturing scheme.
- Adaptive mesh refinement uses a coarse base grid (4x4x4) with 7 (or more) levels of AMR to achieve a resolution up to 512^3 (*the Honda bit?*).
  - Why the wide range? Efficient computation of self-gravity.
- Realistic heating and cooling methods
  - Of key importance as it is the balance of these that establishes the initial condition and defines the consequent evolution.
- Three field strengths considered, with $\underline{B} = B_o \hat{\underline{I}}_x$
  - The hydrodynamic case: $\beta = \infty$
  - Pressure equivalence: $\beta = 1$ - inferred to be the commonest in reality.
  - Magnetically dominated regime: $\beta = 0.1$

$$\beta = \frac{\rho k_B T}{B^2 / 2\mu_0} \quad \frac{\textit{thermal pressure}}{\textit{magnetic pressure}}$$

Aside: EPSRC and Innovate UK research proposals to apply MG in industry: CO_2 machining.

Heating and cooling

Physical model

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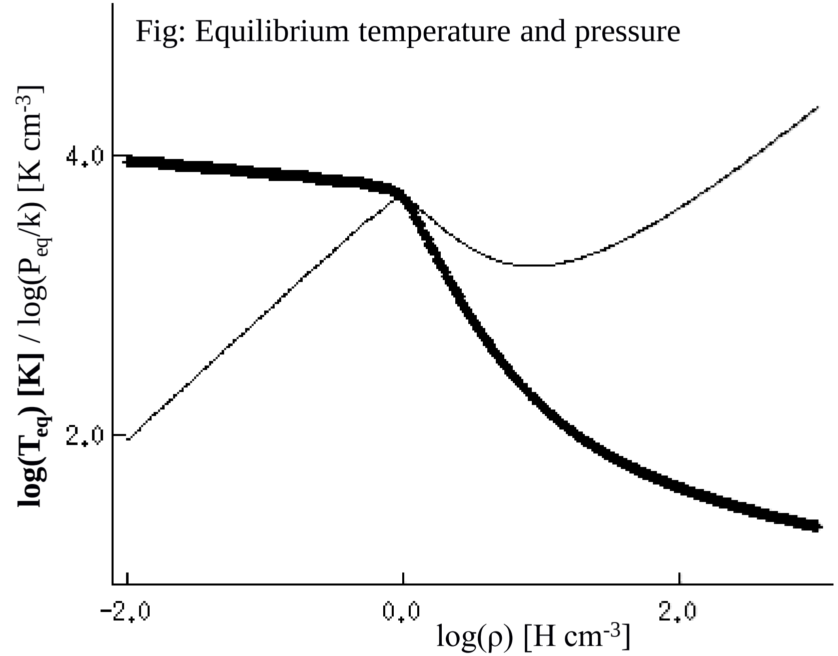
- Constant heating rate: $\Gamma = 2\times10^{-26}$ erg s^{-1} (independent of *ρ* and *T*)
- Multi-stage cooling, in order to apply for molecular cloud formation (10^1K) and stellar feedback (up to 10^8K).
  - Low T (<10^4 K) uses Koyama & Inutsuka 2002, (corr. Vázquez-Semadini et al. 2007)

$$\frac{\Lambda(T)}{\Gamma} = 10^7 \exp\left(\frac{-1.184\times10^5}{T+1000}\right) + 1.4\times10^{-2}\sqrt{T}\exp\left(\frac{-92}{T}\right)$$

  - Above 10^4 K we have used CLOUDY 10.00 rates from Gnat & Ferland 2012.
  - Above 10^8 K a MEKAL curve has been used.



- Establishes thermal equilibrium pressure and temperature by $\rho^2\Lambda = \rho\Gamma$

Initial condition

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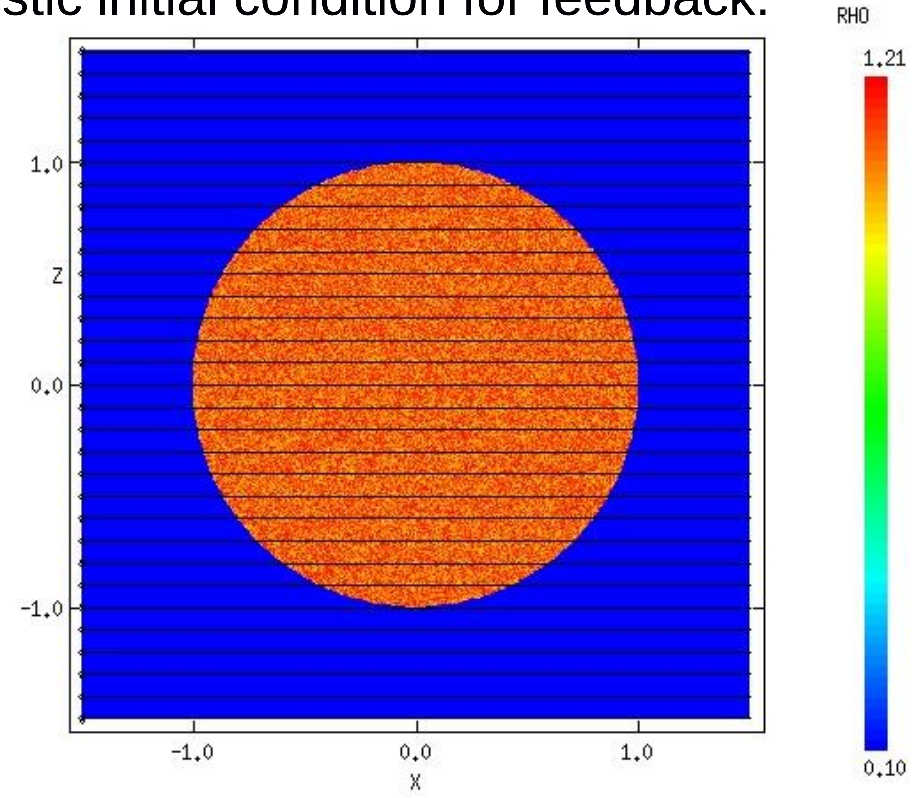
- Previously (Rogers & Pittard 2013/2014), we used a turbulent and inhomogeneous GMC clump, based on Vázquez-Semadini et al. (2008).
  - 3,240 $M_{\odot}$, 8 pc-diameter intersection of filaments, isothermal (15K), turbulent (Mach 15) and no magnetic field.
- Now, start again to generate a realistic initial condition for feedback:
  - 100 pc-diameter diffuse cloud.
  - n_H=1.1±10% - in the thermally unstable regime – 17,500 $M_{\odot}$.
  - Threaded by magnetic field along the x-axis, $\mathbf{B} = B_0\hat{\mathbf{i}}_\mathbf{x}$.
    - For $\beta = 1$, B_0 = 1.15 μG
    - For $\beta = 0.1$, B_0 = 3.63 μG
  - Pressure equilibrium with surroundings; 10x less dense.
  - Quiescent cloud, $\underline{v}$=0



On velocity and turbulence...

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- Larson (1981 MNRAS **194** 809) said two things which I particularly note:
  - “Since the observed motions [in MCs] are in any case always irregular to some extent, it seems reasonable to describe them as “turbulent”; in fact, no sharp distinction can really be drawn between “systematic motions” and “turbulence”, because turbulent flows actually consist of a hierarchy of small-scale irregularities superimposed on larger-scale more systematic motions” *from 1. Introduction.*
  - “This [similarity between the Kolmogoroff law for subsonic turbulence $\sigma \propto L^{1/3}$ and size-internal velocity dispersion correlation for MCs] suggests that the internal motions in molecular clouds are part of a general hierarchy of interstellar turbulent motions. The apparent similarity between these motions and subsonic turbulence may result if molecular clouds form as cold condensations in warmer atomic gas, and if their motions arise from subsonic or mildly supersonic turbulence in the warmer gas” *from the headline paragraph in the conclusions.*
- Can we generate trans/supersonic motions from a non-turbulent I.C.?

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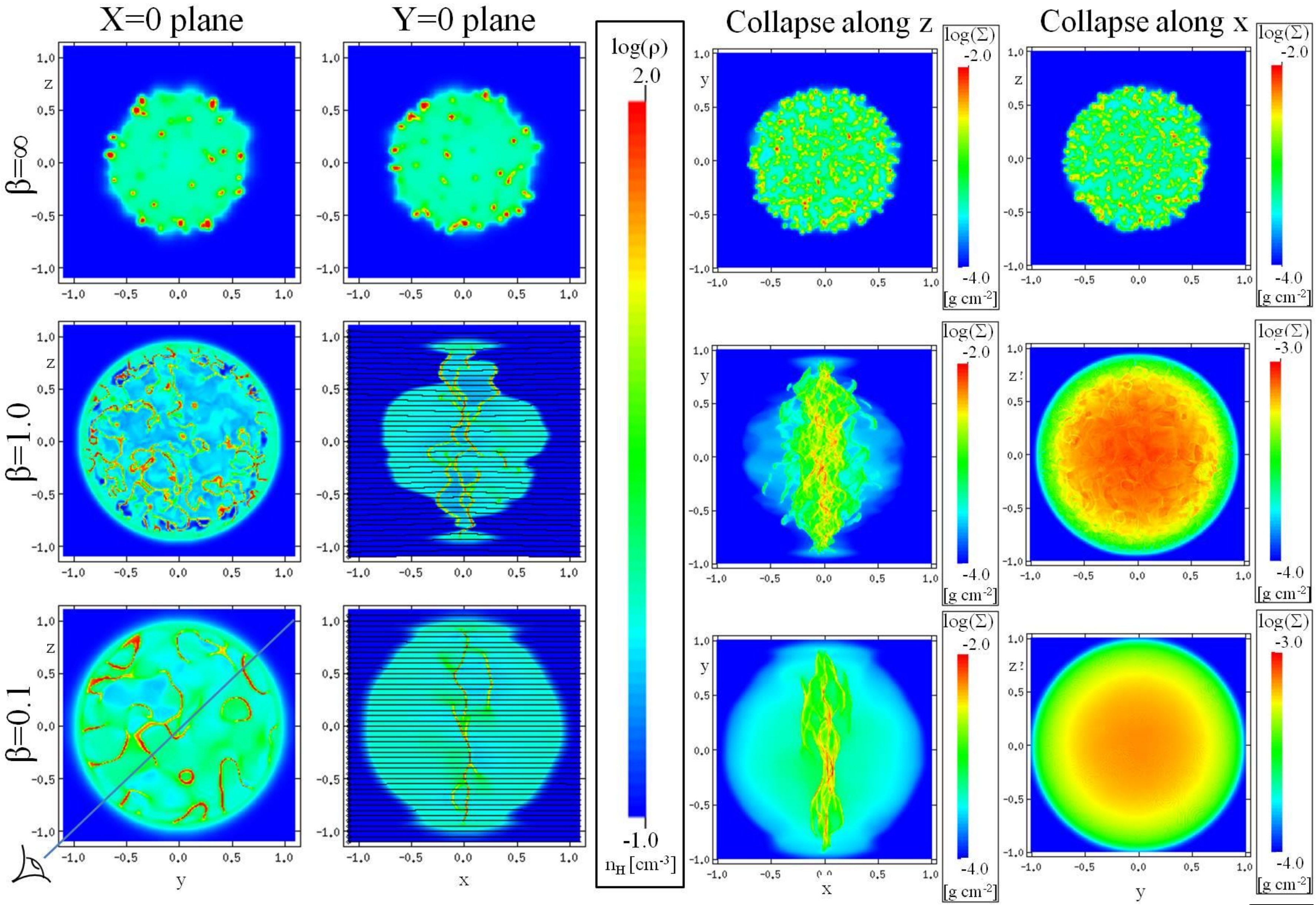
Simulating the initial condition



Logarithmic mass density on planar slices

Logarithmic column density

- t=35.4 Myrs. Only as dense as a MC for last 10Myrs

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Results
INITIAL CONDITION

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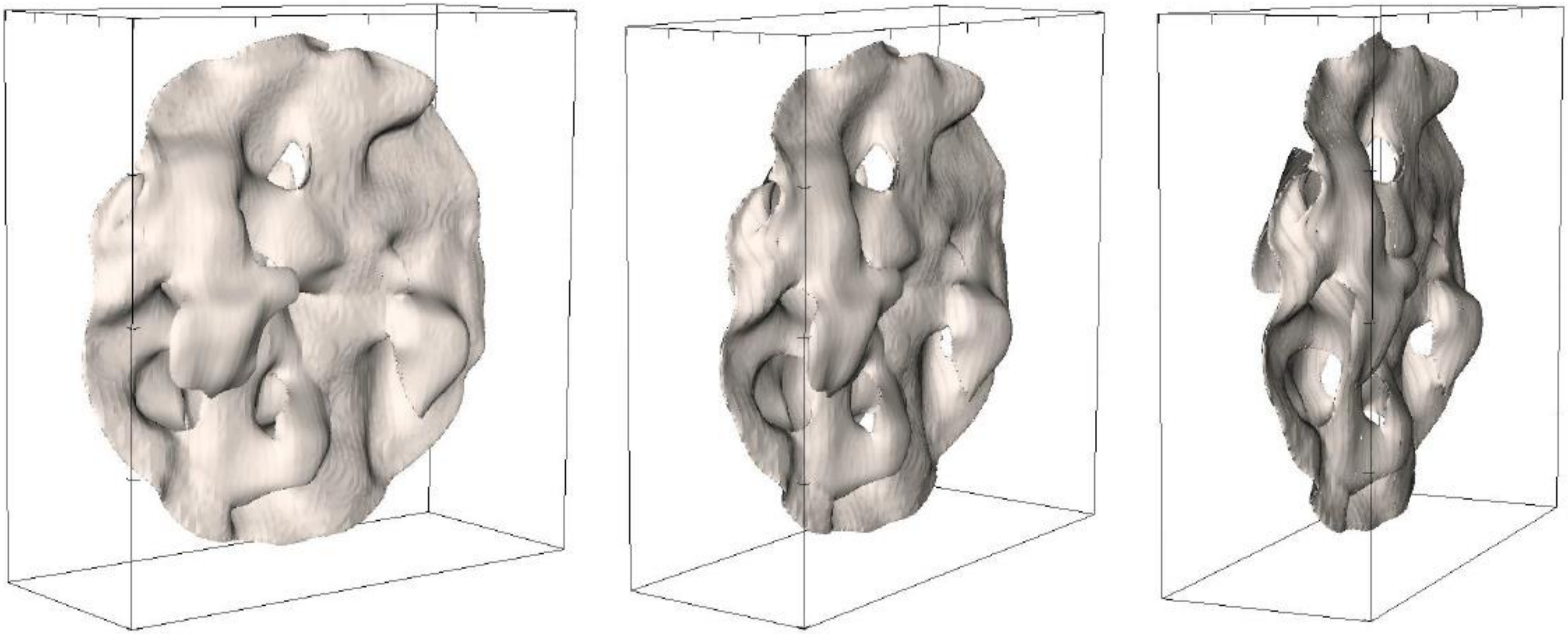
- In the magnetic case, the model forms corrugated sheets...



Density isosurface

Results

INITIAL CONDITION

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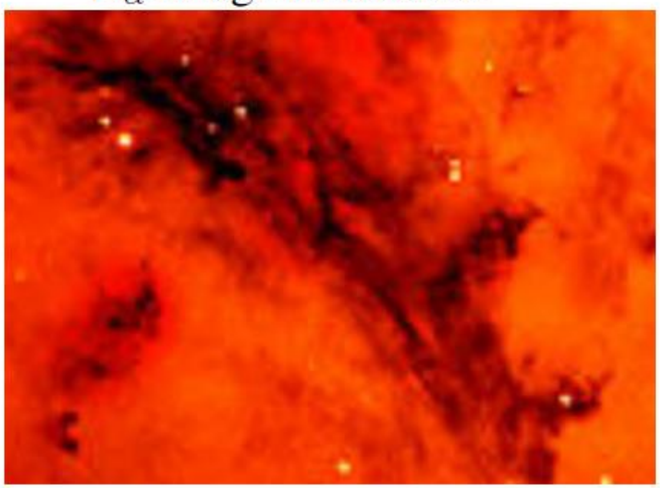
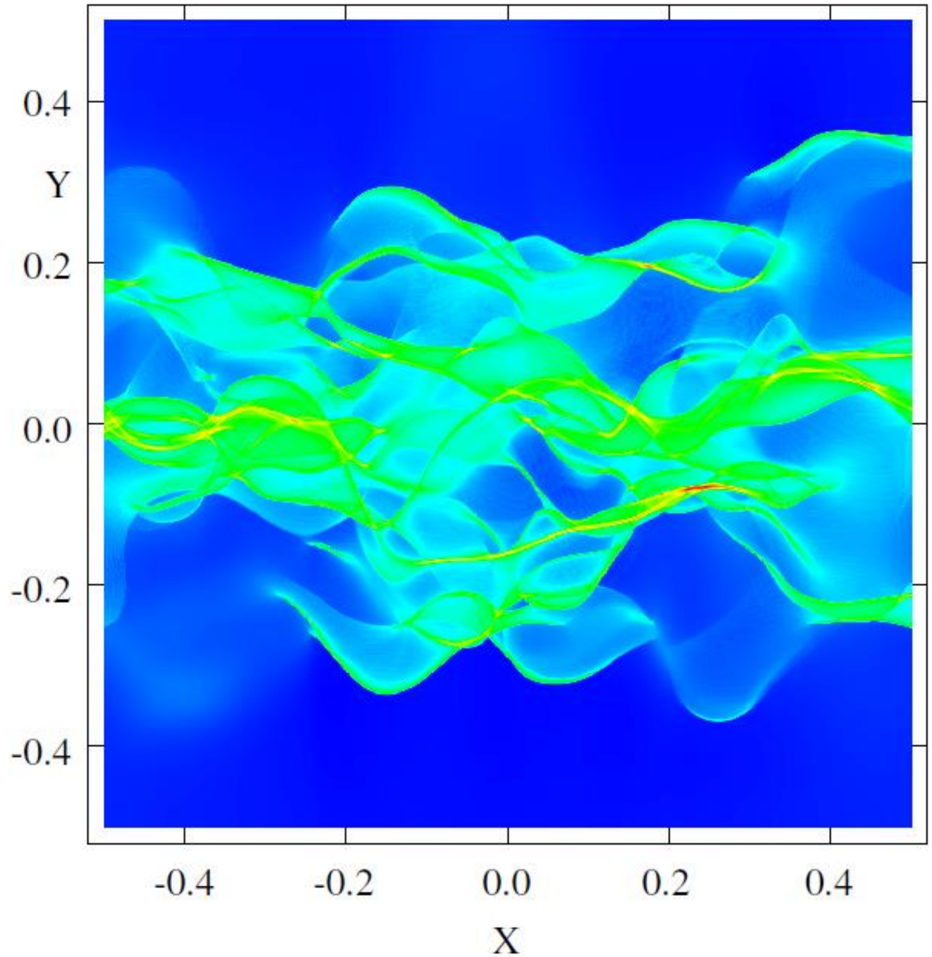
H_α image of Rosette





... that in projection appear filamentary

Results

INITIAL CONDITION

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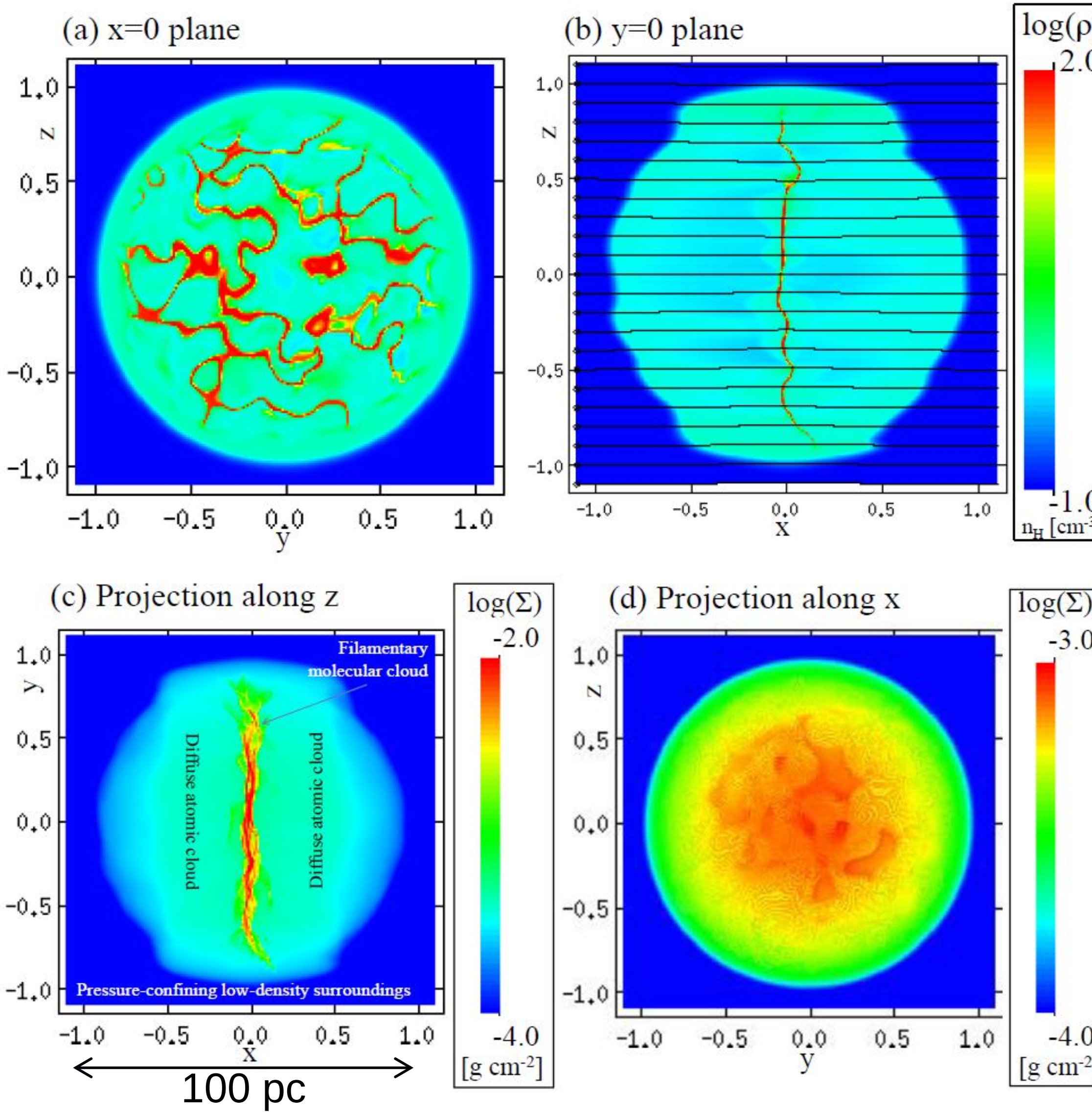
- Provide initial condition.
- 100 pc-diameter ‘corrugated’ sheet
- Filamentary in projection
- 17,500 $M_\odot$
- Density >100 cm^{-3} after 32.9 Myrs of evolution
- Assume free-fall time of 5.89 Myrs to forms stars
- Inject stars at t=38.8Myrs
- Position of central star (-0.025, 0.0, 0.0125)
- Total mass in excess of star formation mass



How reasonable is it?

INITIAL CONDITION

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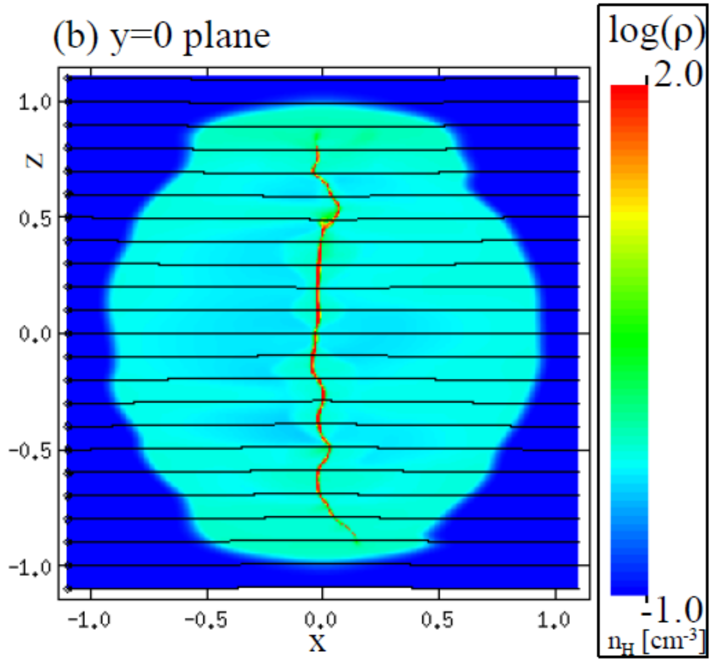
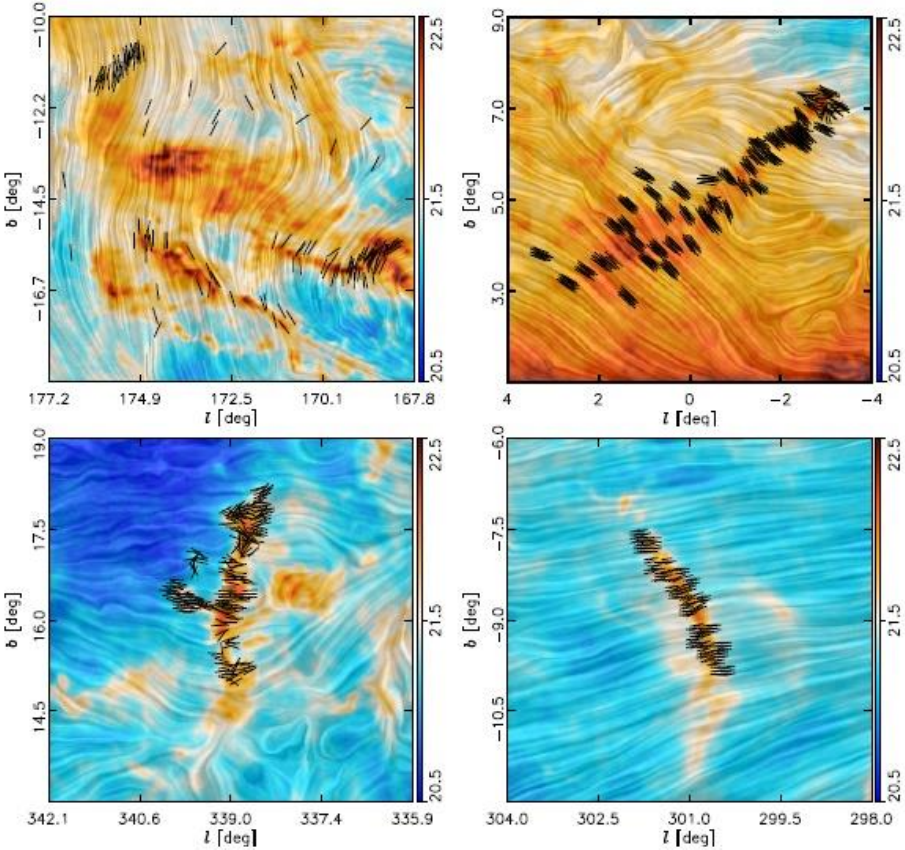
- We should ask how reasonable is this initial condition?
- Given that the magnetic field dominates the evolution leading to thin sheets, do such structures exist?





- Simple answer: yes!

Magnetic field morphology in four nearby clouds (Taurus, Pipe, Lupus I and Musca). Drapery: *Planck* sub-mm, vectors: starlight los polarisation.

Sheet-like structure?

INITIAL CONDITION

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- Consider Larson again...
- "In regions with length-scale L>10pc, the geometric mean of this ratio:

$$\frac{\sigma(V)}{\sigma(\Delta V)} = \frac{\text{Velocity dispersion assoc. with variations in radial velocity across a cloud}}{\text{Velocity dispersion inferred from the line width } \Delta V}$$

  is about 1.7. This larger value (than 0.62 for a sphere and in agreement with smaller regions) can be understood as resulting from ***a filamentary or sheet-like structure of the larger clouds*** if their typical line-of-sight thickness is only about 1/10th of their total linear extent."
- "Such a situation could arise, for example, from collisions between atomic clouds, which produce thick layers of shock heated atomic gas in which *thin sheets of cold molecular gas form by thermal instabilities*"
- A possible scenario for our cloud to enter the *same* thermally unstable regime by different means, is the passage of a subsonic pressure wave – *for example, a spiral arm*.

Realistic timescales?

INITIAL CONDITION

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- Consider Larson again!
- “Such systematic motions would be expected in a turbulent picture of the interstellar medium, since turbulent motions are not random but consist of small-scale irregularities superimposed on large-scale, more systematic flows with larger velocities. The formation of molecular clouds probably requires motions with length-scales of a few hundred parsecs, velocities of ~10 km/s and time-scales of a few 10s of Myrs.”
- Our magnetic initial condition forms in ~35 Myrs, with high density filaments having formed after ~25 Myrs. The hydrodynamic initial condition is quicker still.
- The diffuse cloud is initially stationary, but has been triggered into the unstable warm phase such that thermal instability-driven motion generates structure and velocities on these size- and time-scales.

Realistic clump and filament properties?

PUBLISHED RESULTS

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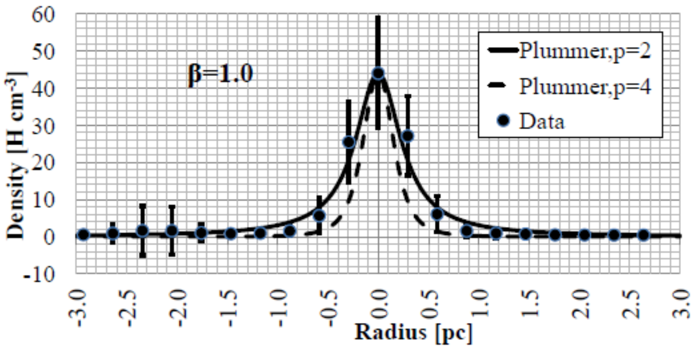
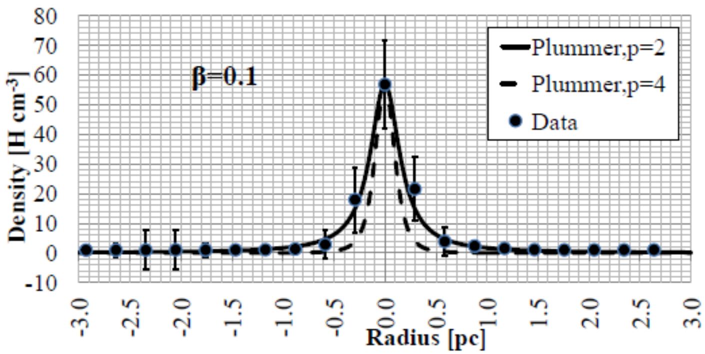
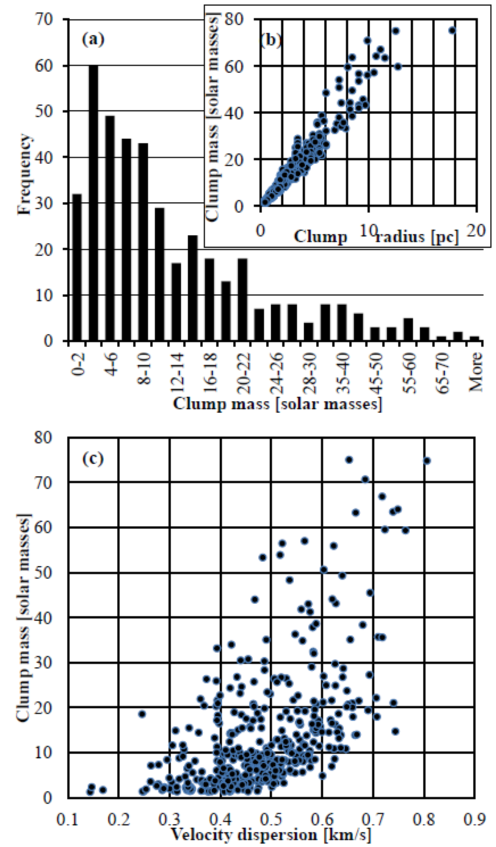
- The filaments and clumps that form in these simulations are interesting in their own right.
- Filament widths consistent with obs.:







"MHD simulation of the formation of clumps and filaments in quiescent diffuse medium by thermal instability" Wareing, Pittard, Falle, Van Loo 2016, MNRAS, **459**, 1803-1818

Feedback simulations

Stellar evolution models

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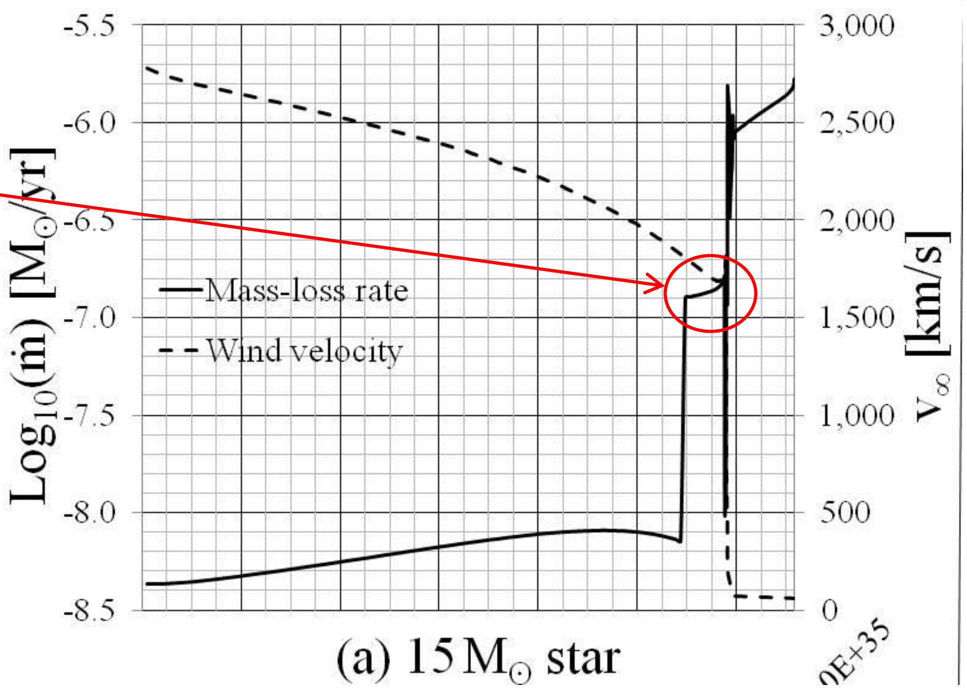
- We started from the Geneva 2003 tracks (Meynet & Maeder 2003).
  - Wind velocity derived using Vink et al. (2000 A&A **362**, 295; 2001 A&A **369**, 574).
- Derived mass and energy source terms (thermalised kinetic energy)

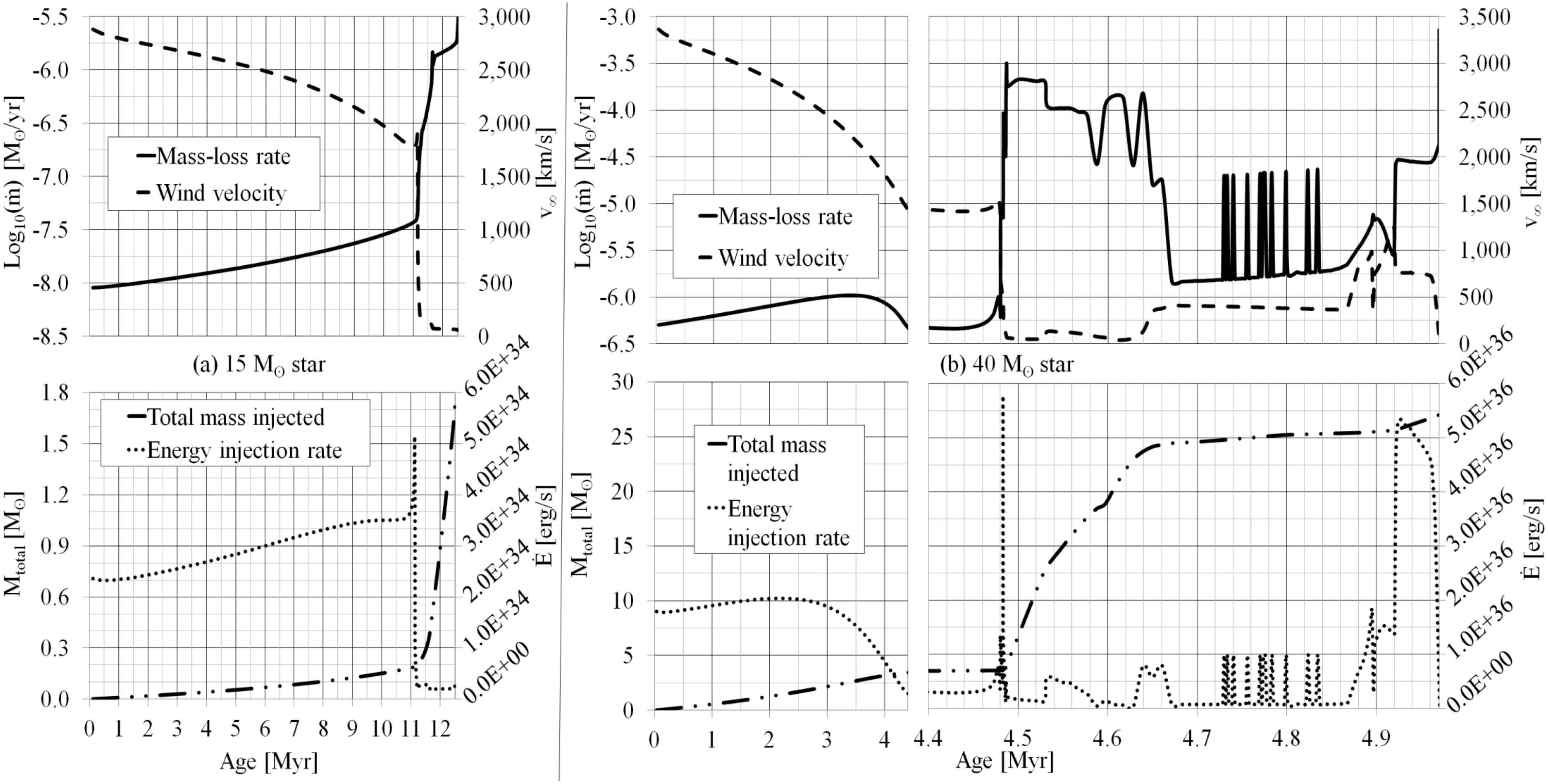
- But, we found a problem:
  - Wind velocity stayed too high during final phases of stellar evolution.
  - Unrealistically high energy sources
- Solution?
  - Use Geneva 2012 tracks (Ekström et al. 2012, A&A, **537**, id.A146)



(a) 15 $M_\odot$ star

Geneva 2012 tracks

STELLAR EVOLUTION MODELS



Supernova conditions

STELLAR EVOLUTION MODELS

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- After 12.5 Myrs and 4.97 Myrs the stars have injected:-
  - 1.75 $M_\odot$ and 1.05×10^{49} erg for the $15 M_\odot$ star.
  - 27.2 $M_\odot$ and 2.50×10^{50} erg for the $40 M_\odot$ star.
- Both then explode in a SN.
  - Modelled as an injection of 10 $M_\odot$ and 10^{51} erg.
  - Injection duration of 500 years to approximate initial expansion in the injection zone.
- Note wind and SN inject comparable amount of energy.
- Resolution checks indicate we are *just about* resolving cooling.

$15M_\odot$ star: wind phase

RESULTS

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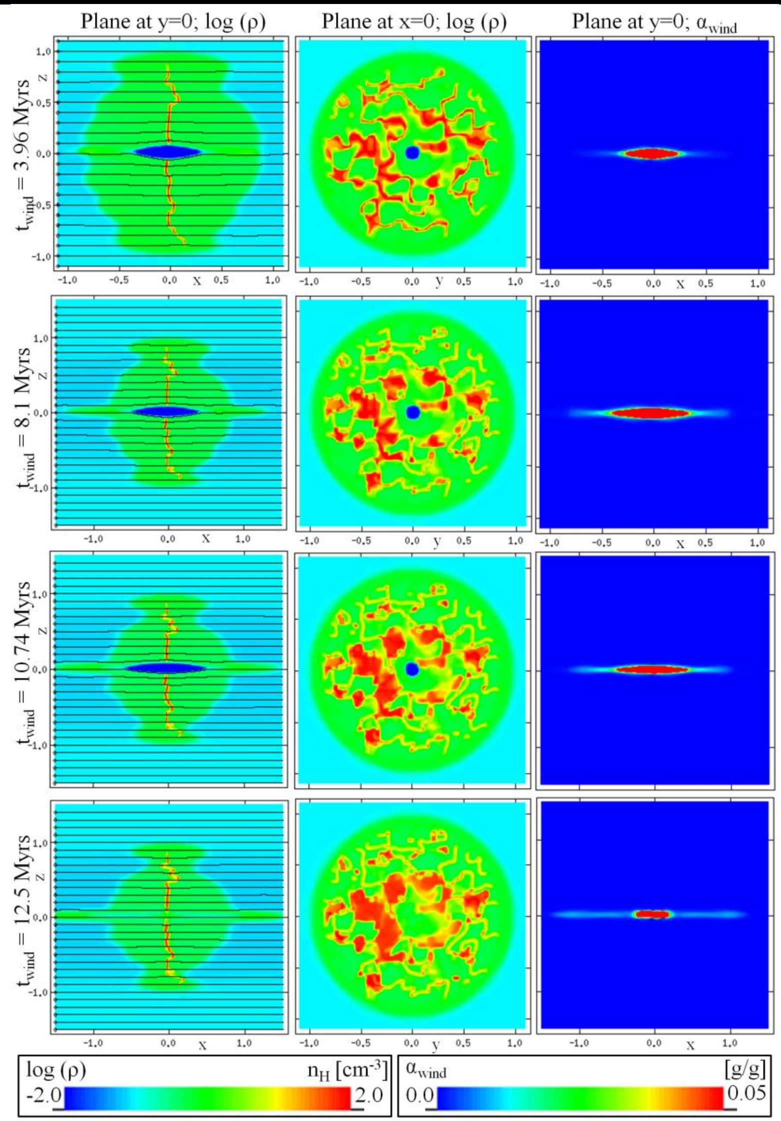
- Showing the wind evolution during the MS at three times and finally at the end of the RSG phase.
- **Low mass-loss rate and low wind energy have minimal effect.**
- Small, local cavity driven through the parental molecular cloud.
- RSG phase deposits considerable material into this cavity.
- RSG affects early evolution of the SN, but only small perturbation.



$15M_\odot$ star: early SN phase

RESULTS

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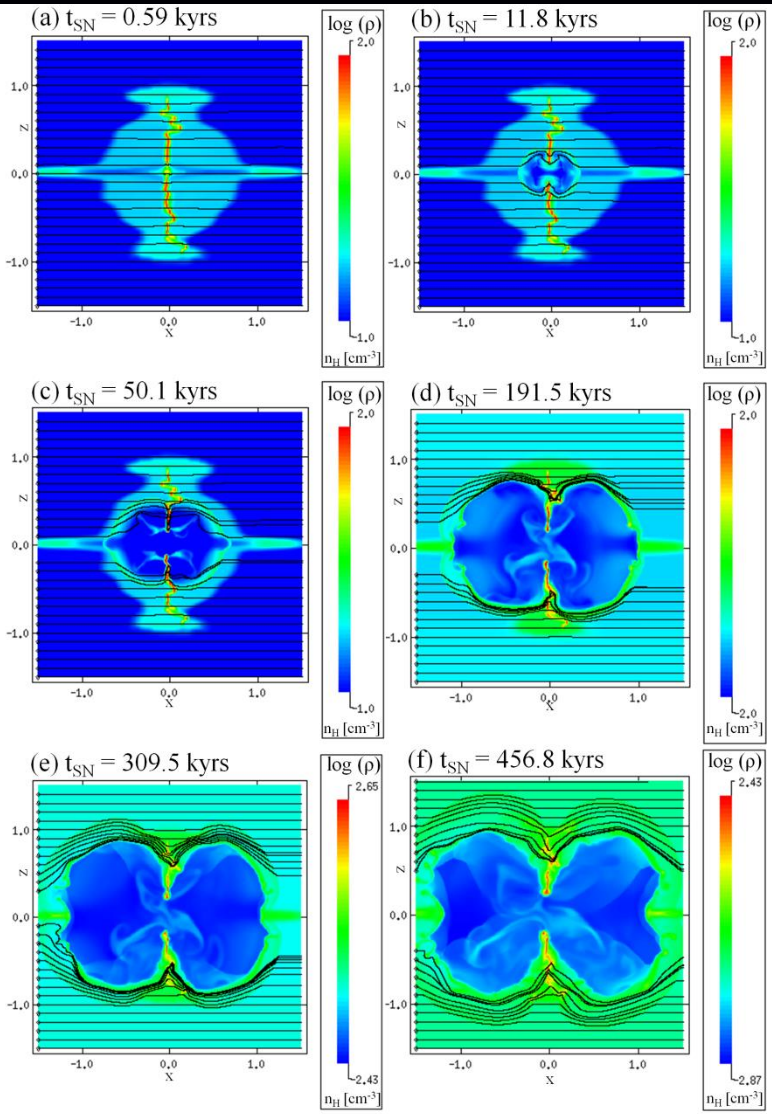
- SN rapidly exits the wind cavity.
- **Expansion is hindered by the high density corrugated molecular cloud.**
- High density filamentary structure is ablated by the expanding SN remnant.
- Magnetic field intensified by a factor of 4 around the shell away from cloud.
- Intensified temporarily by a factor of up to 10 (16 μG) at the edges of the corrugated molecular cloud.
- Hot, dense, ablated molecular material exists inside the remnant and is likely to be emitting strongly.



$15M_{\odot}$ star: late SN phase

RESULTS

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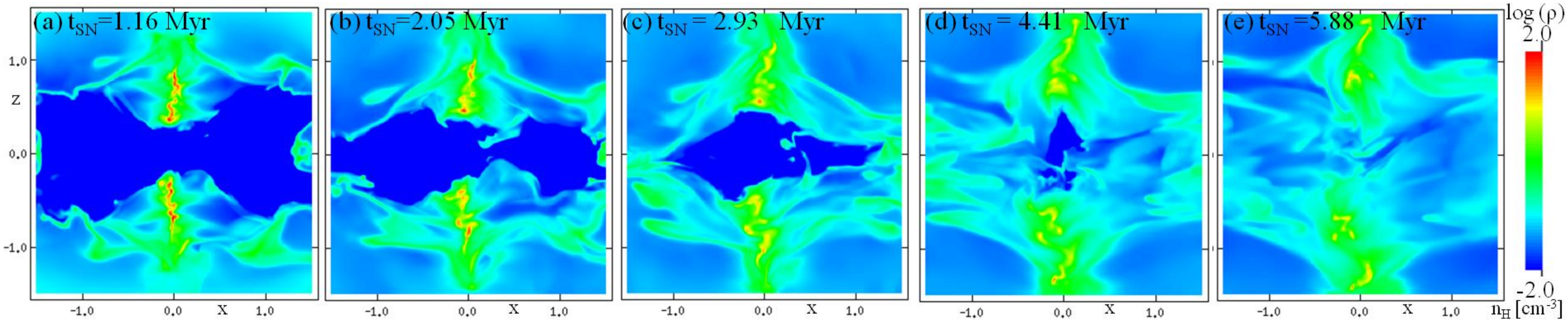

- SN-wind-cloud interaction at late time, once the SN forward shock has left the computational domain.
- Indicative results only – boundary effects now present.
- Considering only the fate of the molecular cloud, after 1.16 Myr, the cloud is still recognisable.
- **After 6 Myrs post SN, the molecular cloud has been dispersed.**
- Simulations with a larger computational volume will investigate further.

$40M_\odot$ star: wind phase

RESULTS

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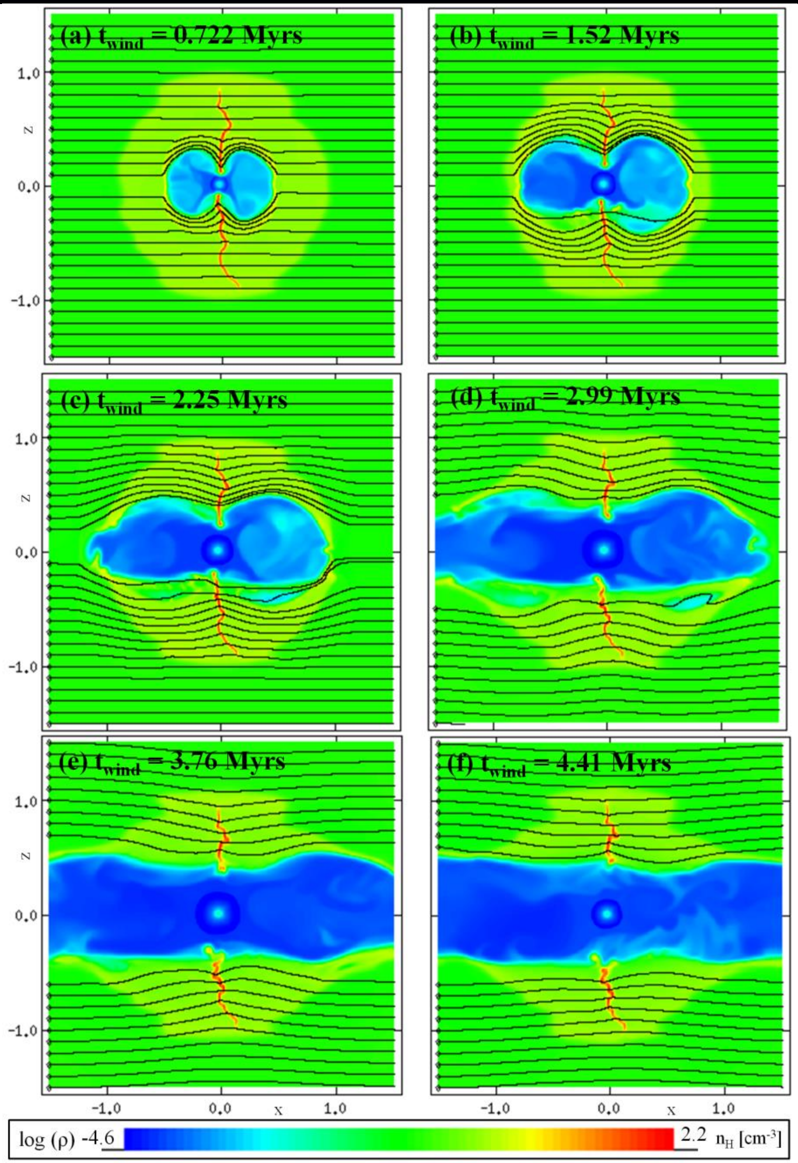
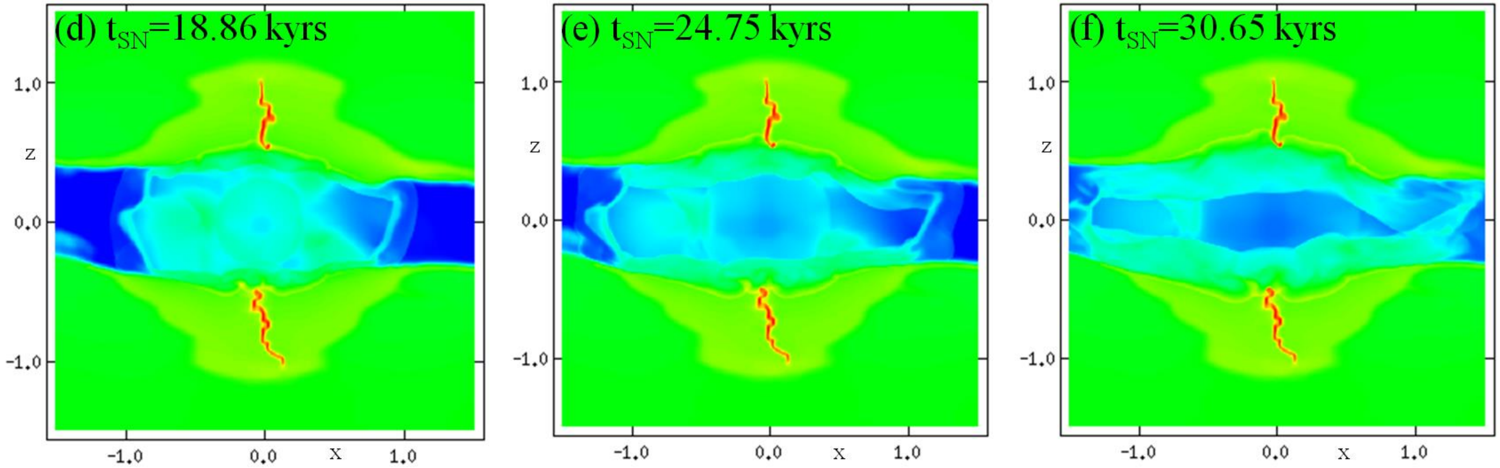
- **For this star, there's a significant impact on the molecular cloud.**
- Large bipolar cavity evolves into a cylindrical cavity (diameter ~40 pc) through the centre of the cloud.
- Cavity filled with hot, tenuous wind material moving at up to 1000 km/s.
- Magnetic field intensified by factors of 3-4 during this wind phase.
- Much of the wind material flows out of the domain along the cavity.



$40M_\odot$ star: SN phase

RESULTS



- Final LBV phase results in a high-density environment around star.
- WR wind sweeps this up into a D=25 pc shell, in which the SN explodes.
- Spherical SN remnant until it reaches the cavity wall (8 kyrs).
- SNR then accelerates away through the cavity, whilst slowing into the denser diffuse cloud and molecular sheet.
- SN forward shock leaves domain in 30 kyrs; c.f. 400 kyrs for 15 $M_\odot$ star.
- **Majority of SN energy and material leaves the cloud unhindered.**

$40M_{\odot}$ star: late SN phase

RESULTS

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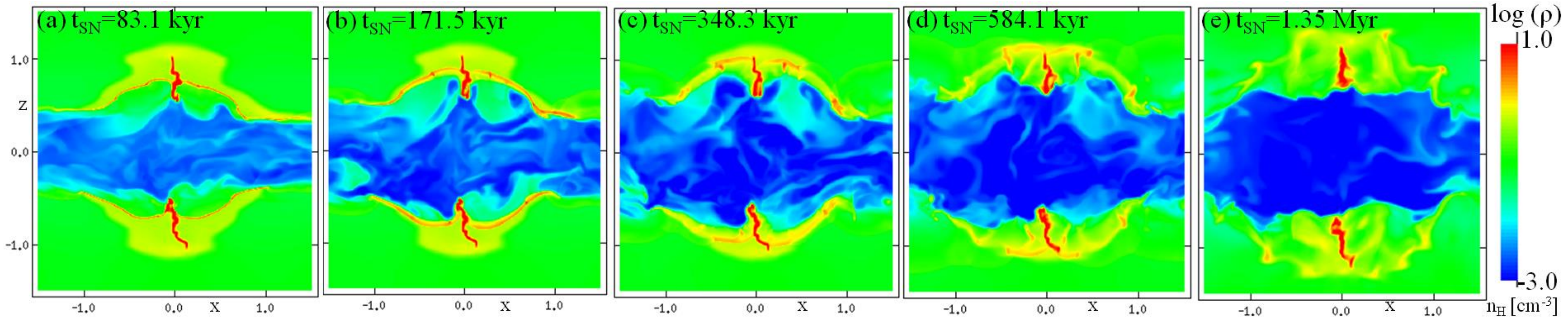

- SN passage through the parent cloud is considerably longer: 1.35 Myrs.
- Reverse shocks bounce off the cavity walls and begin to destroy the cloud.
- After 1.35 Myrs, the shell becomes subject to Rayleigh-Taylor instabilities.
- Molecular cloud survives this part of the evolution mostly in tact!
- Again though, **after 6 Myrs, the parent cloud is dispersed** – subject to the same numerical caveats.

Comparisons to previous work

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- There are large differences, especially in the initial condition, compared to our previous work (Rogers & Pittard) – no straightforward comparison.

- Key differences:
  - R&P: multitude of porous channels allow wind escape.
  - Here: expansion of a coherent bubble.

- Also, similarities:
  - SN can transport large fractions of energy without strongly affecting the parent cloud.

- Key factor**: the shaping effect of pre-SN winds**

Comparisons to other works

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- There's agreement with other authors regarding:
  - Lower mass stars have little effect on parent cloud.
  - Mass-loss rates below 10^{-7} $M_{\odot}$ yr^{-1} have little effect on the parent cloud.

- High levels of turbulence have been shown to resist shaping effects of winds.
  - Are these appropriate? We generate structured large-scale flows in this scenario, leading to trans-sonic motions in the cold gas as observed, without the introduction of turbulence.
  - How are such high levels of turbulence (Mach 10, Mach 15) established and maintained?

Comparisons to observations

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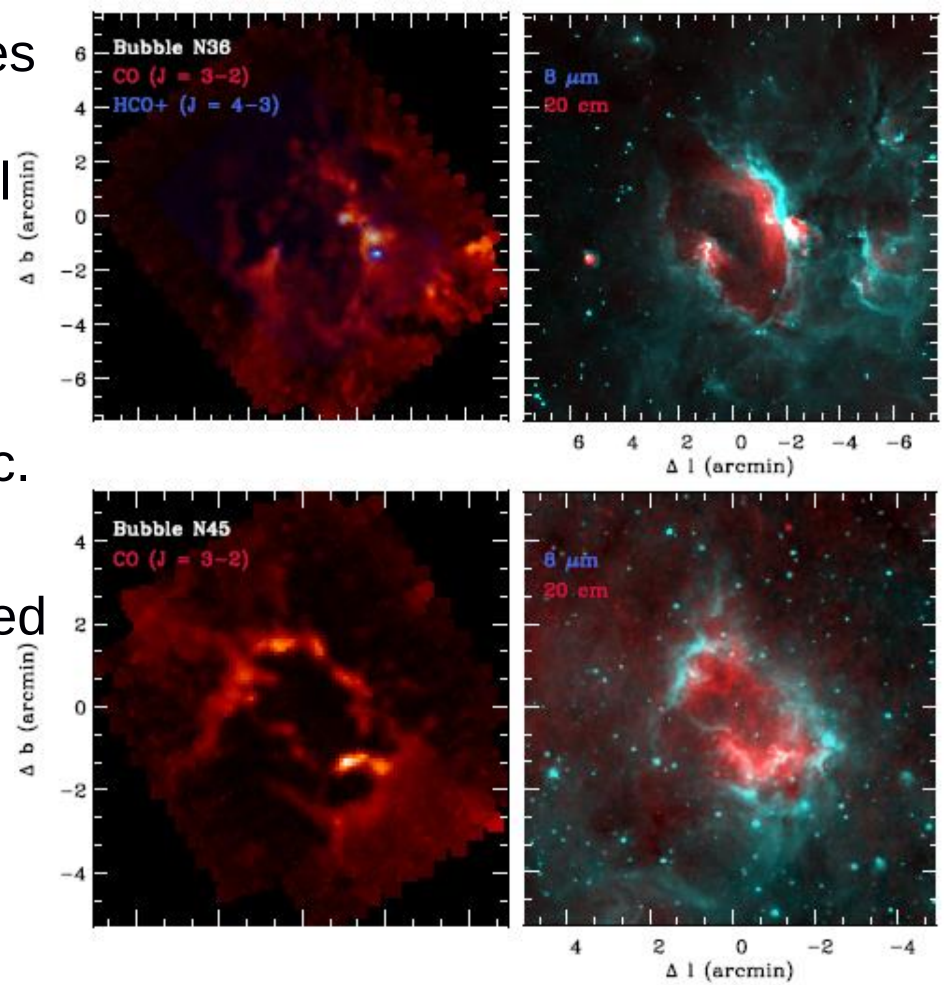
- Bubbles interacting with flattened clouds and bipolar HII regions.
- Observations of wind-blown bubbles often reveal the surrounding gas has a ring-like rather than spherical morphology (controversial!).
- Observations detect little CO with the implication that the molecular clouds have thicknesses of few ~pc.
- Our work naturally produces such structures, along field line dominated evolution.
- Bipolar HII regions would form if we had included photoionization (when!).



Beaumont & Williams 2010, ApJ, **709**, 791-800

Comparisons to observations

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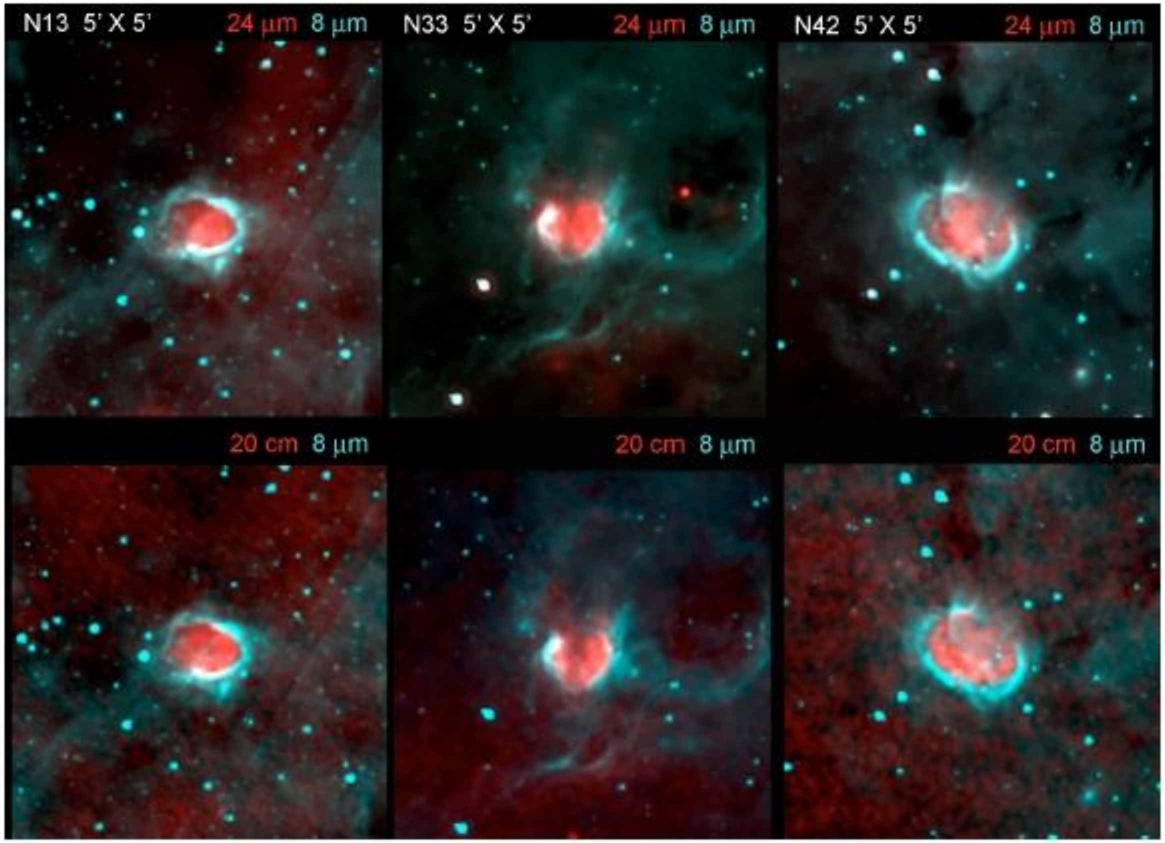

- Beaumont & Williams found 43 small *Spitzer*-GLIMPSE objects with ring, not spherical, cloud structures.
  - Based on failure to identify line of sight velocity components.

The Rosette Nebula

The Rosette Nebula

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- Large HII region in the Monoceros GMC complex.
- Shocked high velocity cloud? (***see 1980s Tenorio-Tagle!***) Or edge of large SN remnant?
- Central cluster is NGC 2244 with age estimates 2-6 Myrs.
- South-Eastern extent is interacting with the Rosette Molecular Cloud.
- Candidate for triggered star formation (controversial!)
- RMC shows triggered star formation at the junction of filaments.

IPHAS Hα image (Credit: N.Wright/IPHAS)

- D ~ 1.6 kpc +/- 250 pc

- Central cavity r = 6.2pc (Celnik 1985, at 1.4kpc), r ~ 5 pc (IPHAS, at 1.53kpc).

NGC 2244

THE ROSETTE NEBULA

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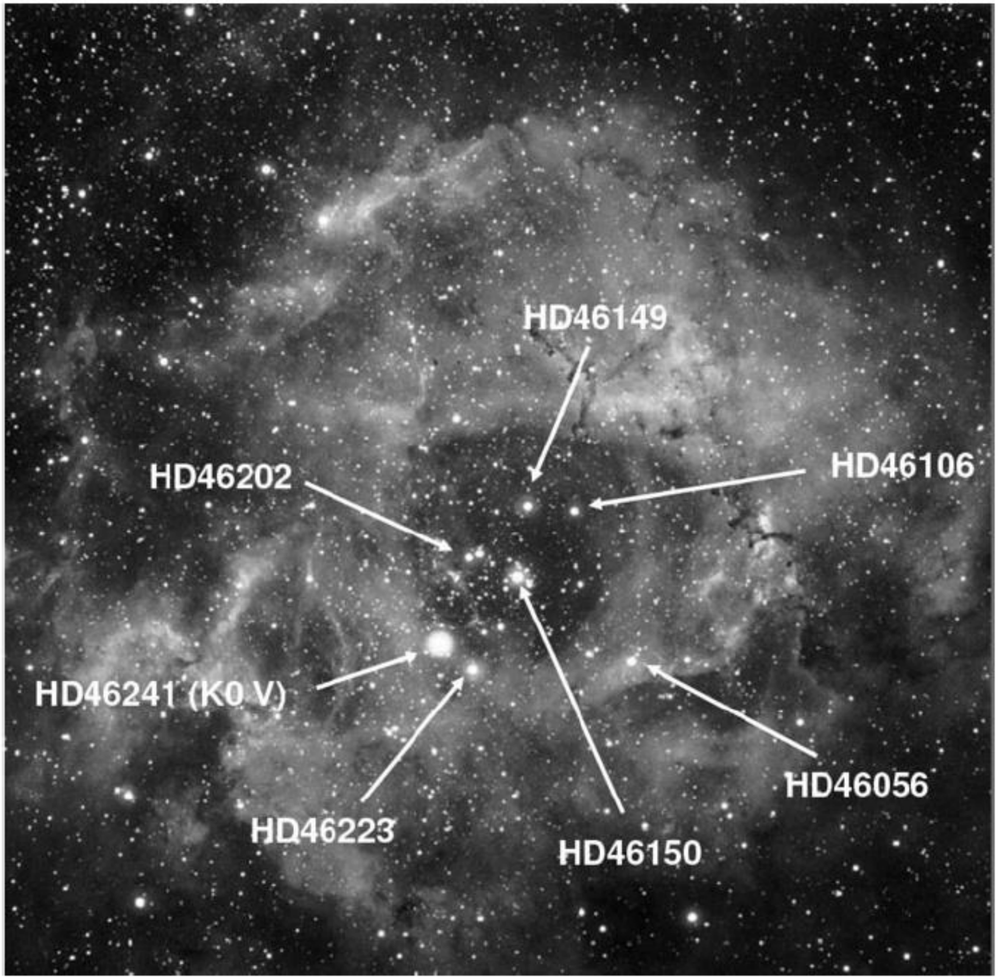
- Central star cluster has 5 O-stars and 1 B-star.
- HD46150 O5 V(f) and HD46223 O4 V(f) have inferred mass-loss rates two orders of magnitude greater than the rest.
- HD46223 (~55 $M_\odot$) is at the edge of central cavity.
- The Rosette Nebula *could* be dominated by a single ~40-50 $M_\odot$ star : HD46150.
- Proper motion analysis in the literature finds no ejection vector for HD46223 - may not be a member of NGC2244.



Bruhweiler et al. 2010, ApJ, **719**, 1872-1883

Dynamical age and missing wind issues

THE ROSETTE NEBULA

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Bruhweiler et al. 2010, ApJ, **719**, 1872-1883

- The shell around the central cavity is expanding at 56 km/s w.r.t. the embedded stars, while the surrounding HII region expanding at 13 km/s.
- Even though the stars are **young (2-4 Myr)**, both the radius and deduced expansion velocity point to an age of the cavity of only **64,000 years**!
- **Strong contradiction** between Strömgren sphere theory and modelling.
- Assuming adiabatic expansion of a sphere, where is the missing wind luminosity that has been injected by the central star(s)?
- Total stellar mass-loss rate may be over-estimated, but not to the level required to provide systematically low enough mass-loss rates.

- Turbulence in low mass clouds may confine radiative feedback, but confining mechanical feedback requires high levels of turbulence (M~10!)

64,000 years!?

THE ROSETTE NEBULA

Bruhweiler et al. 2010, ApJ, **719**, 1872-1883

Properties: r ~ 6.7 pc (1.53kpc); shell expansion vel. 56 km/s; Nebular HII expansion velocity ~13 km/s. HI expansion velocity ~4.5 km/s.

Bruhweiler et al. find:
- average separation for heliocentric radial velocities ~ 43 km/s;
- average photospheric radial velocities ~31 km/s;
- average velocity for NGC 2244 ~ 26 km/s.

Bruhweiler et al.:
- NGC2244 26 km/s result had too many members – adopt 13 km/s;
- find an upper dynamical limit of 6.2pc / (43+13 km/s) = 110,000 yrs;
- calculate a Weaver-based adiabatic bubble estimate of 76,000 yrs, with predicted shell expansion velocity of 48 km/s;
- calculate a momentum-conserving estimate of 270,000 yrs with predicted velocity around 12 km/s.

Thus, adiabatic case is more consistent

Note: emission from HD46223 is **not** line broadened – outside cavity?

Solutions?

THE ROSETTE NEBULA

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- Bruhweiler et al postulate “an ejection event formed the cavity”. Much of the momentum of the stellar winds has gone to drive the expansion of the surrounding HII region.

- But Bruhweiler et al. emphasize they cannot rule out that there is not an asymmetric cavity where the much larger axis is directed toward observer.
  - This also explains the small radius seen in the plane of the sky

- They find an axis ratio >17, which they find “**uncomfortably large**”.

Bruhweiler et al. 2010, ApJ, **719**, 1872-1883

Rejecting the age estimate of 64,000 yrs, V_{exp}~13 km/s leads to an age estimate of ~450,000 yrs, >4x less than 2-6 Myr NGC2244 estimate.

Solutions?

THE ROSETTE NEBULA

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Definitely not Occam's razor!

- Bruhweiler et al postulate "an ejection event formed the cavity". Much of the momentum of the stellar winds has gone to drive the expansion of the surrounding HII region.

- But Bruhweiler et al. emphasize they cannot rule out that there is not an asymmetric cavity where the much larger axis is directed toward observer.
  - This also explains the small radius seen in the plane of the sky

- They find an axis ratio >17, which they find "**uncomfortably large**".

We are much more comfortable with this!

A new model...

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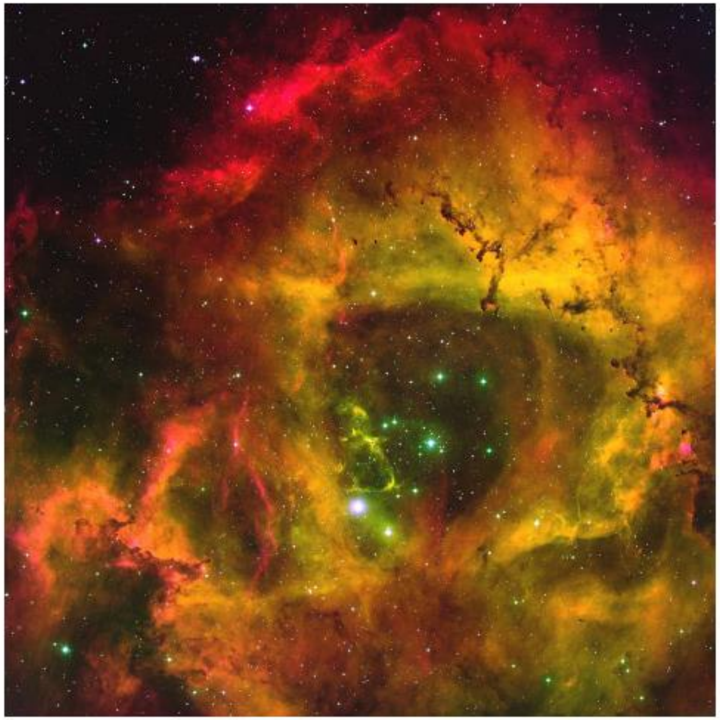
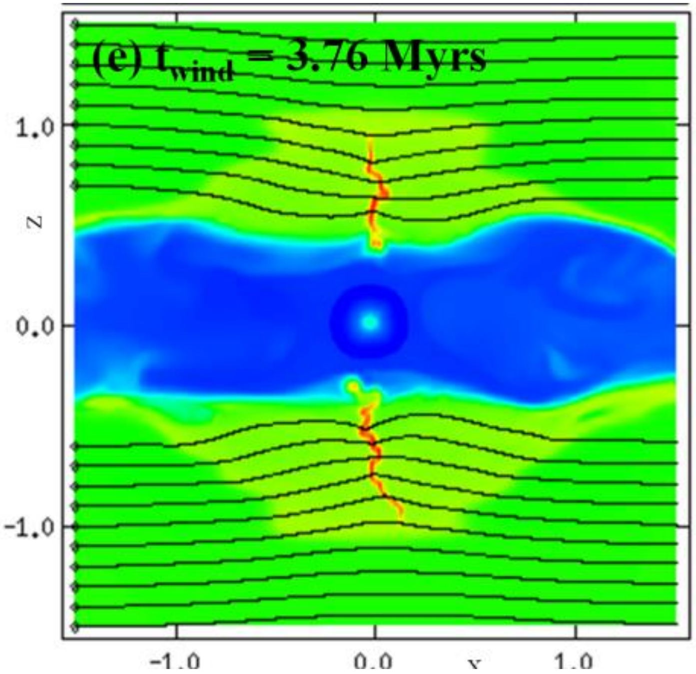
- What if this...



...was formed like this.



- Our simulations have shown it's possible to clear a relatively small central cavity from a sheet-like parent molecular cloud.
- **Instantly solve the deduced age problem!**
- Not an entirely a new idea for the Rosette. (see Meaburn & Walsh 1981 Ap&SS **74** 169)

Rosette surroundings
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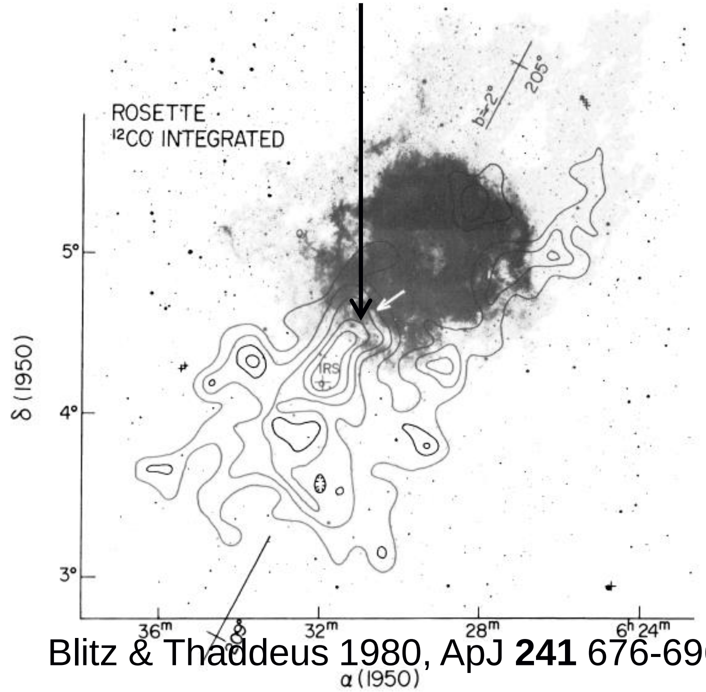
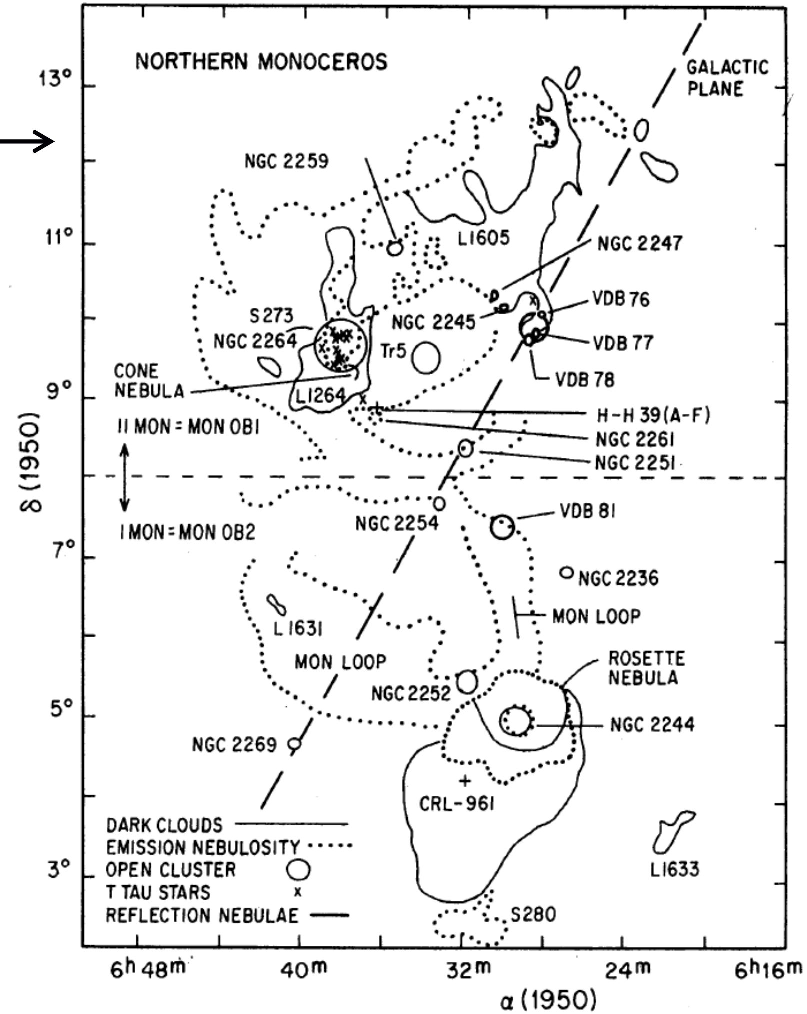
- How do the surroundings look?
- Northern Monoceros complex →
- RMC region of triggered star formation



Blitz & Thaddeus 1980, ApJ **241** 676-696



- So, triggered star formation appears localised.

Pérez 1991 RMxAA **22** 99-111

Background magnetic field

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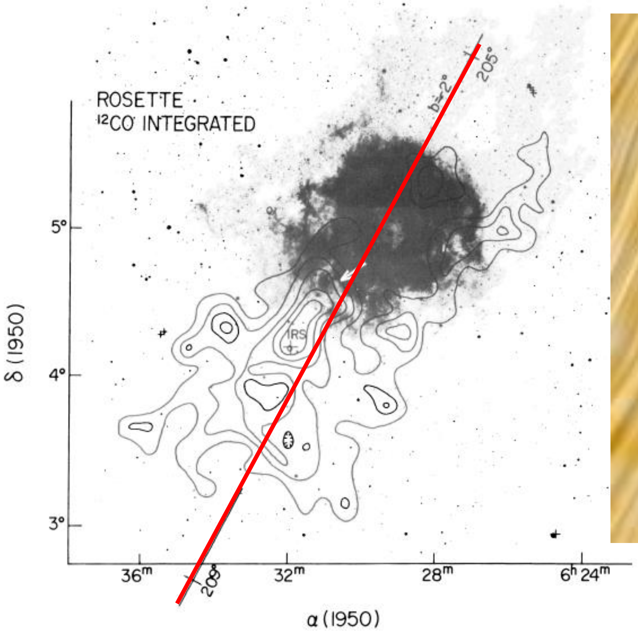
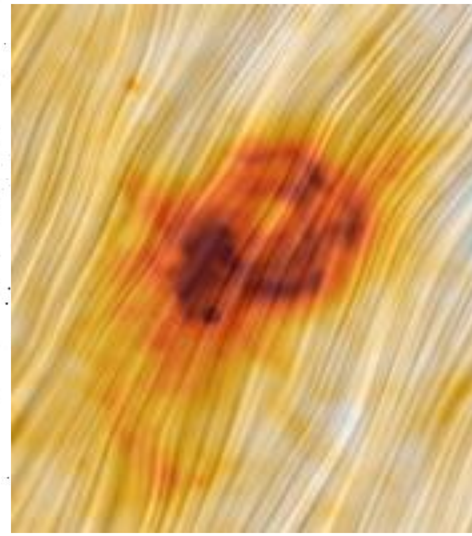
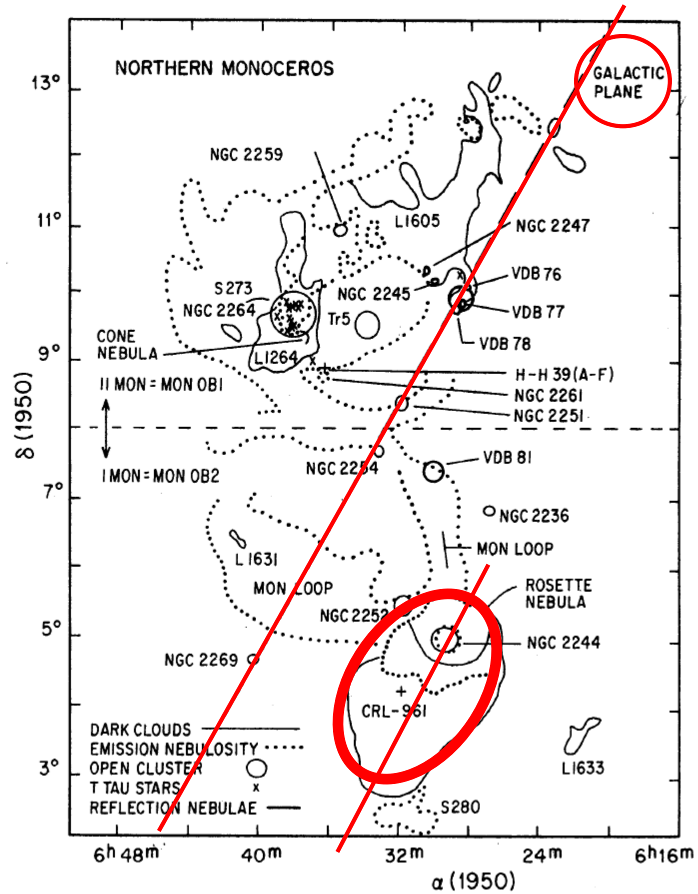
- In our model, wind ejection is along the field lines.
- Where is the magnetic field here?





(Credit: ESA and the Planck Collaboration)



- Wind ejection along **B** is **a perfect fit** for the triggered star formation.

Magnetic field prediction: *Planck*

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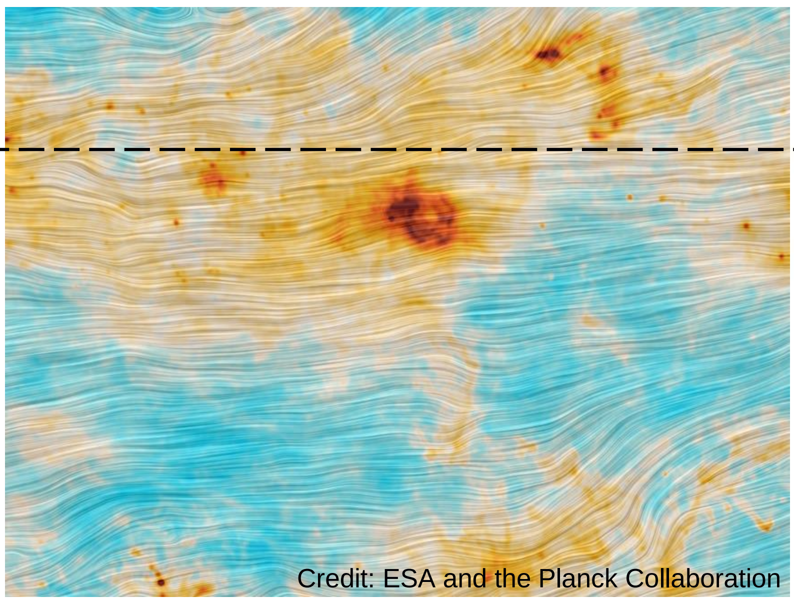
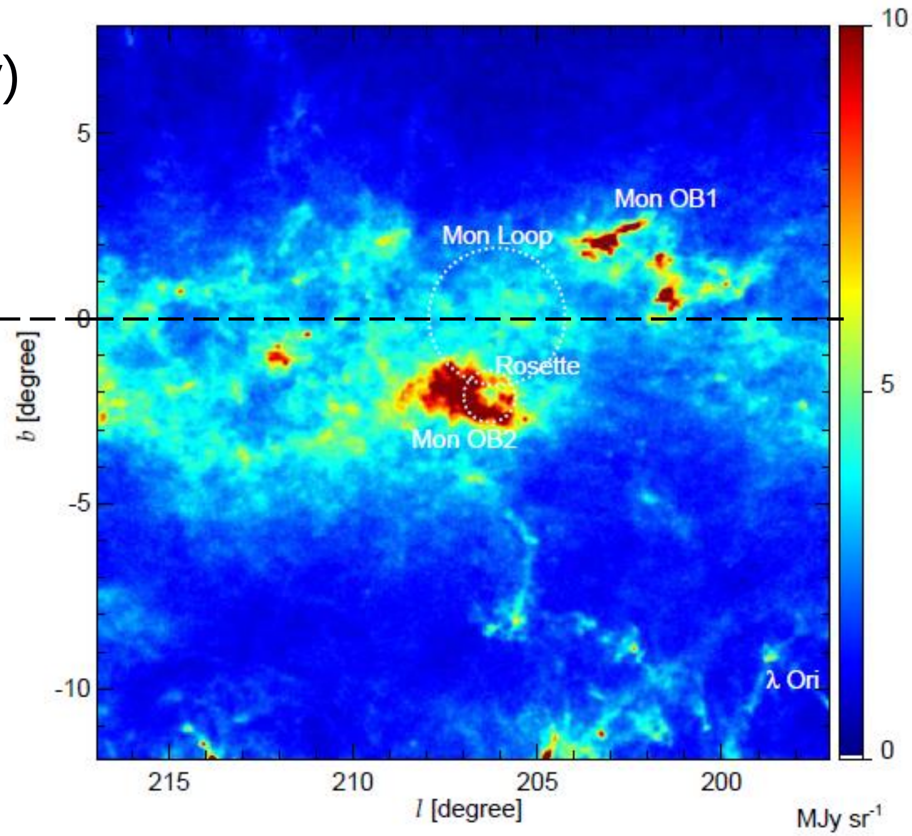
- Confirmation that the field is along the Galactic plane from *Planck*
- Shown below is a detail of the *Planck* observation around the Orion molecular field
  (colour scale: total dust intensity)


Credit: ESA and the Planck Collaboration



Recent *Planck*+starlight results

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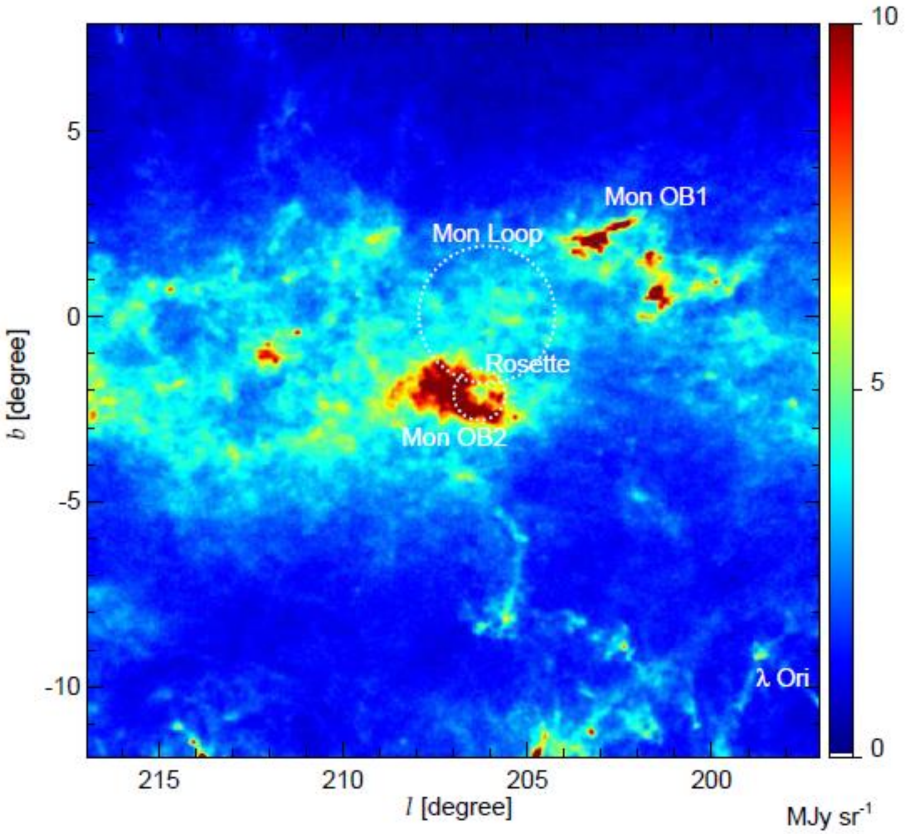
- The location of triggered star formation in the context of our model implies an angle of the wind flow to the line of sight.
- Is there any evidence for this?
- Some from observations of the background magnetic field.
- Observations with *Planck* combined with rotation measure towards the Rosette.
- **Upper limit of 45º of angle to line of sight.**
- In good agreement with what our model would require...



New proper motion analysis

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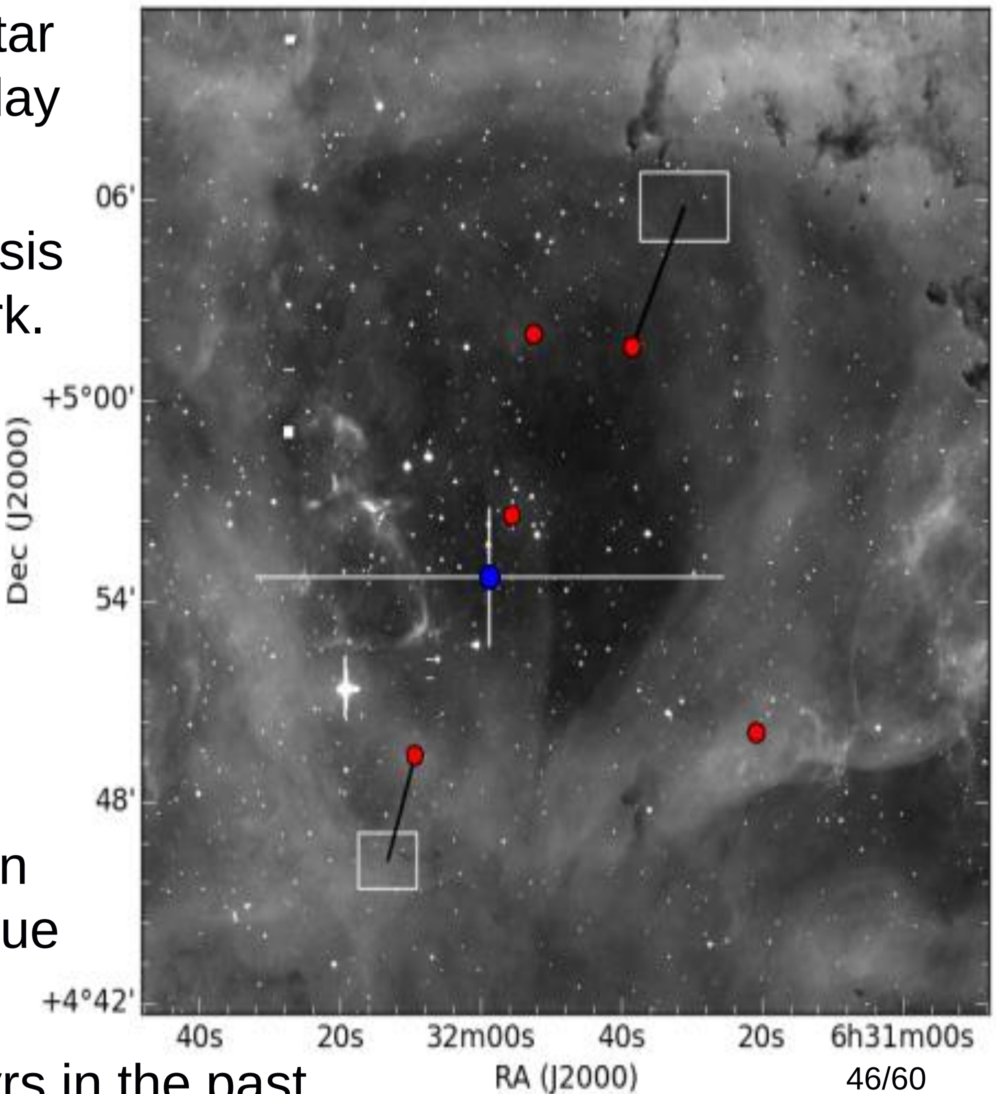
- Our models imply only a single star is required, but does HD46223 play a role? Is it associated?
- New *GAIA* Data Release 1 analysis by N. Wright at Keele for this work.
- Red points: *Hipparcos* and Tycho members of NGC2244.
- Two runaways detected – HD 46149 and **HD 46223!**
- Black lines show proper motion vectors.
- Best fitting back-traced interaction for these two stars shown as a blue circle with 1σ error bars in white.
- Coincident 1.73 (+0.34,-0.25) Myrs in the past.



The first models...

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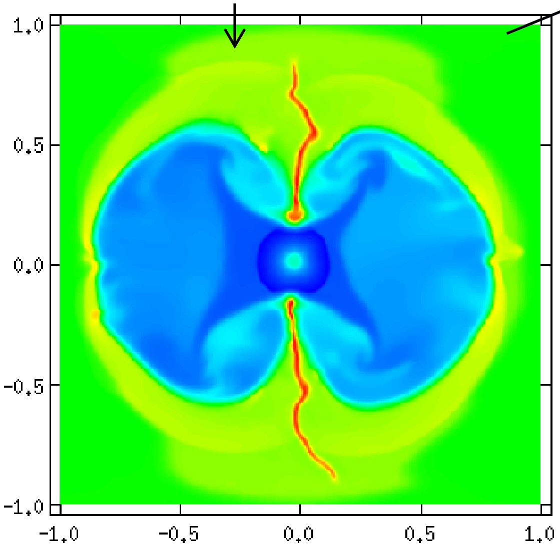
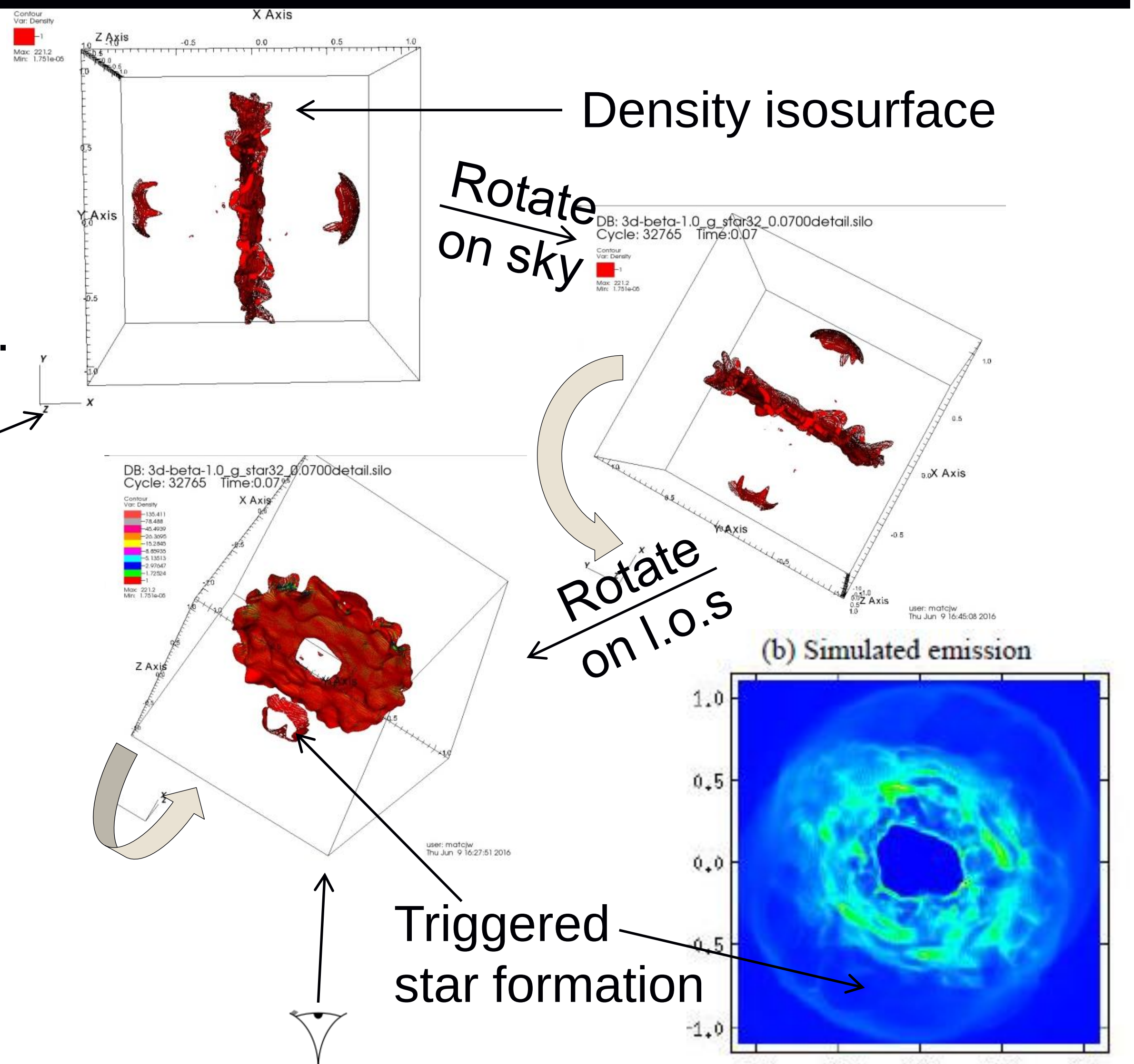
- New simulation of a 60 $M_{\odot}$ star in the same initial condition.
- Evolved for 2 Myrs as implied by proper motion.
- Slice plane at y=0.





- Central hole: D=18-20pc (c.f. IPHAS - 10pc).

…not without problems.

THE ROSETTE NEBULA`

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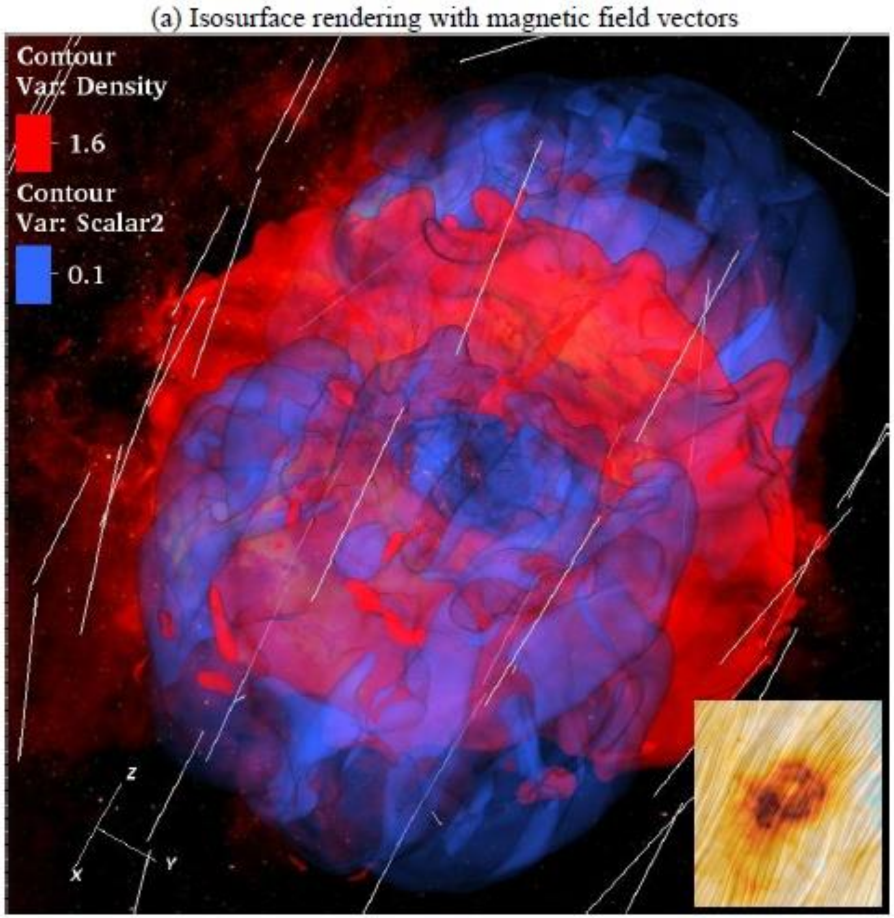

We have a solution for:-

- The overall structure.
- The mismatch of ages.
- The missing wind luminosity problem.
- The position and localised nature of the triggered star formation.
- Magnetic field alignment and the angle to the line of sight.
- Ejection of HD46223 from the cluster.

But have some problems...

- Low mass cloud (17,500 $M_{\odot}$)
- Rosette estimates are 10x more ~1.65e5 $M_{\odot}$ (from CO Measurements).

(The Rosette lies at one end of the cloud so the local region likely has less mass)

A second iteration of simulations...

THE ROSETTE NEBULA

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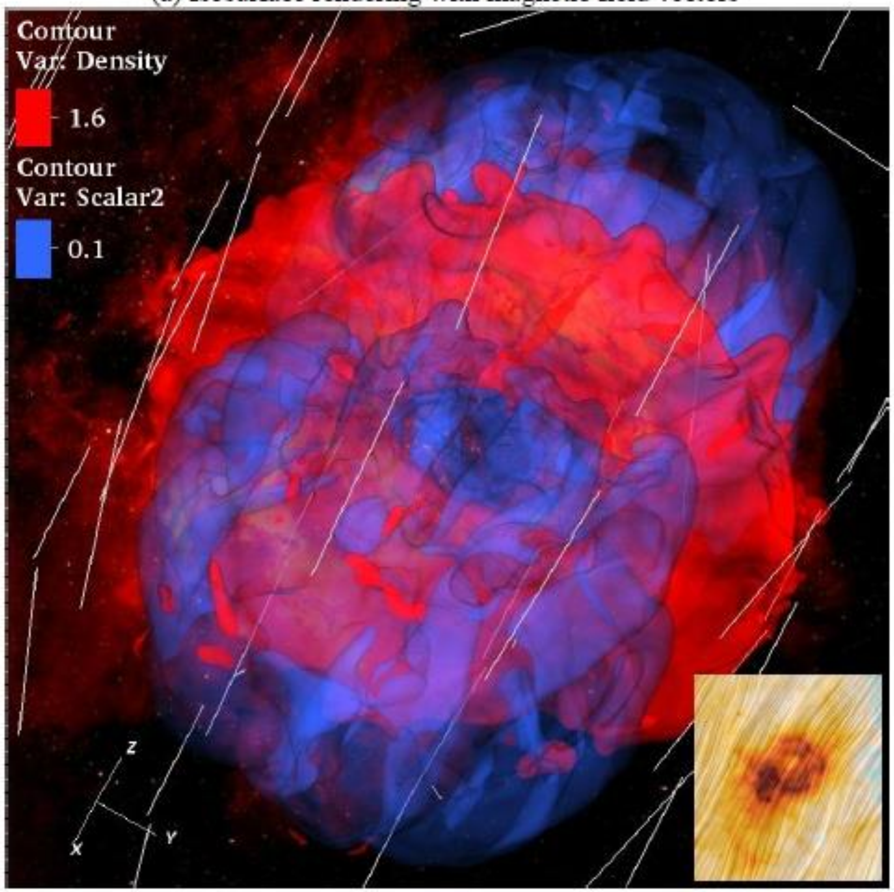
(a) Isosurface rendering with magnetic field vectors



- Refined simulations in a much larger cloud (135,000 $M_{\odot}$):
  - 60 $M_{\odot}$ star: hydro ($\beta=\infty$), pressure equivalence ($\beta=1$), $\beta=1$ double star.
  - 40 $M_{\odot}$ star injected at a later time – thin disc-like cloud.

Initial conditions – 135,000 $M_\odot$ cloud

REFINED SIMULATIONS OF THE ROSETTE NEBULA

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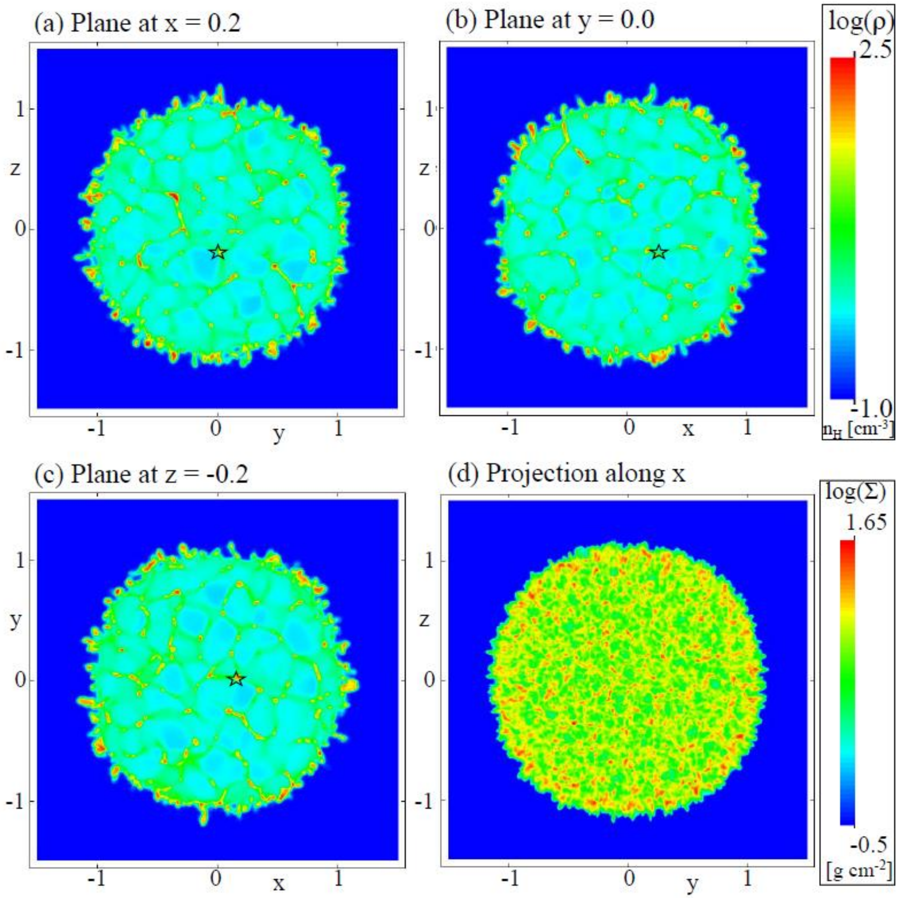
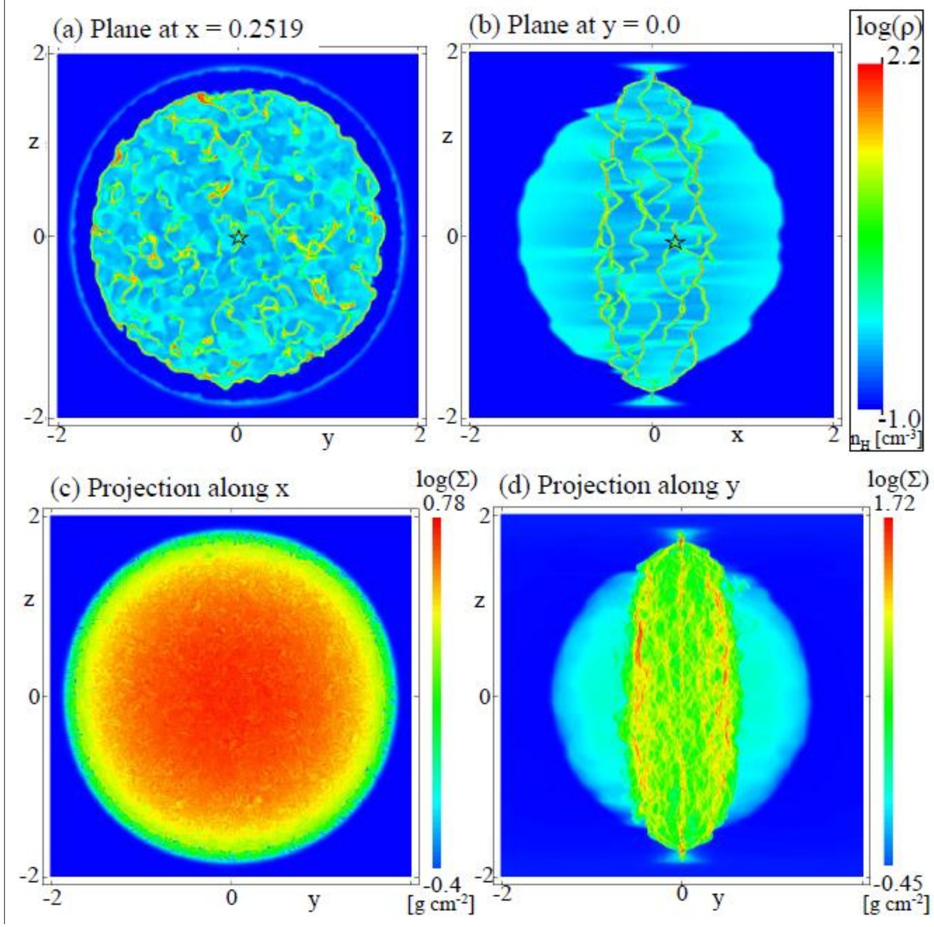
Hydrodynamic case



Magnetic field case



- In both cases, thermal instability drives the evolution on these large scales.

Results: hydrodynamic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA

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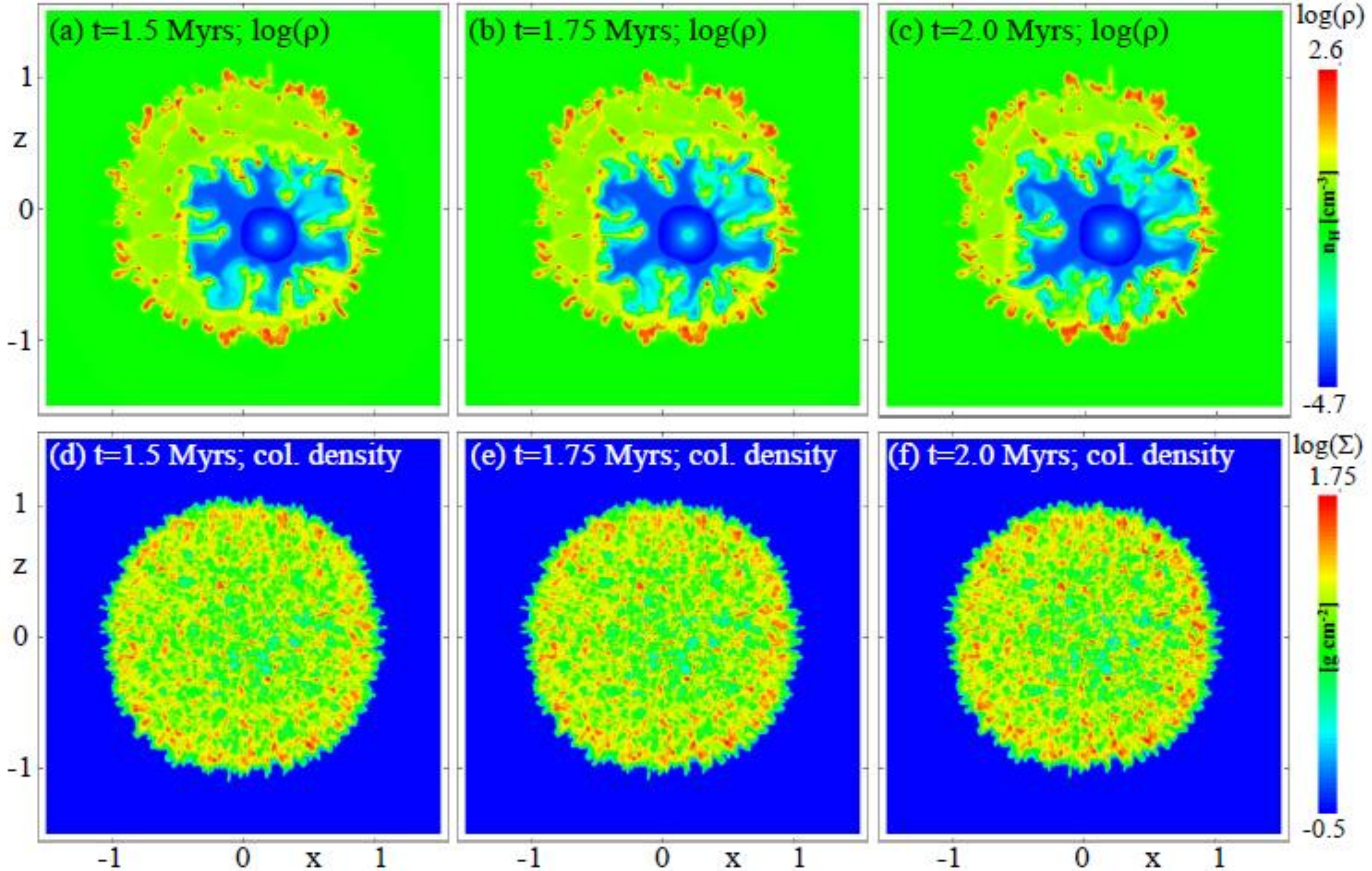

- Hydrodynamic case does not reproduce the Rosette nebula

Results: magnetic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA

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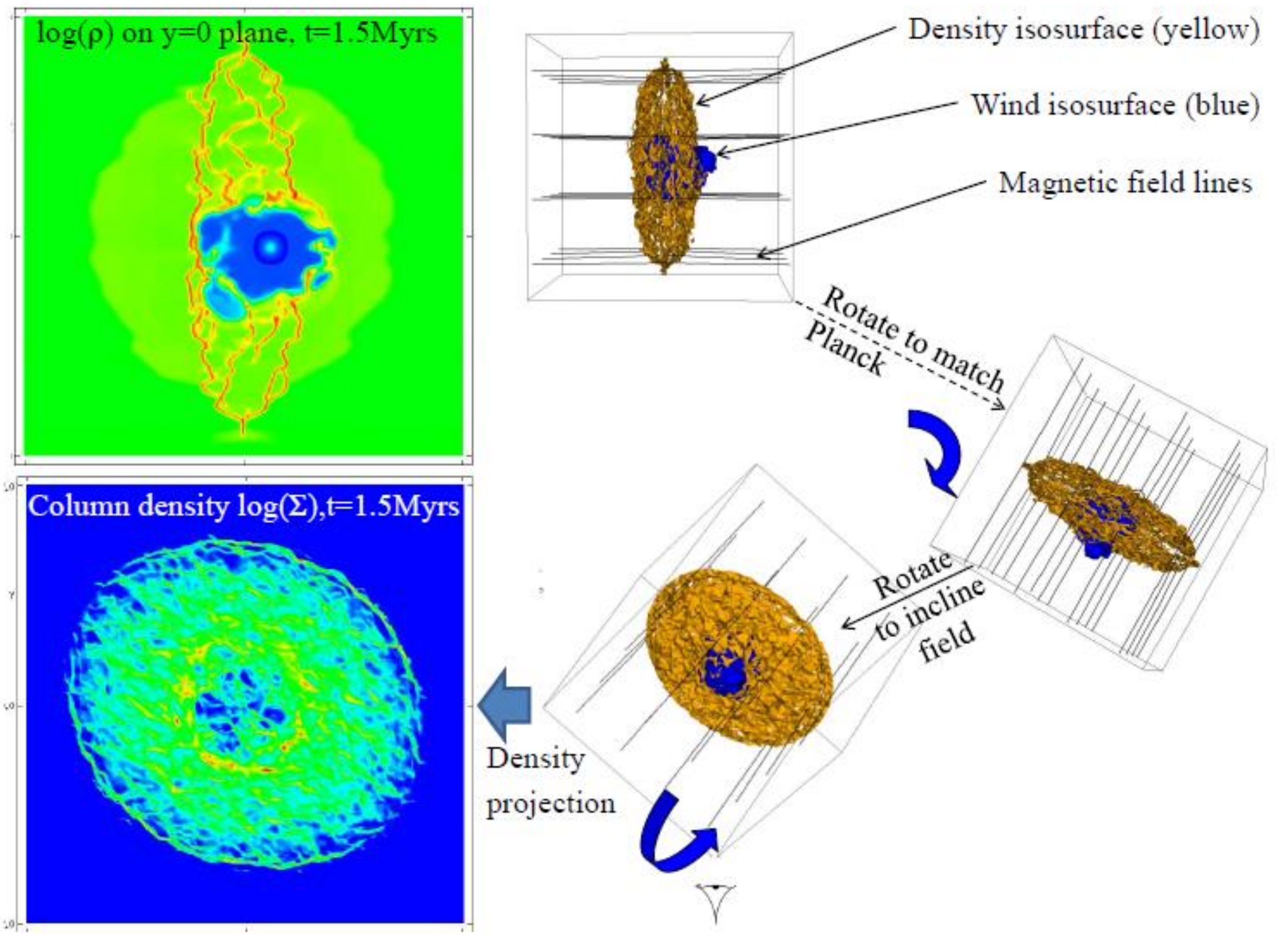
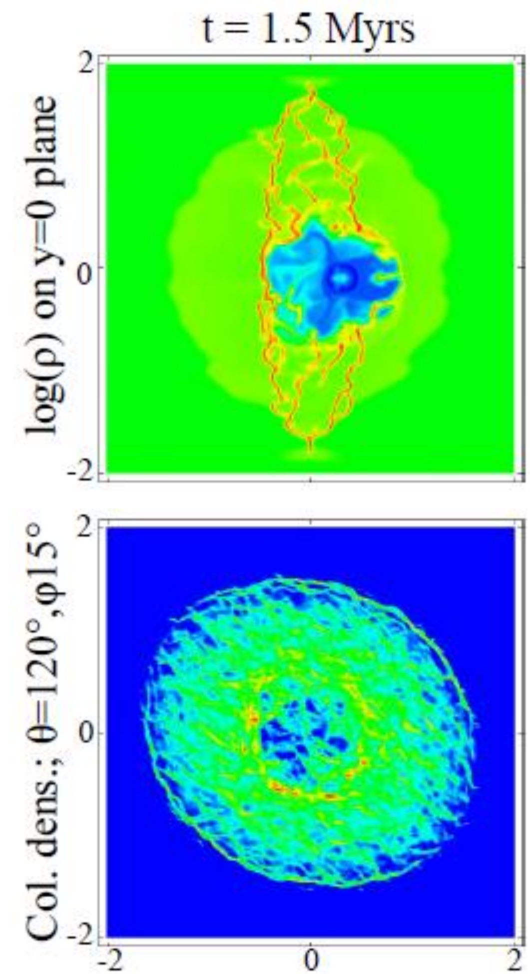
Magnetic field case with a single star



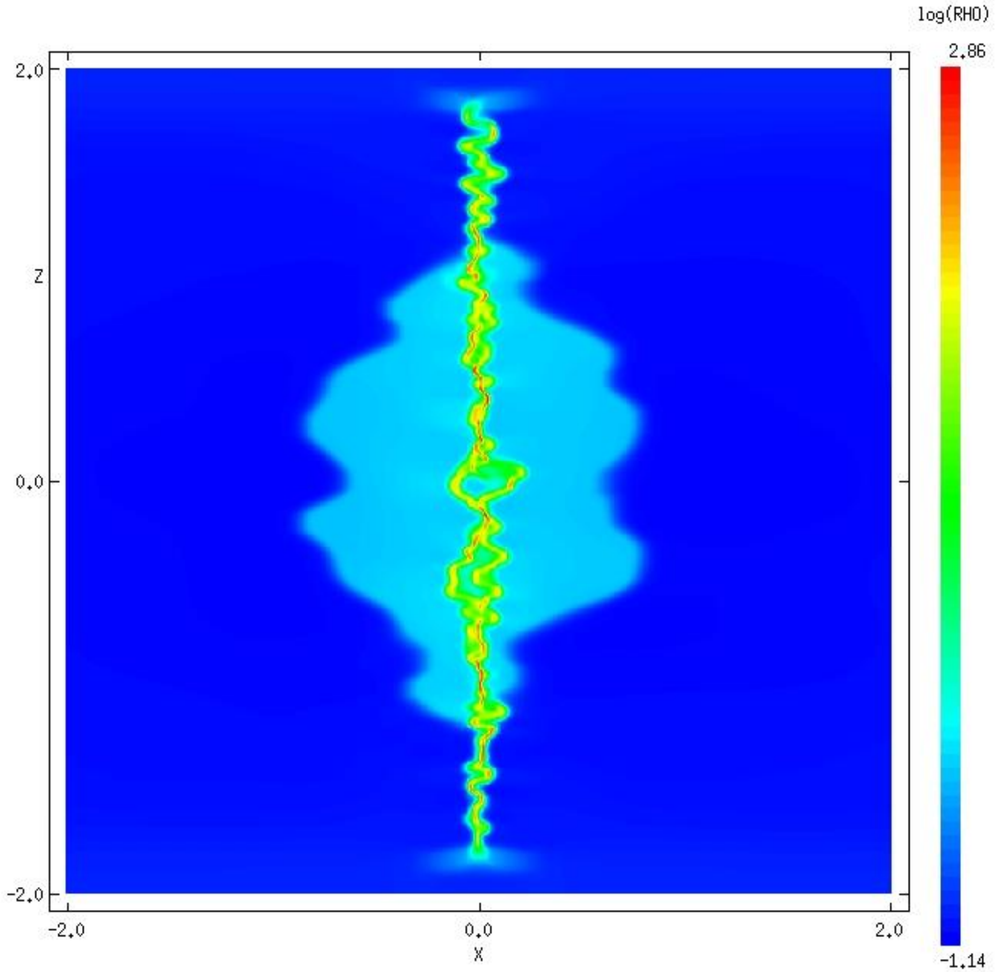
Double star



- Central ‘cavity’ is obscured and far too large – a thick disc does not work!

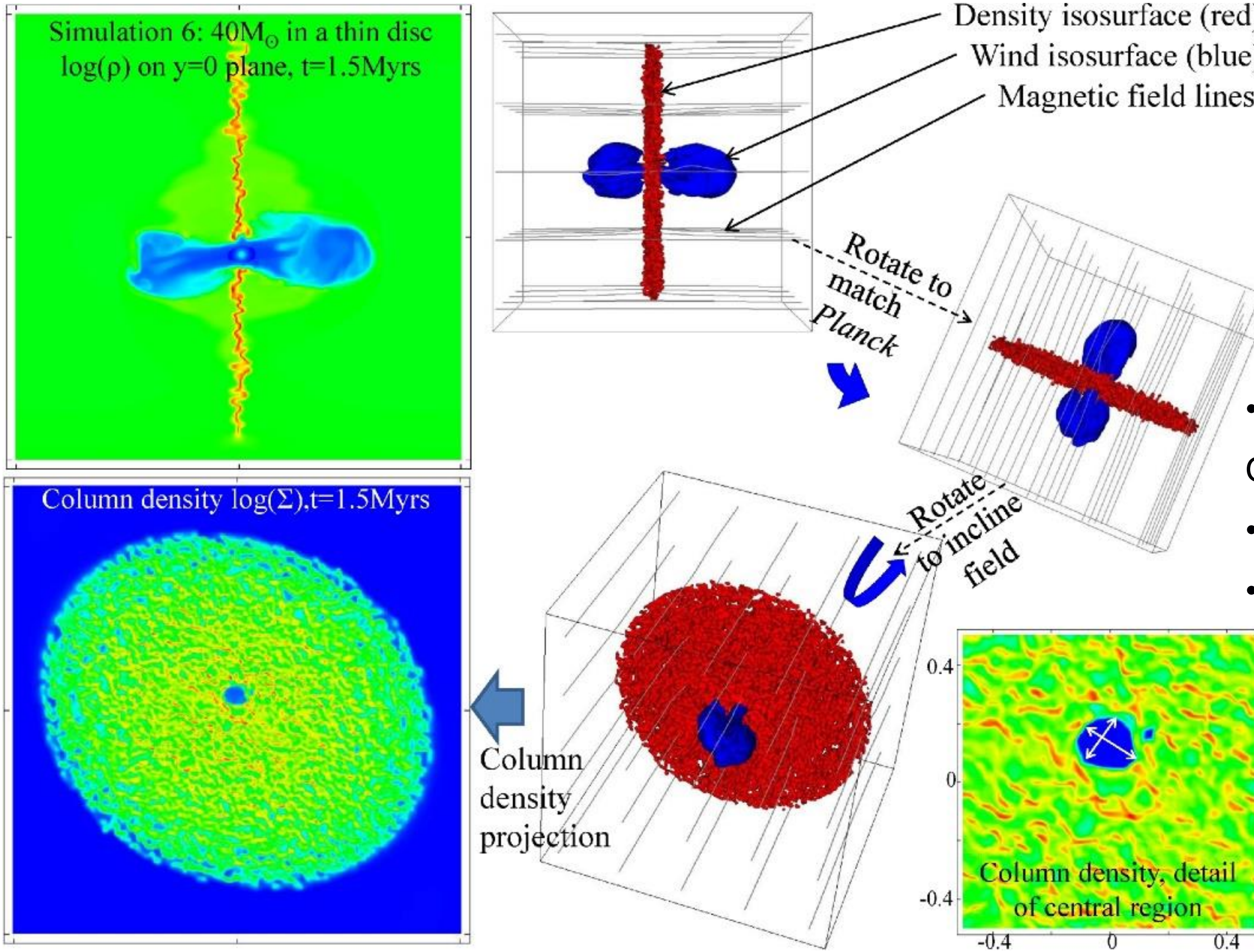
Third iteration… thin disk!

- Allow massive cloud to evolve further until the thick disk has collapsed to the thin corrugated disc similar to the low-mass case.
- Previous massive cloud cases involved the star injected after 36.8 Myrs of evolution (from the diffuse initial condition).
- Massive cloud has collapsed after 46.4 Myrs of evolution.
- Inject 40 $M_{\odot}$ star (to bracket lower mass estimates for HD 46150) and evolve for 2 Myrs.



Success! Thin disk magnetic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



- size:10x7.5 pc

Observations:

- Celnik: d~13 pc
- IPHAS: d~10 pc

What next?

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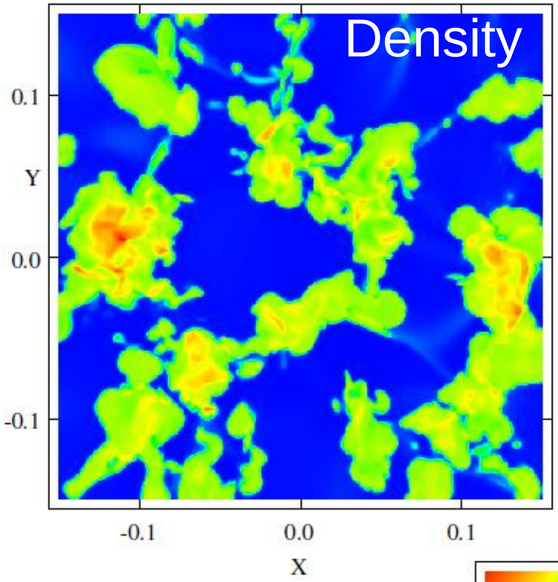
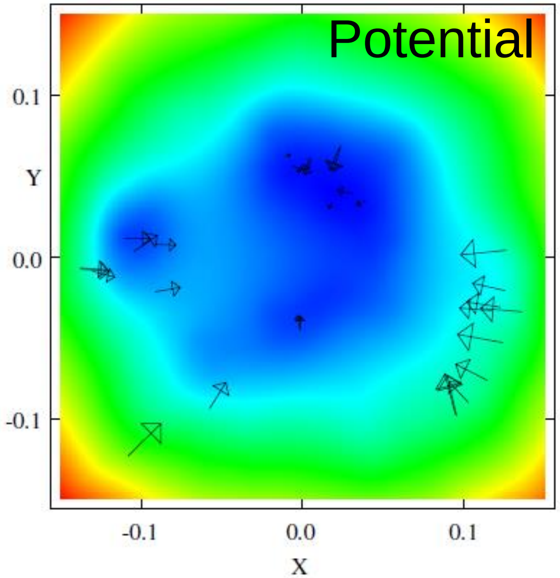
- Our set of simulations of molecular clouds formed through the thermal instability have revealed an intriguing possibility.



- Clumps form in the clouds without magnetic field. These clumps have the right size and mass scales as those observed.

- But do they collapse into true star-forming cores?



- Does this work in the magnetic case?

Turning clouds into clumps and cores

HIGH RESOLUTION HD SIMULATIONS

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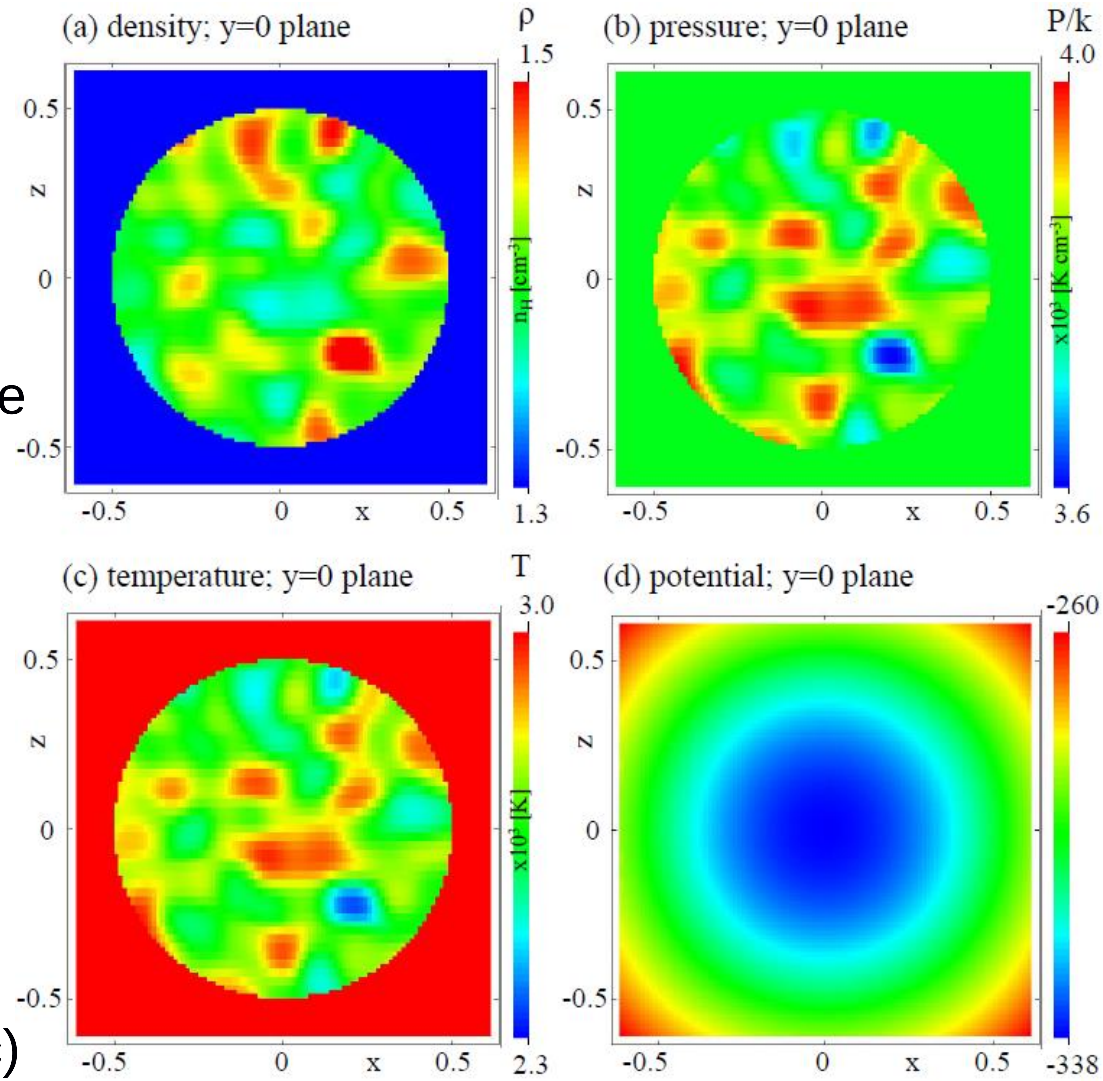
Can TI, subsequently dominated by gravity, create truly star-forming collapsing clumps with realistic properties?

High-resolution simulations

- Central 3000 $M_\odot$ sphere of the HD simulation of large cloud for the Rosette
- Placed in warm stable surroundings to isolate effect of the thermal instability and self-gravity
- Stationary quiescent cloud
- 10x higher resolution:
  0.29 pc -> 0.039 pc (0.016 pc)



Sheets, filaments and clumps

HIGH RESOLUTION HD SIMULATIONS

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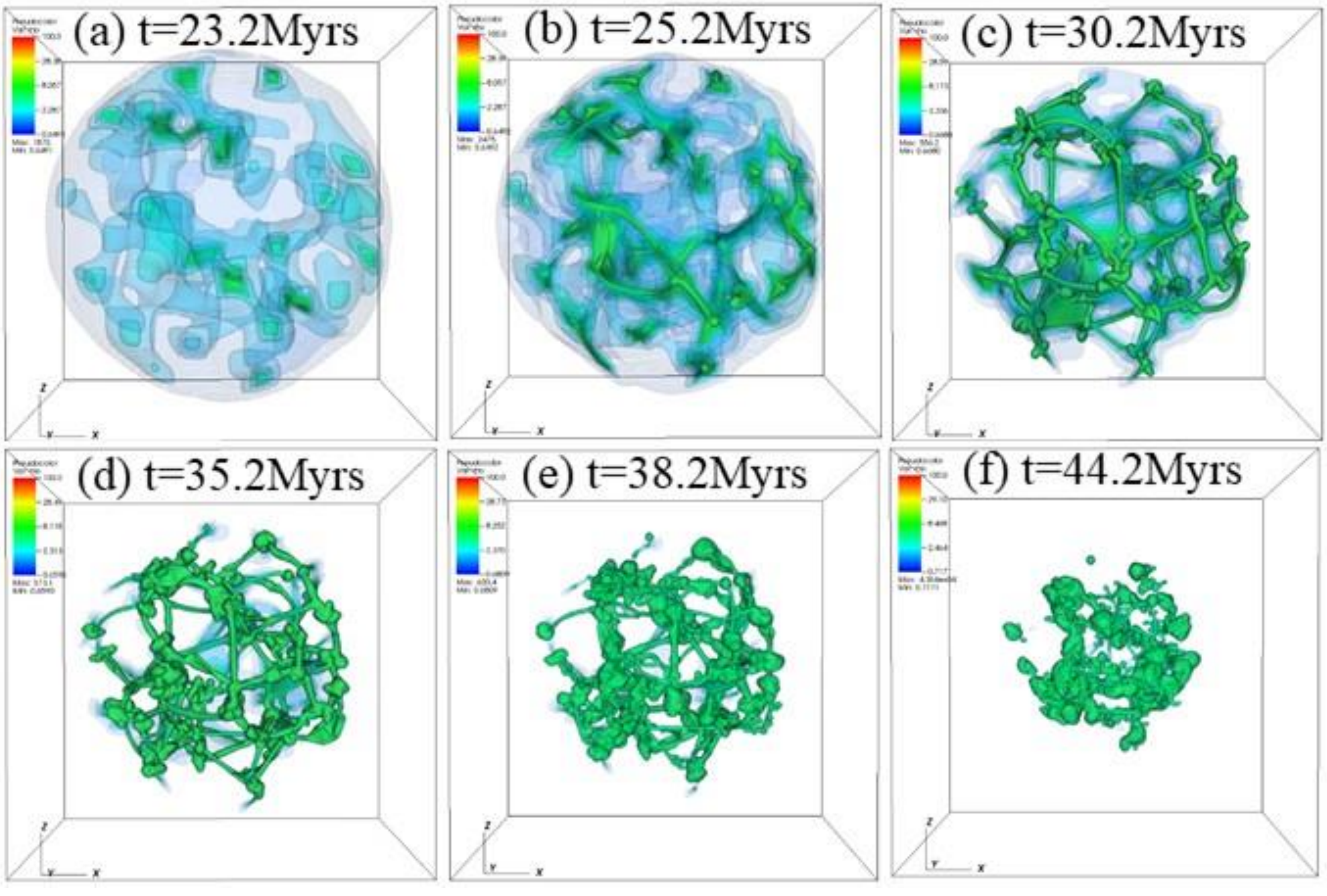
Creates a network of cold, dense clumps, multiply-connected by filaments!



Sheets, filaments and clumps
HIGH RESOLUTION HD SIMULATIONS

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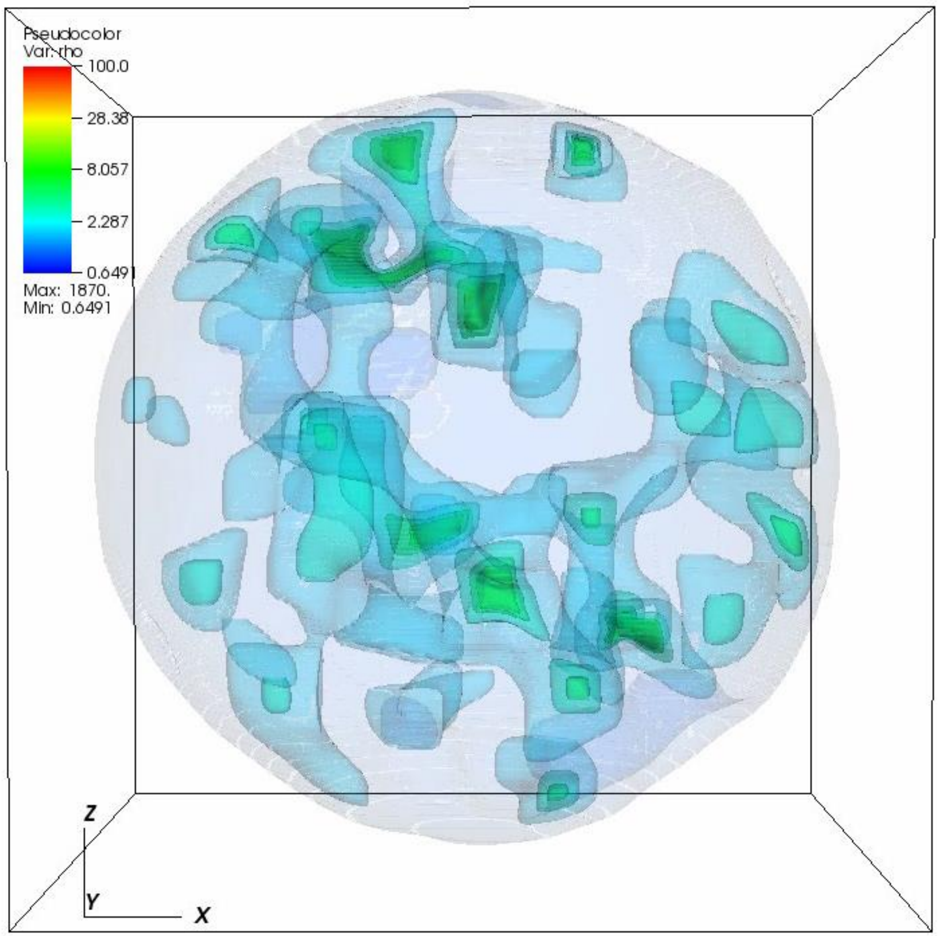

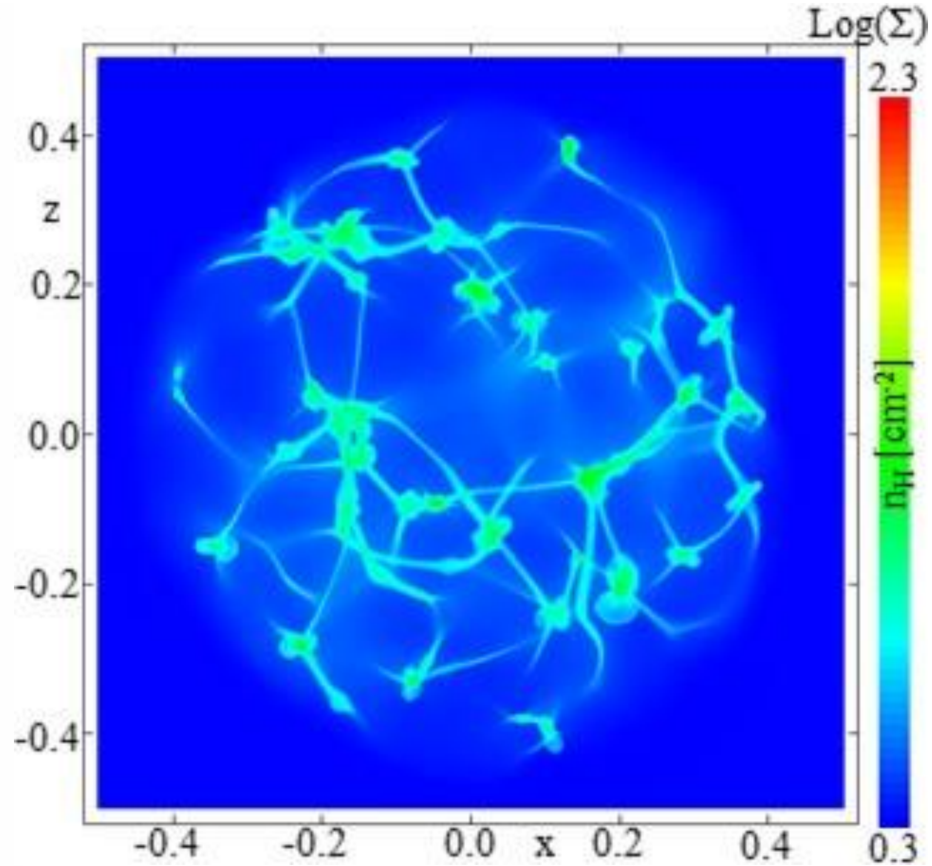

Filament widths 0.1 to 0.3 pc!

At the limit of detectability previously.

Clump properties

HIGH RESOLUTION HD SIMULATIONS

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21 clumps more massive than 20 $M_\odot$.

Table 1. Properties of the 21 clumps with more than 20 $M_\odot$ identified by the FellWalker algorithm, at t=44 Myr in the Model 3 simulation. Snapshots of slices through the clumps are available from https://doi.org/10.5518/XXX.

	M_{total} [$M_\odot$]	M_{warm} [$M_\odot$]	$M_{unstable}$ [$M_\odot$]	M_{cold} [$M_\odot$]	ρ_{max} n_H [cm^{-3}]	T_{min} [K]	Scale [pc]	v_{max} [$km\,s^{-1}$]	v_{min} [$km\,s^{-1}$]	Notes
A	2.37e2	5.39e1	3.19e0	1.78e2	4.62e2	30.5	3.5	2.2	0.11	Spheroidal, extended arms
B	2.64e2	2.36e1	4.10e0	2.37e2	9.92e2	21.5	4.0	2.8	0.31	Prolate spheroid
C	2.71e2	4.49e1	4.25e0	2.22e2	7.76e2	22.9	4.0	2.4	0.12	Pyramidal
D	3.54e2	5.65e1	6.49e0	2.92e2	1.46e4	10.6	4.0	2.5	0.17	Multiple lobes
E	7.27e1	1.05e1	1.01e0	6.12e1	4.16e2	31.3	2.5	1.9	0.03	Spheroidal
F	1.08e2	1.55e1	1.01e0	9.12e1	4.32e2	28.8	4.0	2.6	0.06	Double sphere merger
G	1.77e2	1.94e1	2.65e0	1.55e2	3.31e2	32.7	4.0	2.1	0.04	Peanut
H	2.65e1	2.01e0	3.19e-1	2.42e1	1.54e2	32.4	2.4	2.5	0.03	Clump on a filament?
I	7.57e1	5.88e0	1.06e0	6.88e1	1.94e2	33.4	3.0	2.2	0.18	Results of a merger?
J	3.13e1	2.59e0	2.93e-1	2.84e1	2.16e2	32.0	3.0	3.2	0.08	Co-flowing clumps
K	1.04e2	5.10e0	1.14e0	9.76e1	4.18e2	26.9	2.5	1.8	0.03	Isolated. Spherical
L	2.37e1	1.02e0	3.28e-1	2.23e1	2.83e2	31.1	1.0	2.5	0.01	Tadpole, 2.5 pc elongated tail
M	6.83e1	1.16e1	1.07e0	5.57e1	4.95e2	26.1	3.0	2.7	0.03	Elongated. Chain?
N	9.14e1	8.50e0	1.42e0	8.15e1	3.33e2	29.3	3.0	2.4	0.33	Spheroidal, linked filament?
O	4.85e1	8.63e0	1.28e0	3.87e1	2.34e2	29.9	3.0	1.7	0.02	Spheroidal - 2 filaments
P	6.84e1	2.20e1	1.66e0	4.47e1	1.89e2	33.1	3.0	1.9	0.07	Large tadpole
Q	6.63e1	5.19e0	9.80e-1	6.01e1	2.86e2	32.1	4.0	1.8	0.03	Sph. Off-centre max rho
R	2.96e2	3.19e1	2.76e0	2.62e2	3.25e3	16.9	5.0	2.4	0.13	Multiple lobes - subclumps?
T	7.25e1	7.70e0	1.00e0	6.38e1	3.92e2	27.4	5.0	2.5	0.02	Double merger
U	3.57e1	1.53e0	7.64e-1	3.34e1	2.06e2	33.0	3.0	2.3	0.03	Prolate spheroid
V	3.36e1	3.72e-1	3.91e-1	3.28e1	2.03e2	33.6	2.5	2.7	0.15	Spherioidal, sub-clumps

Up to 300 $M_\odot$ of cold material.

Clump properties

HIGH RESOLUTION HD SIMULATIONS

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21 clumps more massive than 20 $M_{\odot}$.

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E	7.27e1	1.05e1	1.01e0	6.12e1	4.16e2	31.3	2.5	1.9	0.03	Spheroidal
F	1.08e2	1.55e1	1.01e0	9.12e1	4.32e2	28.8	4.0	2.6	0.06	Double sphere merger
G	1.77e2	1.94e1	2.65e0	1.55e2	3.31e2	32.7	4.0	2.1	0.04	Peanut
H	2.65e1	2.01e0	3.19e-1	2.42e1	1.54e2	32.4	2.4	2.5	0.03	Clump on a filament?
I	7.57e1	5.88e0	1.06e0	6.88e1	1.94e2	33.4	3.0	2.2	0.18	Results of a merger?
J	3.13e1	2.59e0	2.93e-1	2.84e1	2.16e2	32.0	3.0	3.2	0.08	Co-flowing clumps
K	1.04e2	5.10e0	1.14e0	9.76e1	4.18e2	26.9	2.5	1.8	0.03	Isolated. Spherical
L	2.37e1	1.02e0	3.28e-1	2.23e1	2.83e2	31.1	1.0	2.5	0.01	Tadpole, 2.5 pc elongated tail
M	6.83e1	1.16e1	1.07e0	5.57e1	4.95e2	26.1	3.0	2.7	0.03	Elongated. Chain?
N	9.14e1	8.50e0	1.42e0	8.15e1	3.33e2	29.3	3.0	2.4	0.33	Spheroidal, linked filament?
O	4.85e1	8.63e0	1.28e0	3.87e1	2.34e2	29.9	3.0	1.7	0.02	Spheroidal - 2 filaments
P	6.84e1	2.20e1	1.66e0	4.47e1	1.89e2	33.1	3.0	1.9	0.07	Large tadpole
Q	6.63e1	5.19e0	9.80e-1	6.01e1	2.86e2	32.1	4.0	1.8	0.03	Sph. Off-centre max rho
R	2.96e2	3.19e1	2.76e0	2.62e2	3.25e3	16.9	5.0	2.4	0.13	Multiple lobes - subclumps?
T	7.25e1	7.70e0	1.00e0	6.38e1	3.92e2	27.4	5.0	2.5	0.02	Double merger
U	3.57e1	1.53e0	7.64e-1	3.34e1	2.06e2	33.0	3.0	2.3	0.03	Prolate spheroid
V	3.36e1	3.72e-1	3.91e-1	3.28e1	2.03e2	33.6	2.5	2.7	0.15	Spherioidal, sub-clumps

Cold material <100 K, down to ~10 K
(under final collapse conditions)

Clump properties

HIGH RESOLUTION HD SIMULATIONS

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21 clumps more massive than 20 $M_\odot$.

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A	2.37e2	5.39e1	3.19e0	1.78e2	4.62e2	30.5	3.5	2.2	0.11	Spheroidal, extended arms
B	2.64e2	2.36e1	4.10e0	2.37e2	9.92e2	21.5	4.0	2.8	0.31	Prolate spheroid
C	2.71e2	4.49e1	4.25e0	2.22e2	7.76e2	22.9	4.0	2.4	0.12	Pyramidal
D	3.54e2	5.65e1	6.49e0	2.92e2	1.46e4	10.6	4.0	2.5	0.17	Multiple lobes
E	7.27e1	1.05e1	1.01e0	6.12e1	4.16e2	31.3	2.5	1.9	0.03	Spheroidal
F	1.08e2	1.55e1	1.01e0	9.12e1	4.32e2	28.8	4.0	2.6	0.06	Double sphere merger
G	1.77e2	1.94e1	2.65e0	1.55e2	3.31e2	32.7	4.0	2.1	0.04	Peanut
H	2.65e1	2.01e0	3.19e-1	2.42e1	1.54e2	32.4	2.4	2.5	0.03	Clump on a filament?
I	7.57e1	5.88e0	1.06e0	6.88e1	1.94e2	33.4	3.0	2.2	0.18	Results of a merger?
J	3.13e1	2.59e0	2.93e-1	2.84e1	2.16e2	32.0	3.0	3.2	0.08	Co-flowing clumps
K	1.04e2	5.10e0	1.14e0	9.76e1	4.18e2	26.9	2.5	1.8	0.03	Isolated. Spherical
L	2.37e1	1.02e0	3.28e-1	2.23e1	2.83e2	31.1	1.0	2.5	0.01	Tadpole, 2.5 pc elongated tail
M	6.83e1	1.16e1	1.07e0	5.57e1	4.95e2	26.1	3.0	2.7	0.03	Elongated. Chain?
N	9.14e1	8.50e0	1.42e0	8.15e1	3.33e2	29.3	3.0	2.4	0.33	Spheroidal, linked filament?
O	4.85e1	8.63e0	1.28e0	3.87e1	2.34e2	29.9	3.0	1.7	0.02	Spheroidal - 2 filaments
P	6.84e1	2.20e1	1.66e0	4.47e1	1.89e2	33.1	3.0	1.9	0.07	Large tadpole
Q	6.63e1	5.19e0	9.80e-1	6.01e1	2.86e2	32.1	4.0	1.8	0.03	Sph. Off-centre max rho
R	2.96e2	3.19e1	2.76e0	2.62e2	3.25e3	16.9	5.0	2.4	0.13	Multiple lobes - subclumps?
T	7.25e1	7.70e0	1.00e0	6.38e1	3.92e2	27.4	5.0	2.5	0.02	Double merger
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Size-scales of a few pc.

Clump properties

HIGH RESOLUTION HD SIMULATIONS

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R	2.96e2	3.19e1	2.76e0	2.62e2	3.25e3	16.9	5.0	2.4	0.13	Multiple lobes - subclumps?
T	7.25e1	7.70e0	1.00e0	6.38e1	3.92e2	27.4	5.0	2.5	0.02	Double merger
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Maximum velocities typical of infalling material passing through phase boundary

Clump properties

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Minimum velocities representative of internal velocity dispersion

Power spectra

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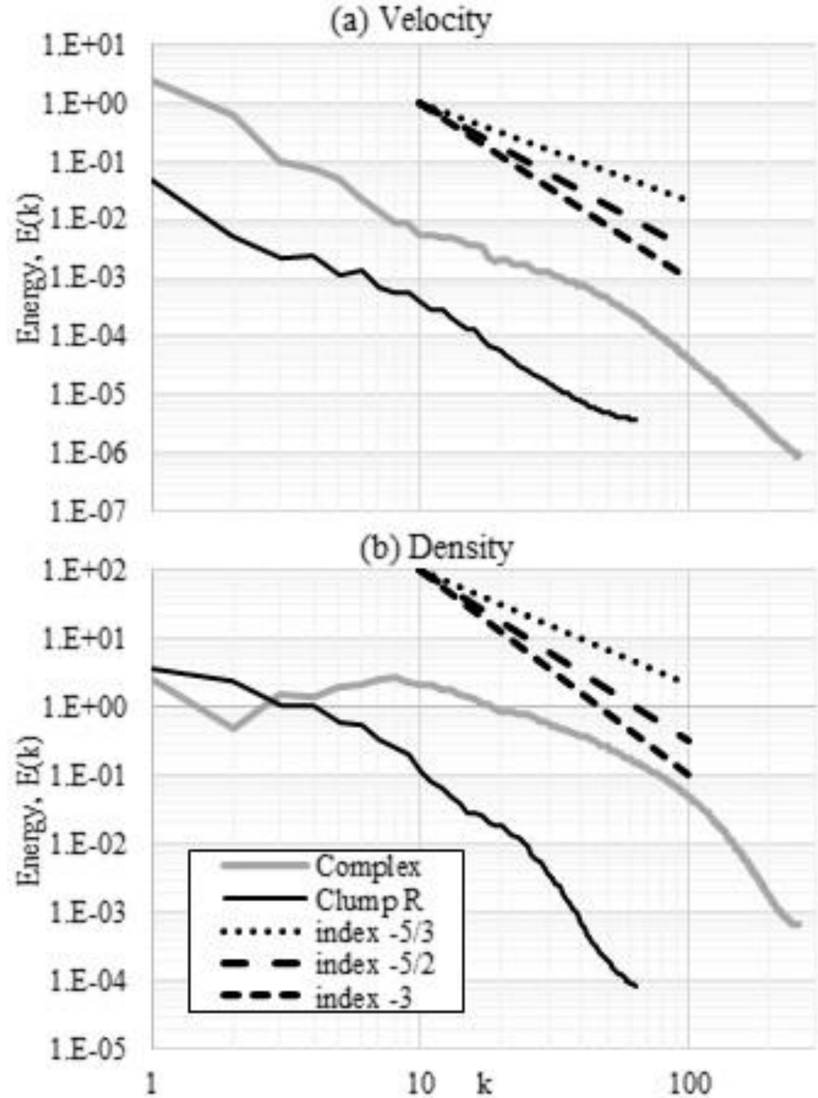
- Turbulence-like (-5/3) power spectra in the warm stable medium
- Short inertial range (1 decade) -> by no means fully developed turbulence.
- Should extend to larger scales.
- Akin to Larson-like turbulence:-

  "hierarchy of small-scale irregularities superimposed on larger-scale more systematic motions"
- Spectral break at ~1 pc, on the size-scale of the clumps – could be consider a "dissipative limit".
- Steeper spectral index of -3 implied inside the clumps.

Cloud complex – 40pc box.
Clump R – 10pc box.



Power spectra calculated by validated IDL script

An individual 250$M_\odot$ clump

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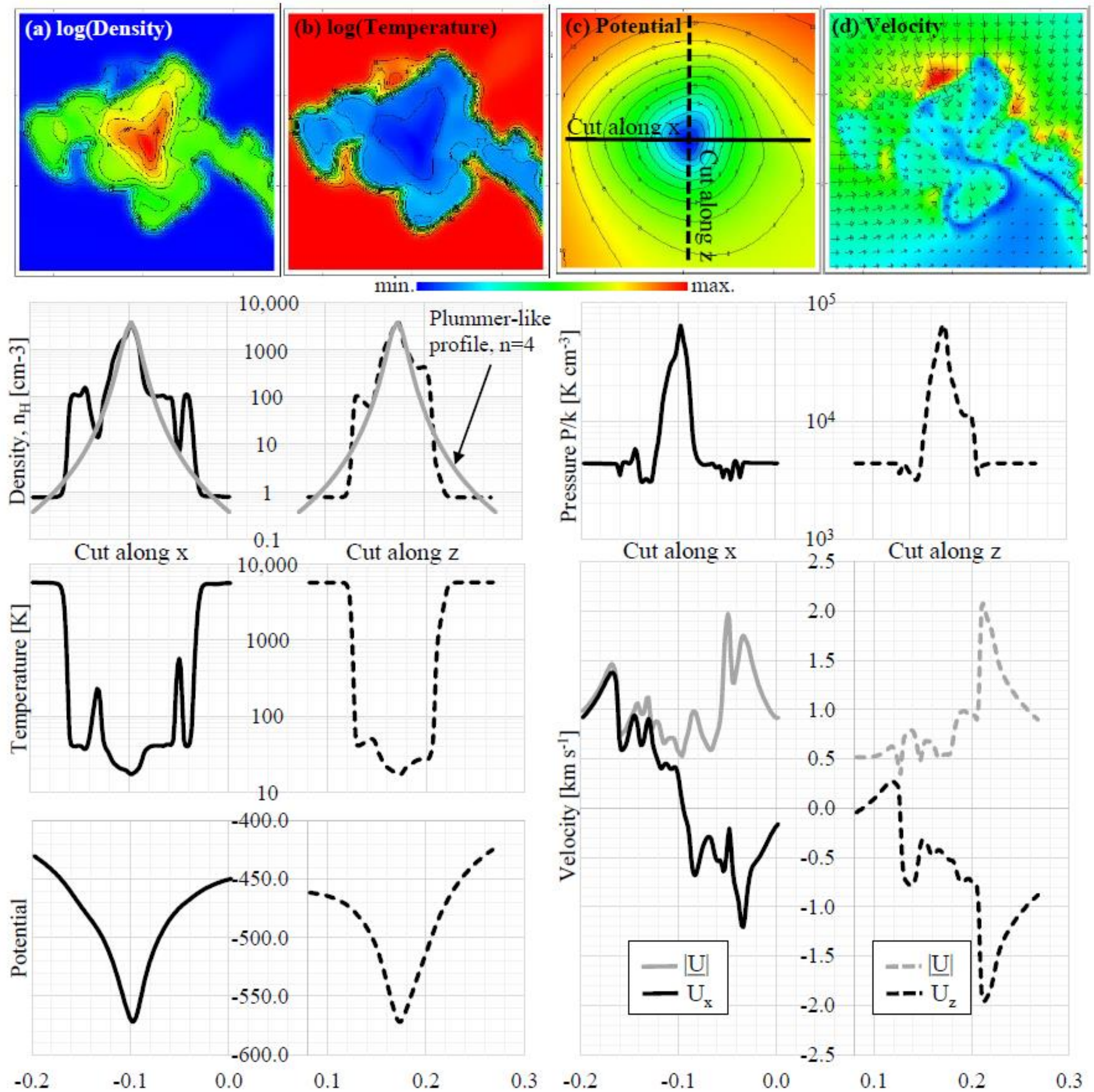
- Complex non-spherical nature.
- Central density distribution fits a Plummer-like n=4 curve.
- Clearly defined sharp boundary, noticeable in temperature distribution.
- Increased internal pressure indicates gravitational collapse.



Striations, hour-glasses and integrals

HIGH RESOLUTION MHD SIMULATIONS

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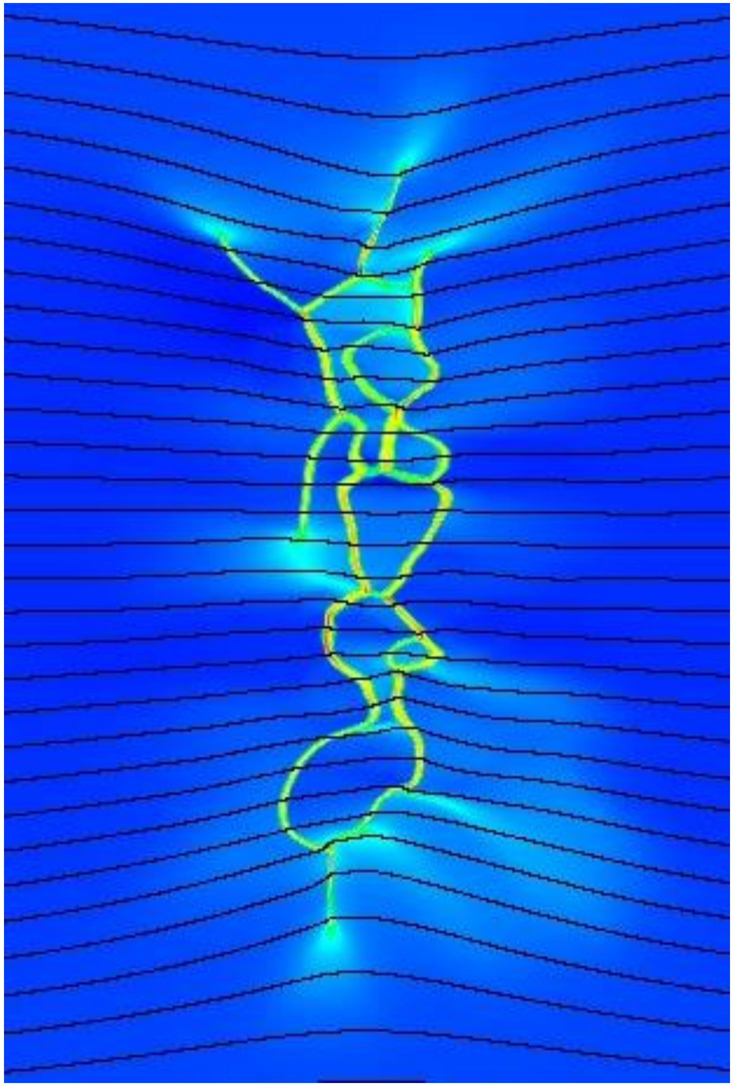
MHD case…

- Observations have revealed striations that are typically parallel to the inferred magnetic field direction.

- Other authors (Tritsis & Tassis) have inferred they are results of MHD waves and dismissed other models on the basis of isothermal simulations.

- MHD, non-isothermal simulations from a diffuse initial condition reveal clear dense structures aligned to the magnetic field, feeding onto the filaments.



Striations, **hour-glasses** and integrals

HIGH RESOLUTION MHD SIMULATIONS

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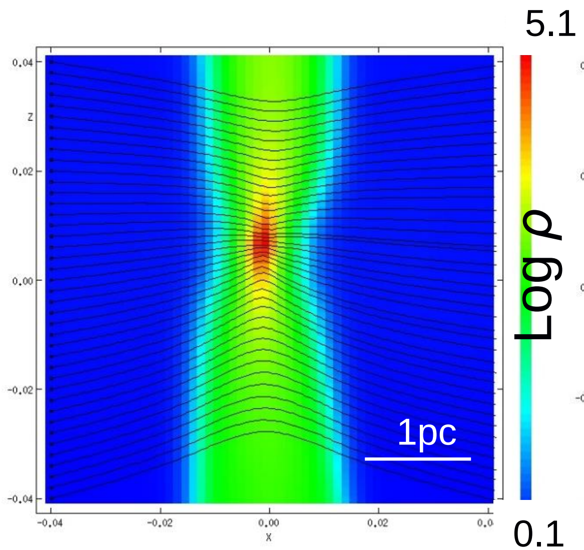
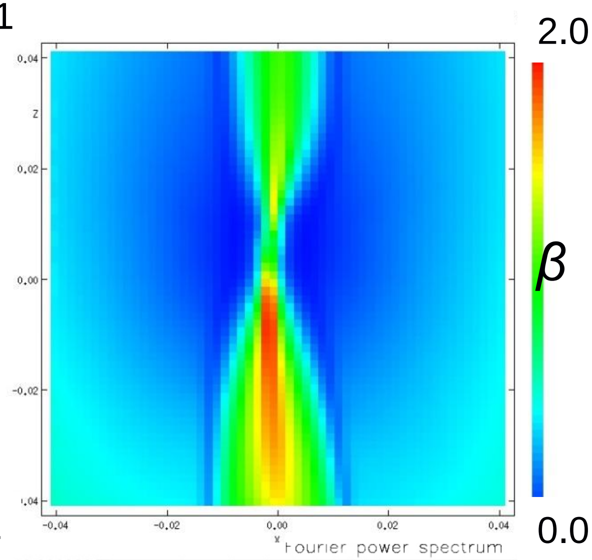
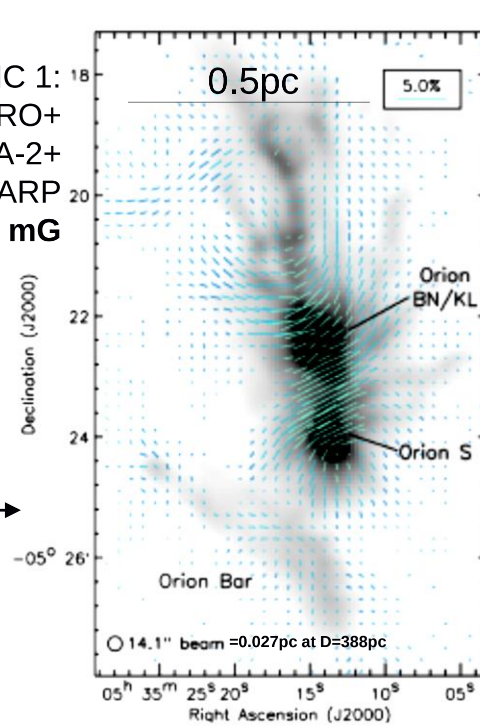




OMC 1:
BISTRO+
SCUBA-2+
HARP
6.7±4.7 mG



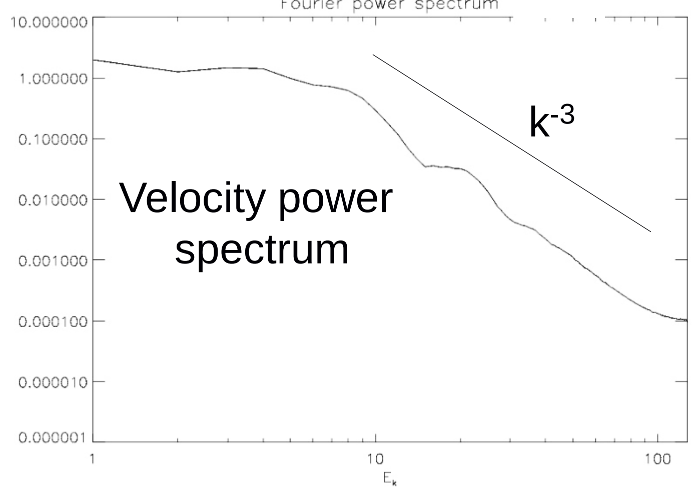
Pattle, Ward-Thompson et al., 2017, ApJ, 846, id.122

Gravitational collapse once the sheet has formed is dragging the field.

Field intensified in places from 0.3μG to ~0.1mG

V_{max}~3 km s^{-1}, M_{max}~2.9, T~10K, M~150M_{sun}

Density spectrum $k^{-5/2}$



Beginning to show similarities?

=> Next step: re-simulate central section; sink particles

Striations, hour-glasses and **integrals**

HIGH RESOLUTION MHD SIMULATIONS

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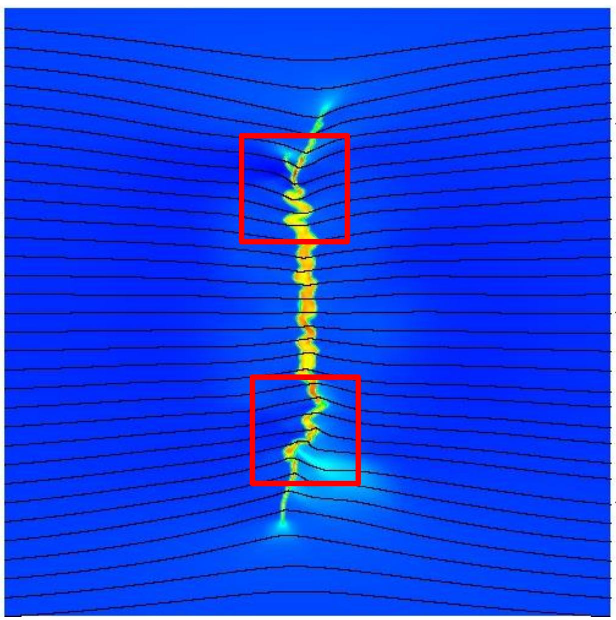
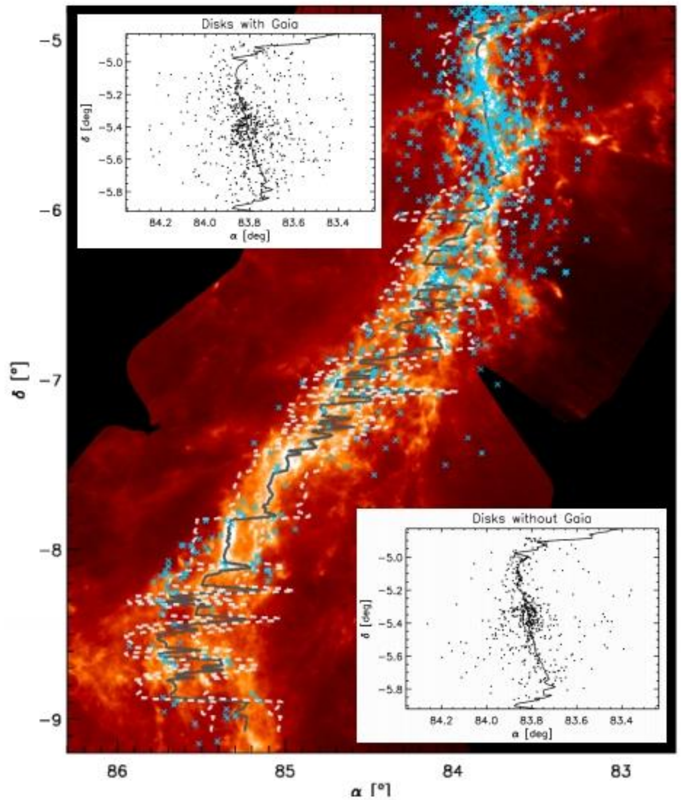
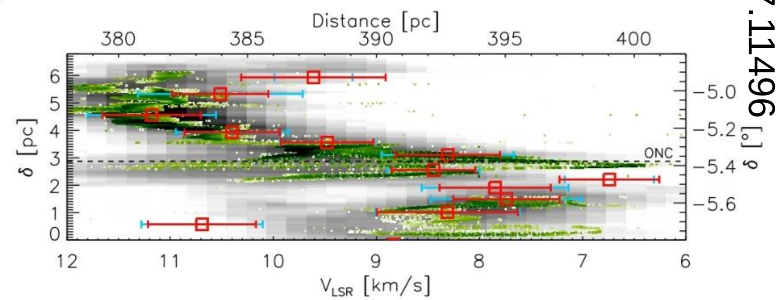
- Recent work **submitted** to MNRAS concludes that an “*integral”*-shaped filament in Orion is a standing wave
- We obtain apparently similar structure, with disconnects in the velocity caused by the TI-driven flow.
- Not a standing wave, just a flow artefact



- Further work required.





Stutz et al. MNRAS, **submitted**. arXiv:1807.11496

Conclusions

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- The thermal instability in diffuse interstellar medium can, together with self-gravity, create realistic molecular clouds.
- Without magnetic field, the cloud complex contains realistic very cold, very dense clumps.
  - The clumps are connected by a network of cooler, less dense filaments.
  - The clouds create their own “turbulence”
- With magnetic field, the cloud flattens into a corrugated sheet-like structure.
  - In projection, the clouds appear very filamentary.
  - Mechanical stellar wind feedback can be directed away from the structure and provide an elegant explanation for the nature of the Rosette Nebula.
  - Collapse of the sheet intensifies magnetic field up to tens of μG, creating hour-glass-shaped field distributions.
  - Disconnects in the sheet, driven by the flow set up, create integrals.

- To add a robust star-forming particle mechanism, sampling a realistic IMF.
- To investigate mechanical *and radiative* feedback from multiple stars in these clouds and the subsequent effects on the cloud complexes and their SFR.

Thank you for listening. Any comments or questions?

Thermal instability driven initial condition: Wareing, Pittard, Falle & Van Loo, 2016, MNRAS, **459**, 1803

Magnetic feedback general case: Wareing, Pittard & Falle, 2017, MNRAS, **465**, 2757

Hydrodynamic feedback general case: Wareing, Pittard & Falle, 2017, MNRAS, **470**, 2283

Rosette special case: Wareing, Pittard & Falle, 2018, MNRAS, **475**, 3598

HD clouds with collapsing clumps: Wareing, Falle & Pittard, MNRAS to submit this week.

Thermal instability revisited: Falle, Wareing & Pittard, in prep.

Striations, hour-glasses and integrals in MHD clouds
Wareing, Pittard & Falle, in prep.

Column density variations?

THE ROSETTE NEBULA

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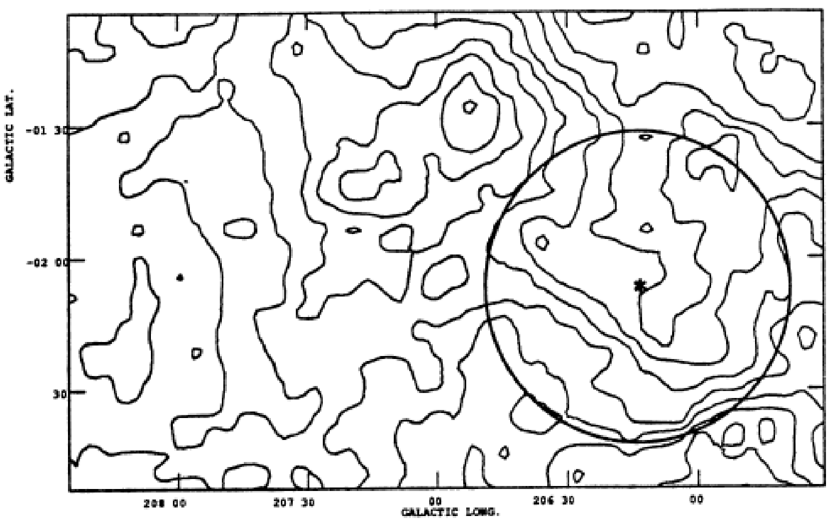
- Column density through Rosette nebular gas should (naively) be constant across the nebula, if this is a ‘disc’ or increasing toward centre if spherical.
    - Nothing seems to indicate increasing density towards centre

FIGURE 1: HI Integrated Intensity



Kuchar and Bania 1991 ASP Conf Series 13, 151-153

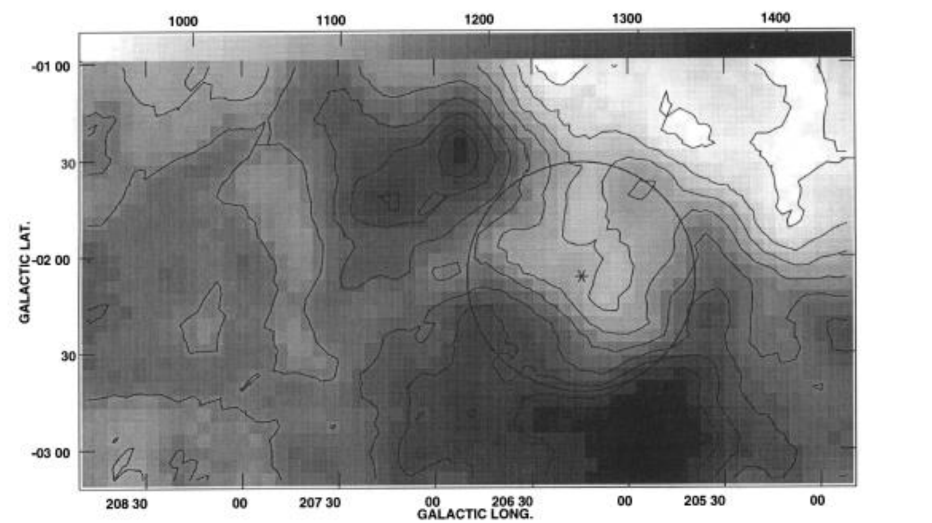


FIG. 1.—Velocity integrated H I intensity map $\int T_A dv$, where T_A is expressed in antenna temperature units (brightness temperature, $T_b = 1.3T_A$). The integration was performed over $V_{LSR} = 3.1$–24.2 km s^{-1}. The contours range from 950 to 1450 K km s^{-1} and are spaced every 50 K km s^{-1}. The gray scale ranges from 930 to 1440 K km s^{-1}. If the emission is optically thin, then the map corresponds to H I column densities. The central Hα minimum of the Rosette Nebula is marked as is a circular approximation to the maximum extent of the nebula emission as it appears on the red POSS plate ($R = 38' = 17.7$ pc at a distance of 1600 pc).

Kuchar and Bania ApJ 414 664-671 (1993)

- A collapsed sphere will not be uniform across the ‘disc’ though.

Evidence for spherical distribution?

THE ROSETTE NEBULA

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Radio continuum observations show no significant gradient of brightness temperature.

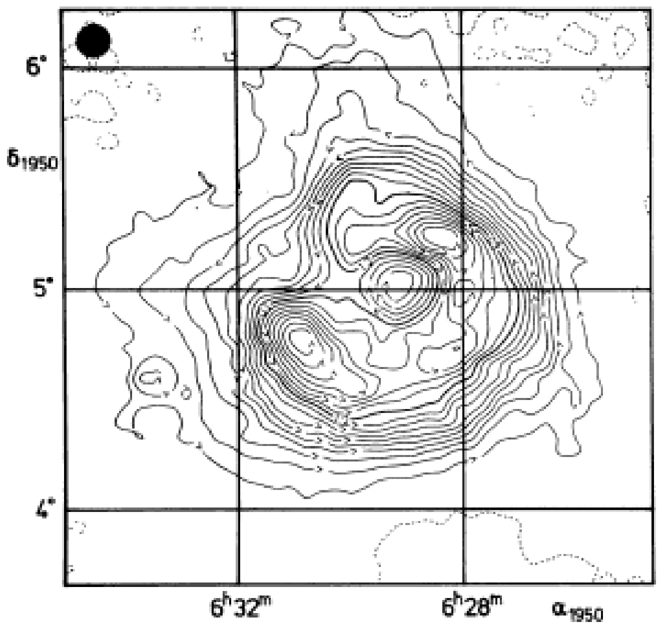

Fig. 1. Distribution of brightness temperature across the Rosette nebula at 1410 MHz, lowest (dashed) contour line at 0, line No. 10 at 8.0 K, thin lines at 0.8 K intervals, lines with arrows indicating clock wise rotation enclose decreasing temperature values, angular resolution is 9.'24

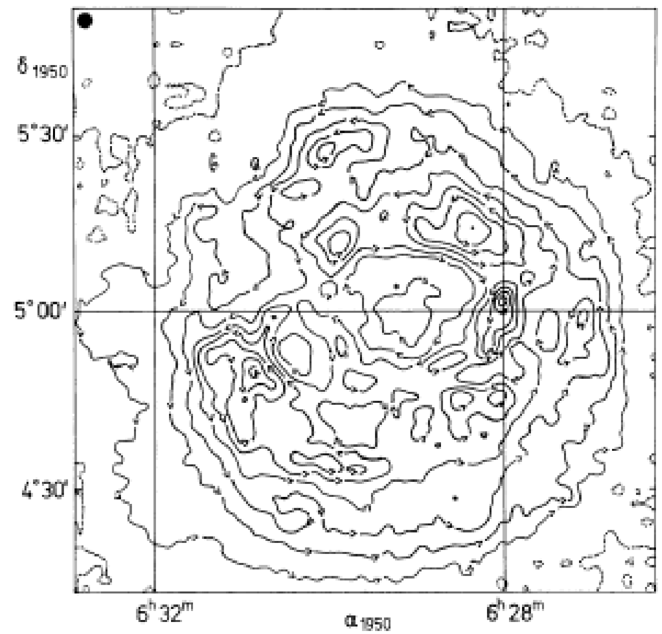

Fig. 2. Distribution of brightness temperature across the nebula at 4750 MHz, lowest (dashed) contour line at 0.1 K, contour lines at 0.2 K intervals, lines with arrows indicating clock wise rotation enclose decreasing temperature values, angular resolution is 2.'43

Spherical symmetry model for density distribution doesn't seem to work, although radial density gradient looks to exist.

Celnik 1985 A&A 144 171-178