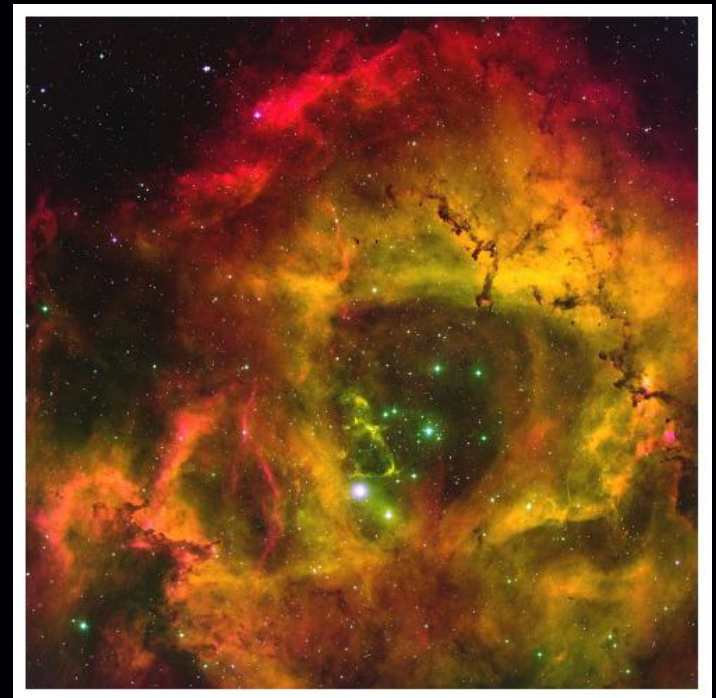
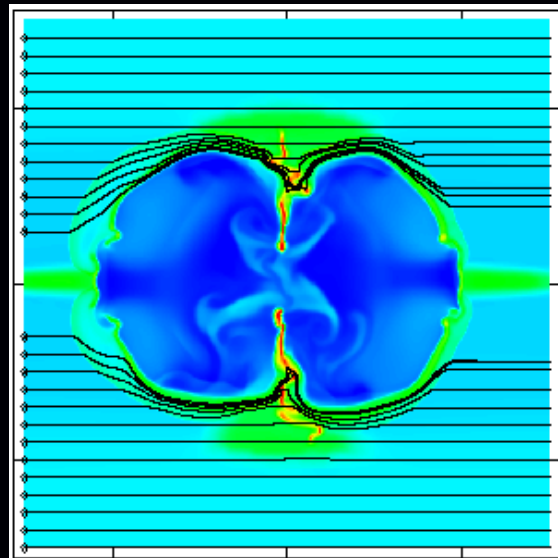
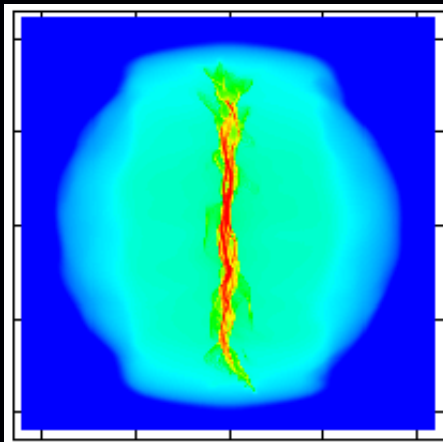


Filaments, feedback and forming the Rosette

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, N. Wright

- 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.

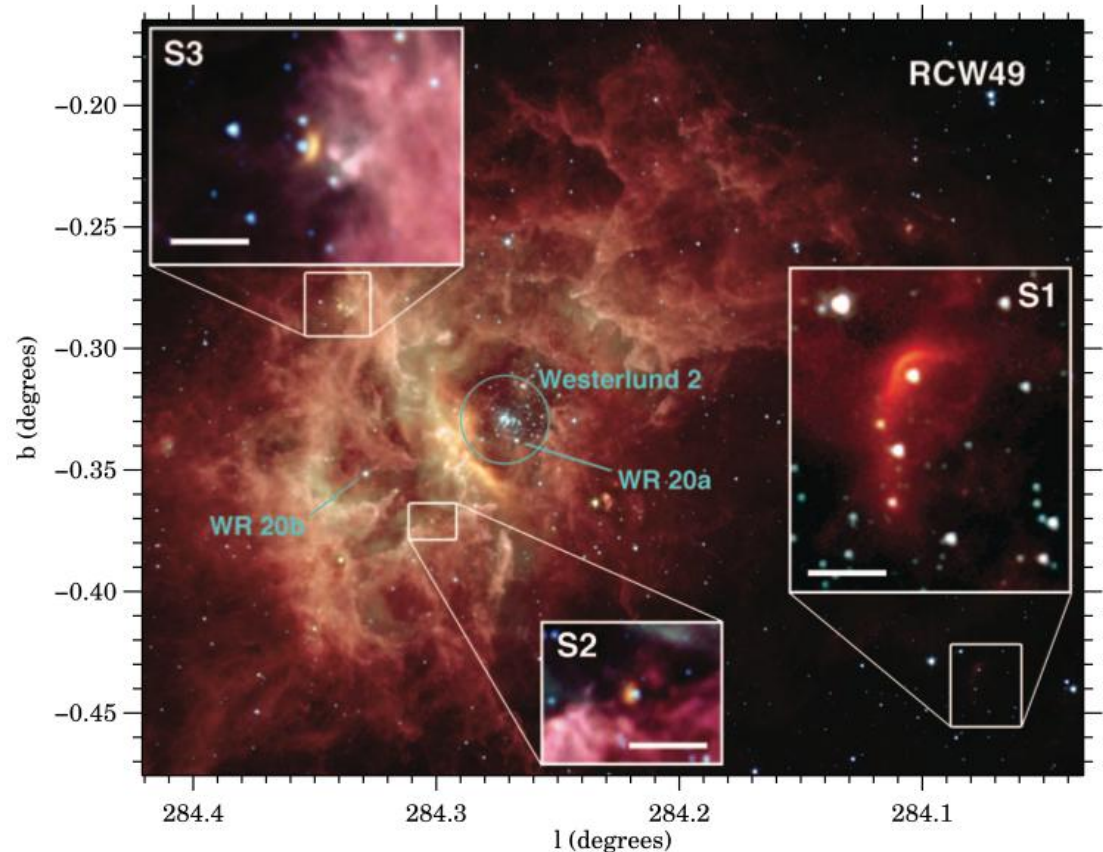
Winds are important

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 4.2kpc.
- 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

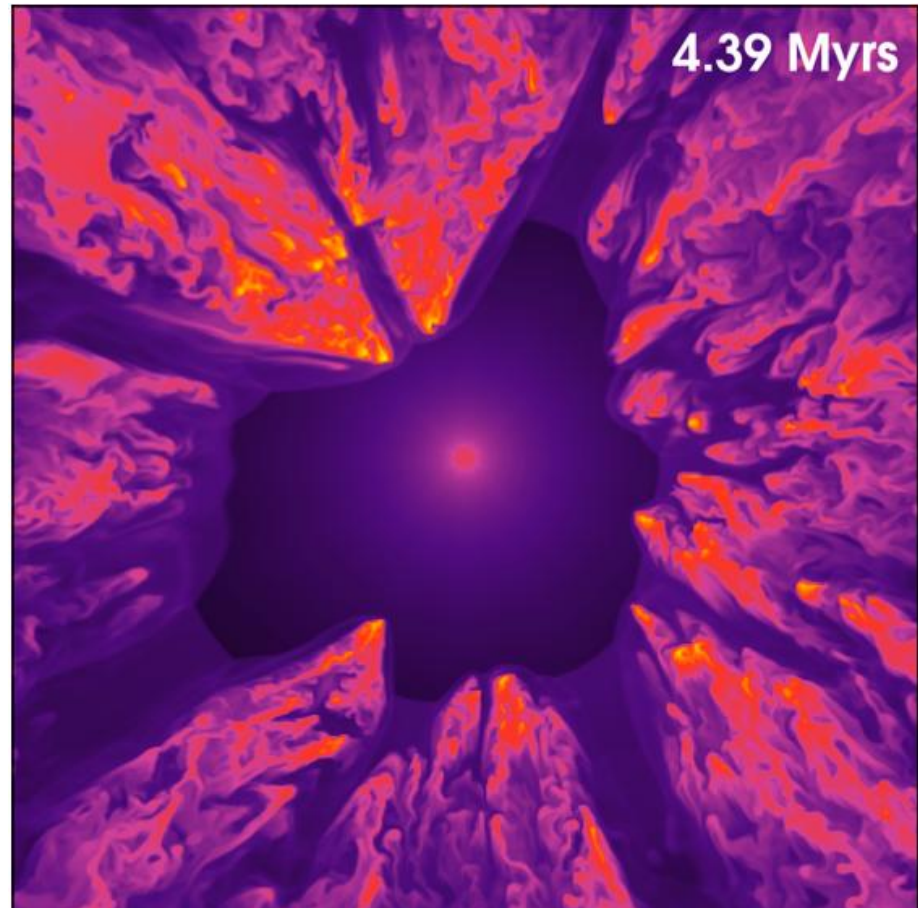
Winds *can* disengage SN and cloud

CONTEXT & AIM



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



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

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

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.
- The results!
- Comparisons to previous work and observations.
- Serendipitous application to the Rosette Nebula.

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

- 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 MHD
 - Self-gravity
 - Multi-phase ISM, requiring a prescription for heating and cooling
- In future, extra additions may be explored:
 - Shear and spiral shocks, 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

On 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 [the 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.?

The engine

Physical model



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- 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: $\beta = 0.1$



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

Aside: STFC Innovation Fellowship to convert **MGf** -> **MGtf** for turbulent multi-fluids and use with industry.



Heating and Cooling

Physical model



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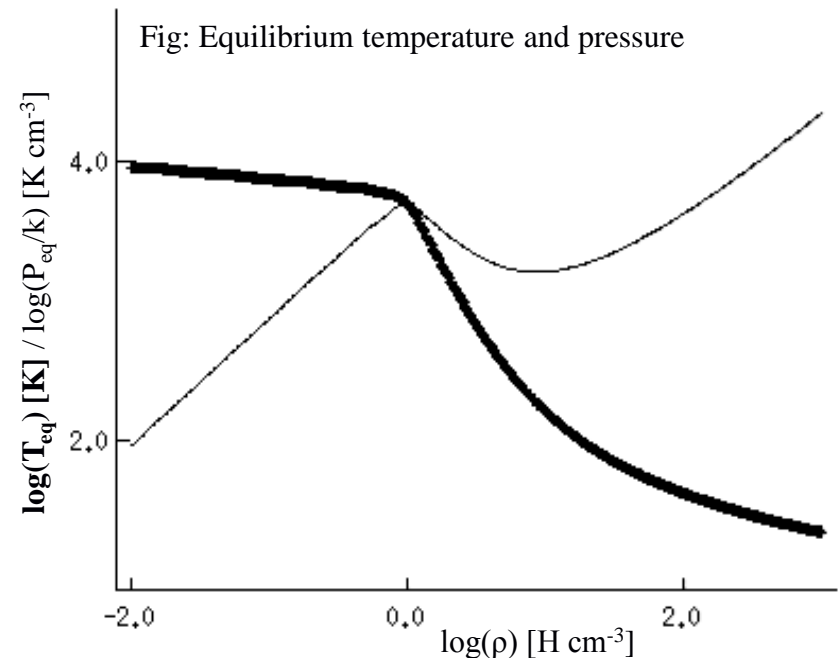
- Constant heating rate: $\Gamma = 2 \times 10^{-26} \text{ erg s}^{-1}$ (independent of ρ and T)
- Multi-stage cooling, in order to apply for molecular cloud formation (10^1K) and stellar feedback (up to 10^8K).

- Low T ($< 10^4 \text{ K}$) uses Koyama & Inutsuka 2002, (corr. Vázquez-Semadini et al. 2007)

$$\frac{\Lambda(T)}{\Gamma} = 10^7 \exp\left(\frac{-1.184 \times 10^5}{T + 1000}\right)$$

$$+ 1.4 \times 10^{-2} \sqrt{T} \exp\left(\frac{-92}{T}\right)$$

- 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 $\rho^2 \Lambda = \rho \Gamma$

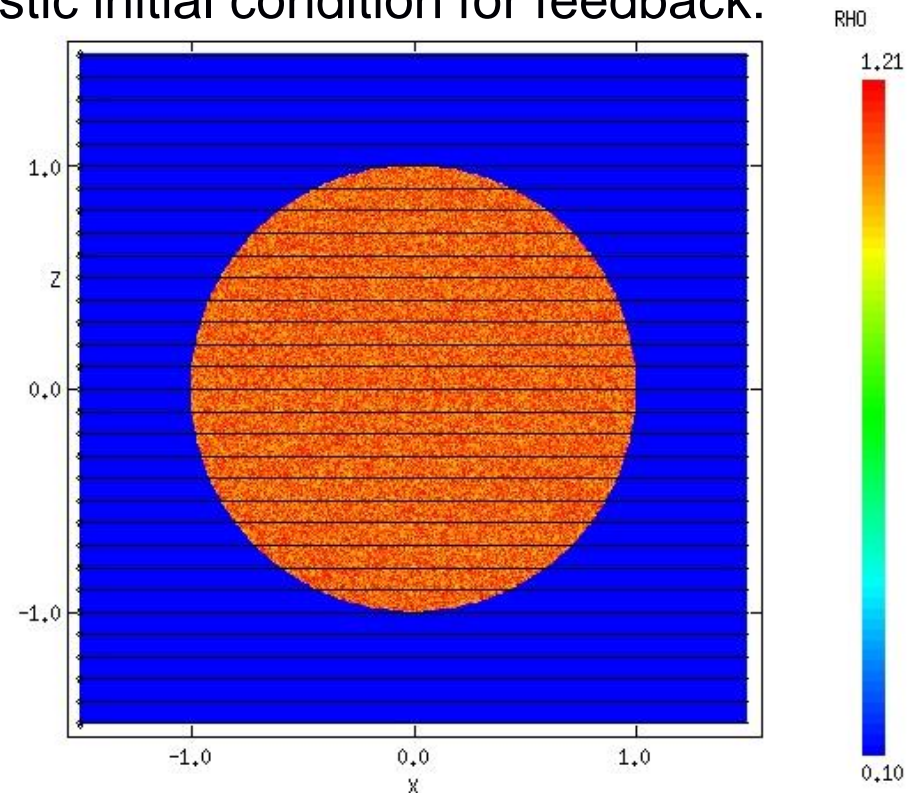


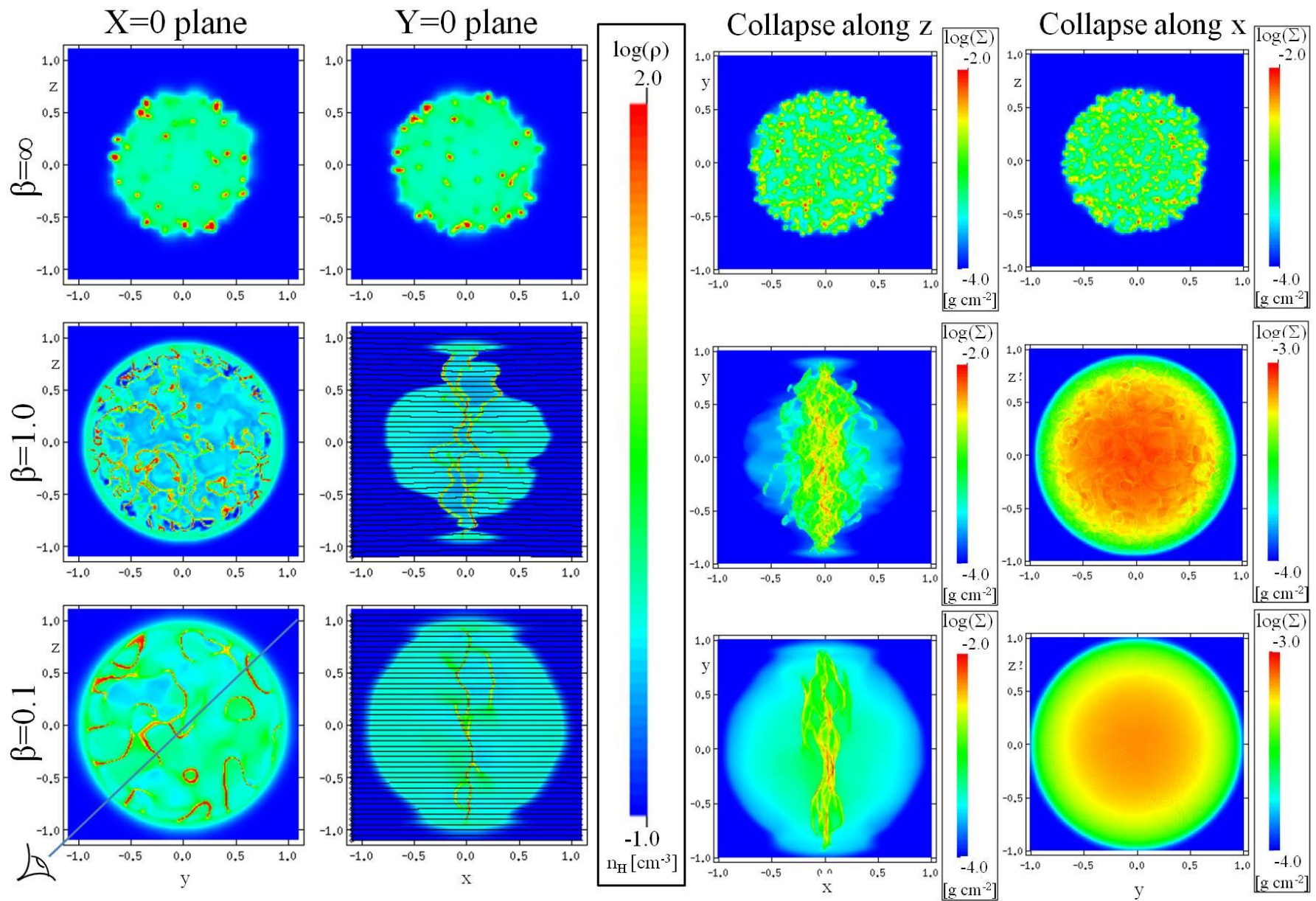
Initial Condition



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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.
 - $n_H = 1.1 \pm 10\%$ - in the thermally unstable regime.
 - Threaded by magnetic field along the x-axis, $\mathbf{B} = B_0 \hat{\mathbf{x}}$.
 - For $\beta = 1$, $B_0 = 1.15 \mu\text{G}$
 - For $\beta = 0.1$, $B_0 = 3.63 \mu\text{G}$
 - Pressure equilibrium with surroundings; 10x less dense.
 - Quiescent cloud, $\underline{v}=0$





Logarithmic mass density on planar slices

Logarithmic column density

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



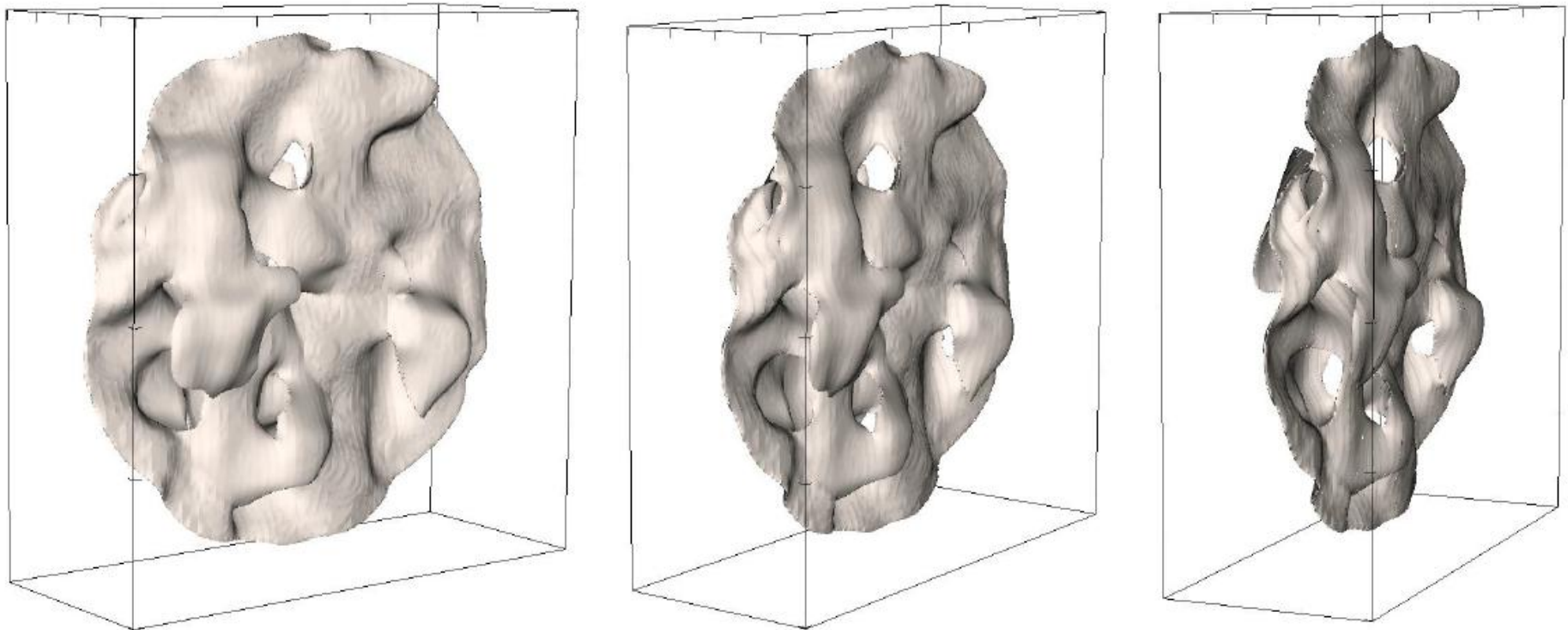
Results

INITIAL CONDITION



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



Density isosurface

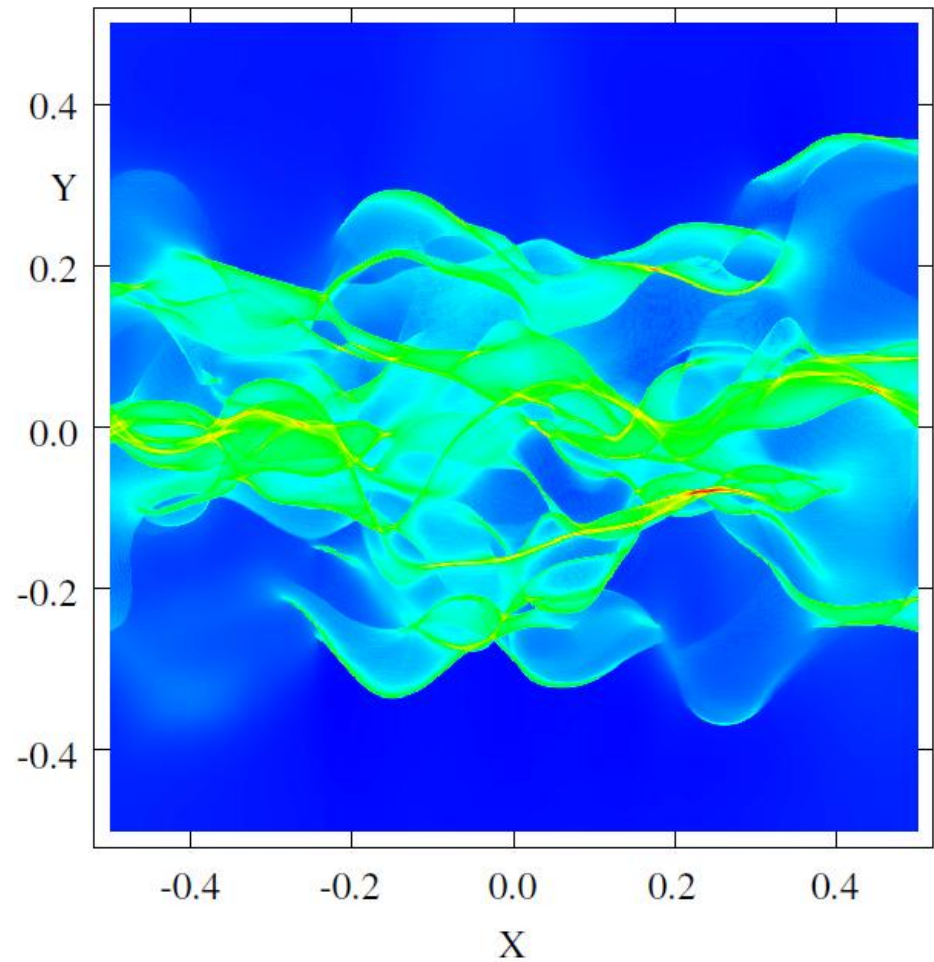
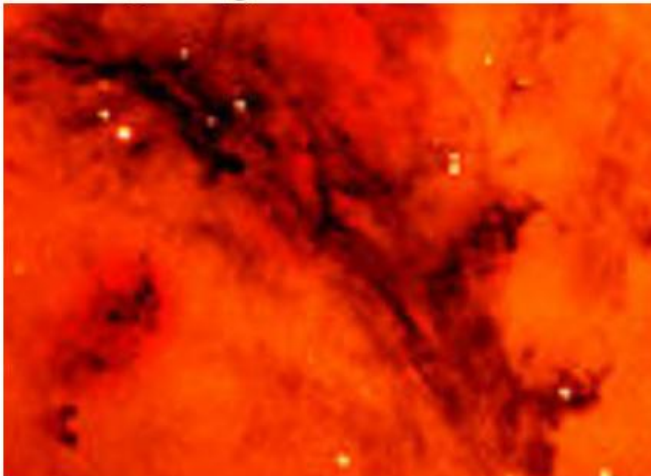
Results

INITIAL CONDITION



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H_α image of Rosette



... that in projection appear filamentary

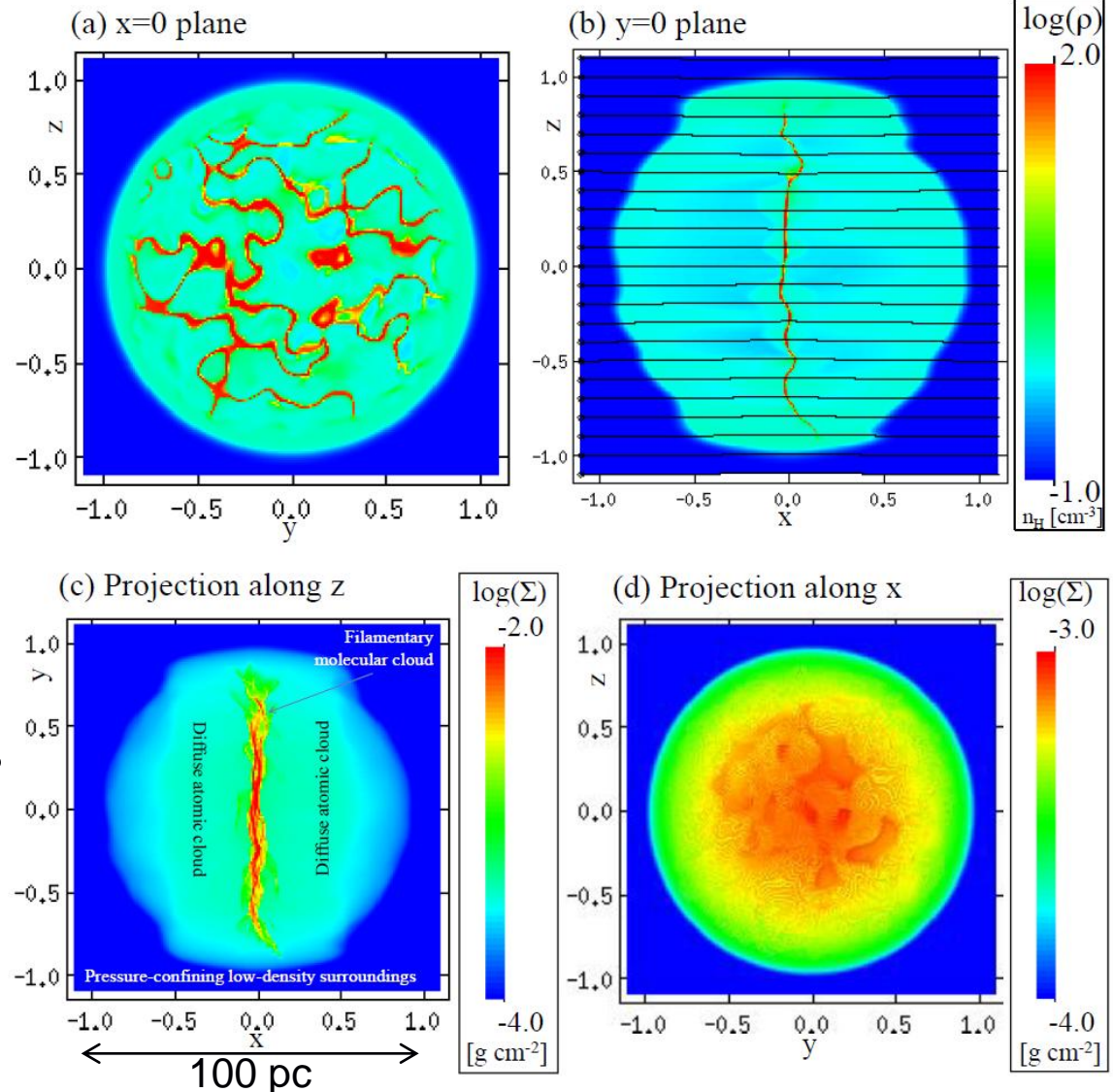
Results

INITIAL CONDITION



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- Provide initial condition.
- 100 pc-diameter 'corrugated' sheet
- Filamentary in projection
- $17,000 M_{\odot}$
- Density $>100 \text{ cm}^{-3}$ after 32.9 Myrs of evolution
- Assume free-fall time of 5.89 Myrs to form stars
- Inject stars at $t=38.8 \text{ Myrs}$
- Position of central star $(-0.025, 0.0, 0.0125)$
- Total mass in excess of star formation mass



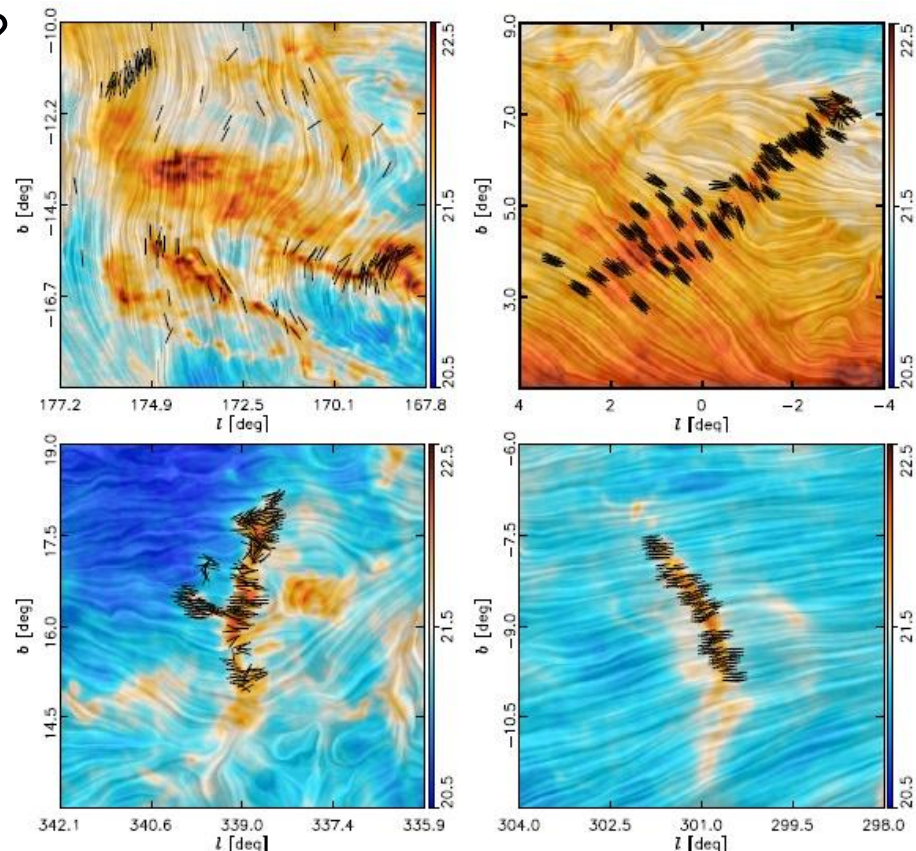
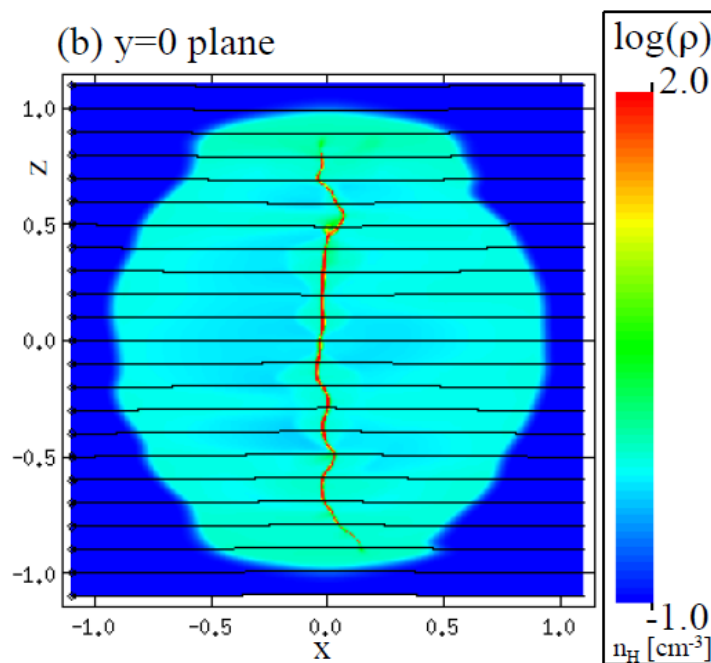
How reasonable is it?

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?



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 $L > 10\text{pc}$, 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 $1/10^{\text{th}}$ 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.

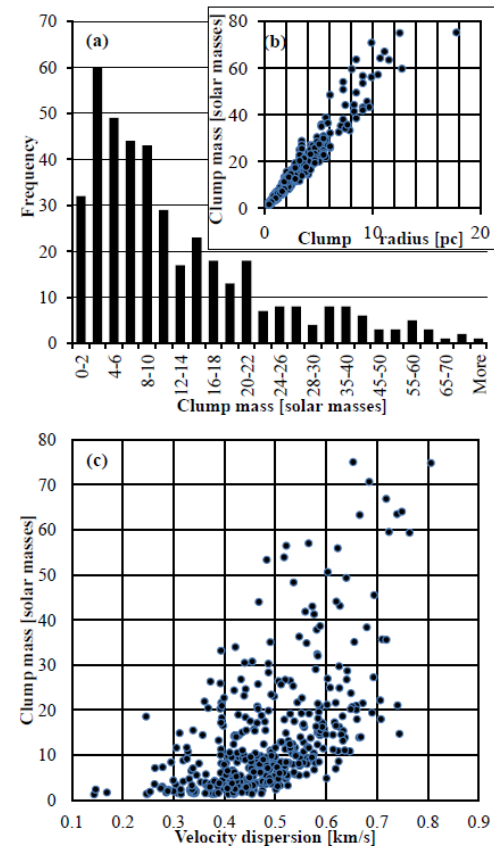
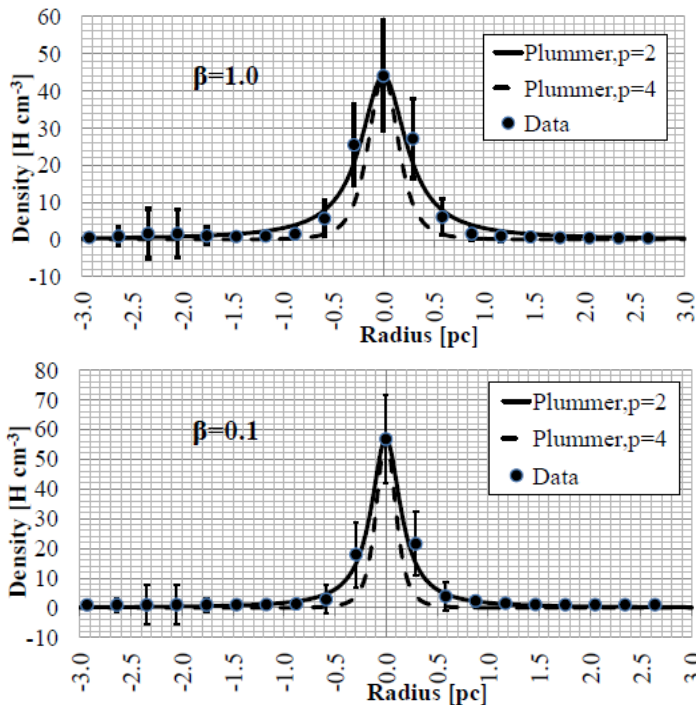
Realistic clump and filament properties?

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.:



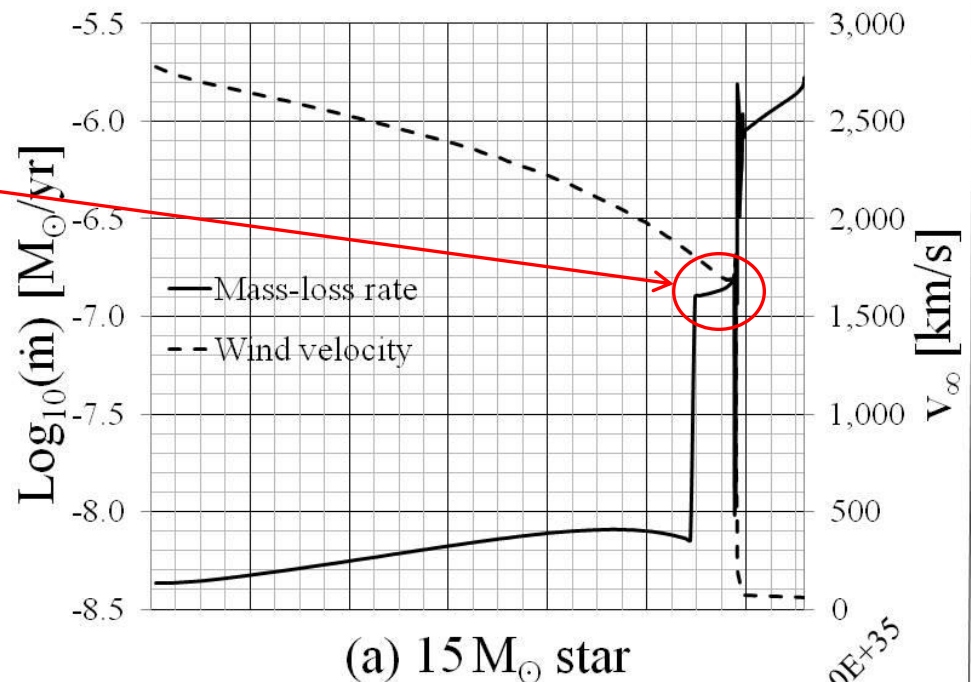
“MHD simulation of the formation of clumps and filaments in quiescent diffuse medium by thermal instability” Wareing, Pittard, Falle, Van Loo 2016, MNRAS, **459**, 1803-1818

Stellar Evolution Models



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- We started from the Geneva 2003 tracks (Meynet & Maeder 2003).
 - Wind velocity derived used Vink et al. (2000, 2001).
- 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)

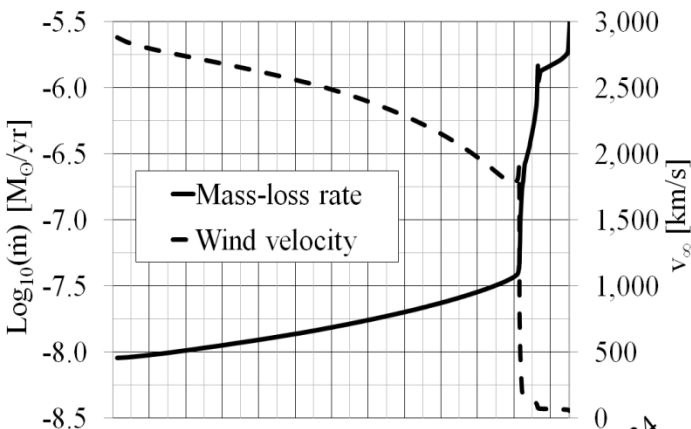


Geneva 2012 Tracks

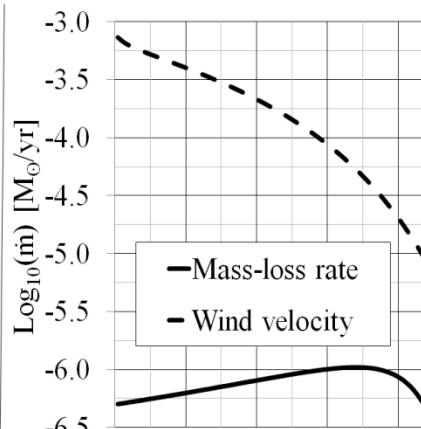
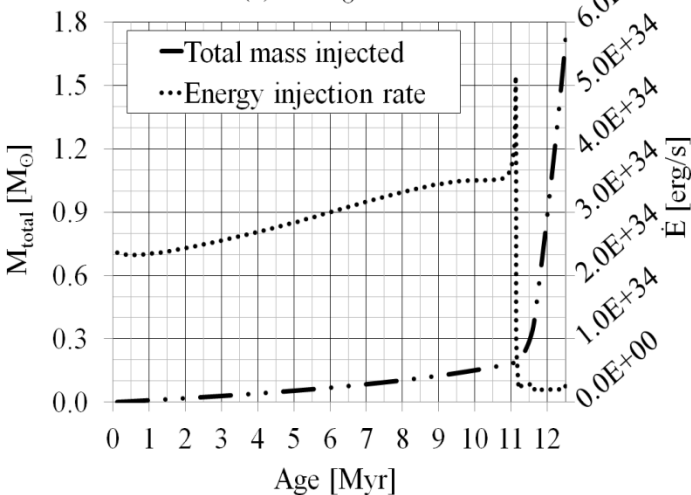
STELLAR EVOLUTION MODELS



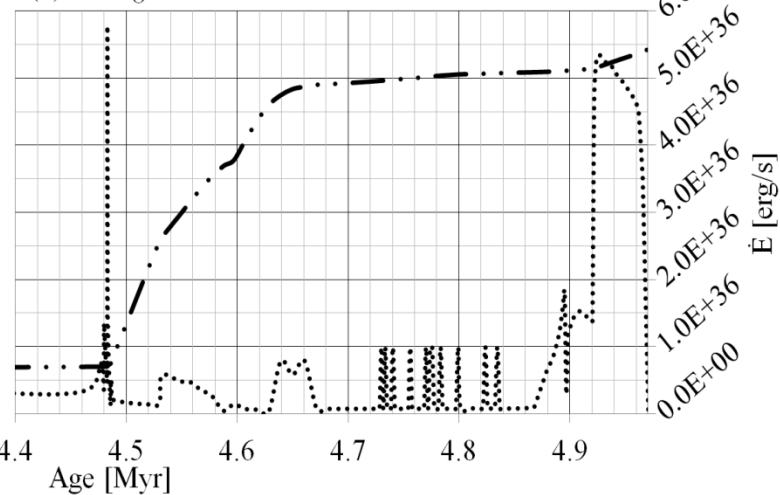
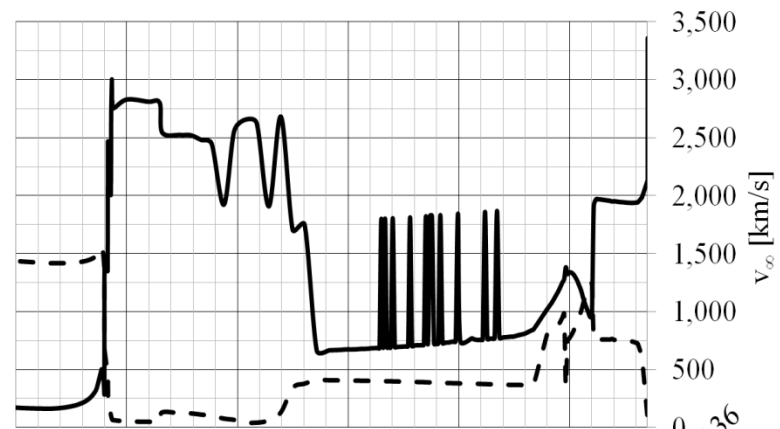
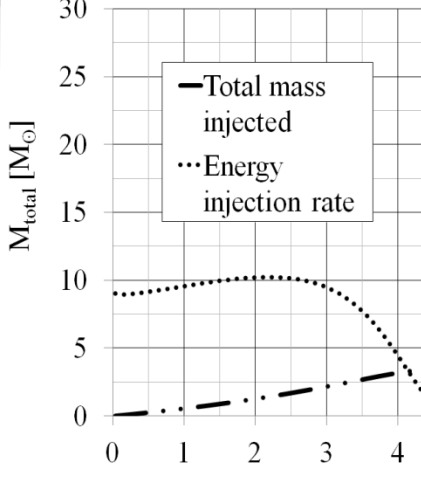
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(a) 15 M_{\odot} star



(b) 40 M_{\odot} star



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.



Finally, the resulting feedback simulations!

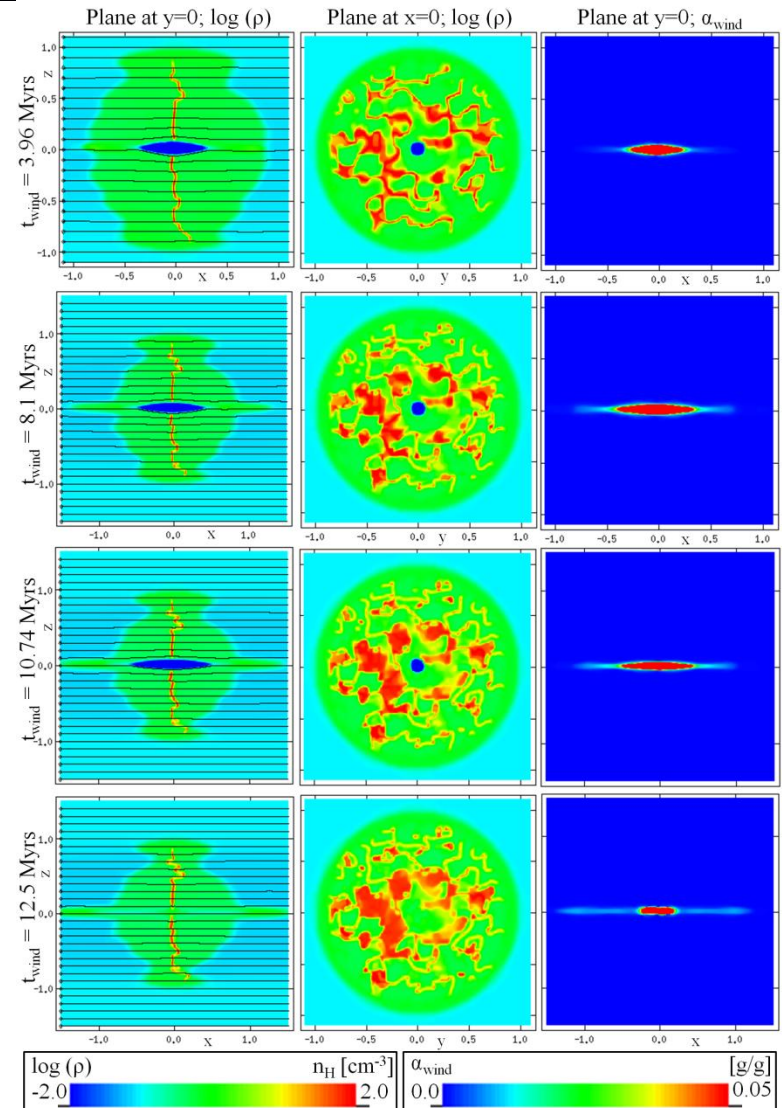
15M_⊙ star: wind phase

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.



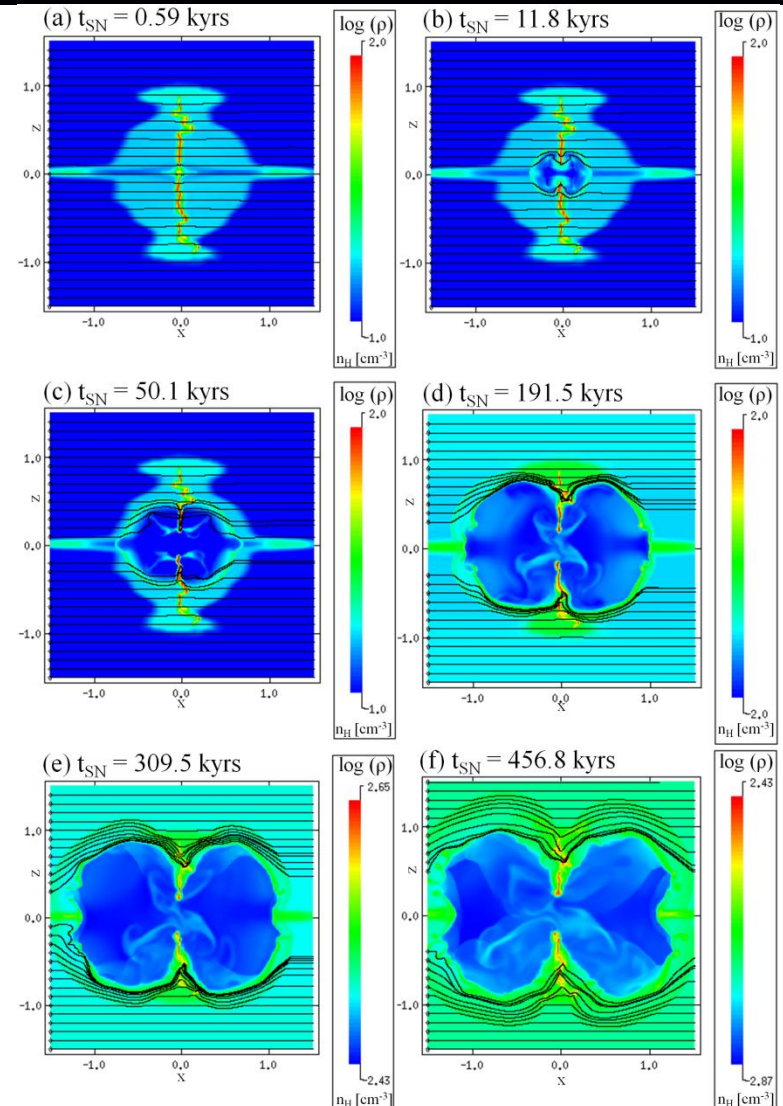
15M_⊙ star: early SN phase

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.

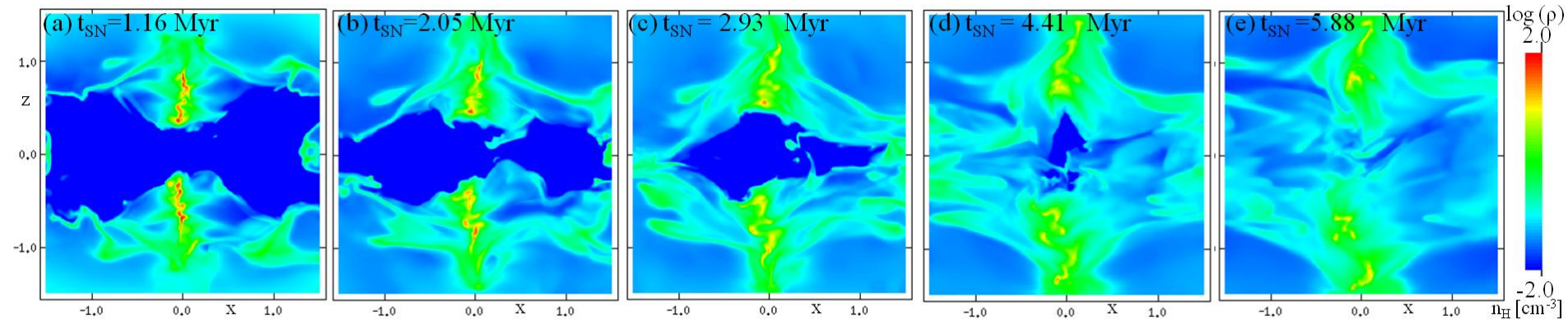


15M_⊙ star: late SN phase

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.

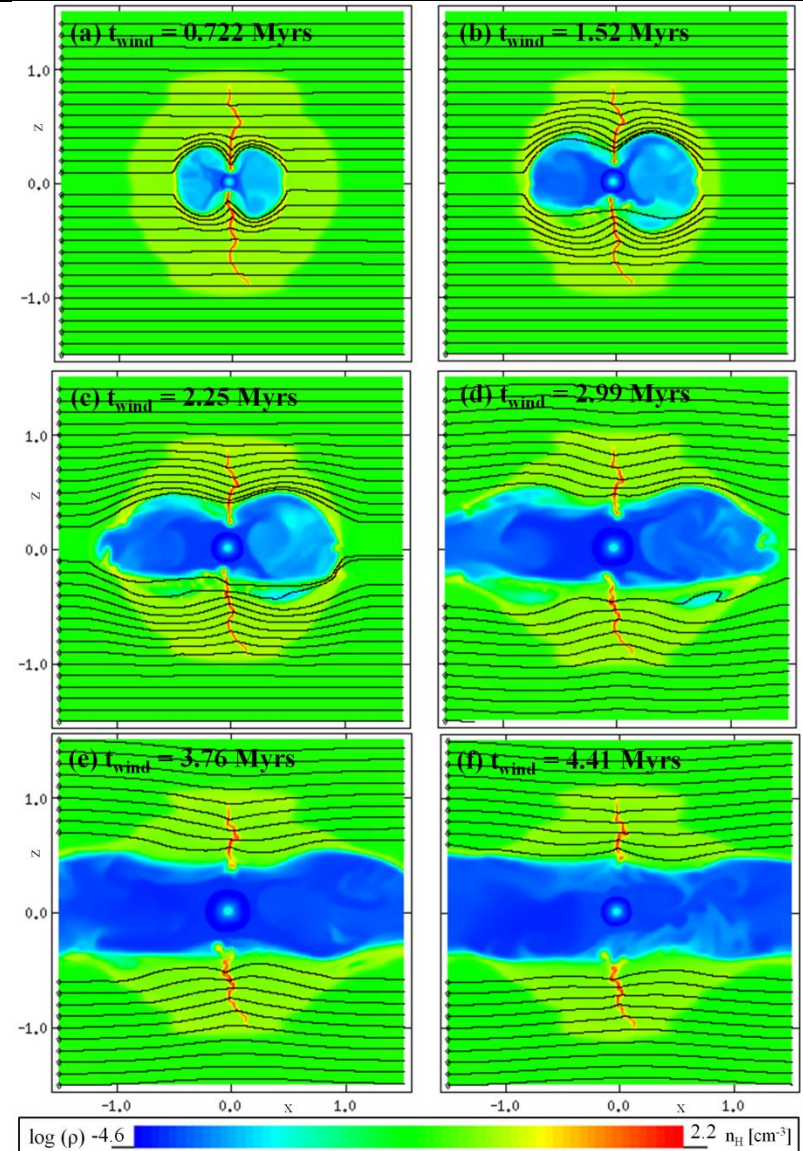
40M_⊙ star: wind phase

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~40pc) 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.

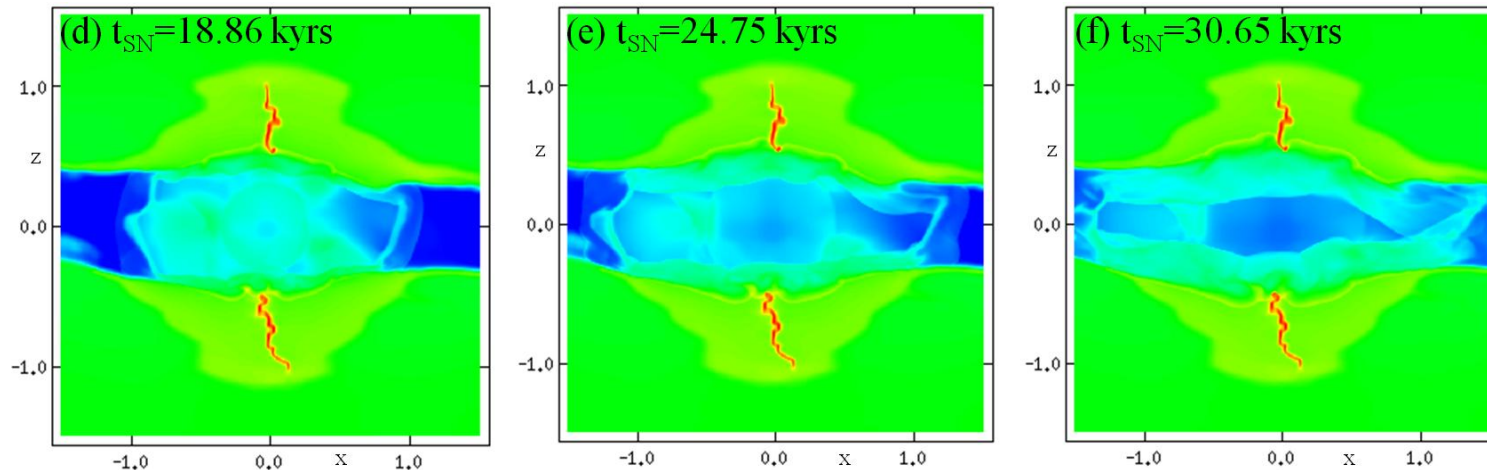


40M_⊙ star: SN phase

RESULTS



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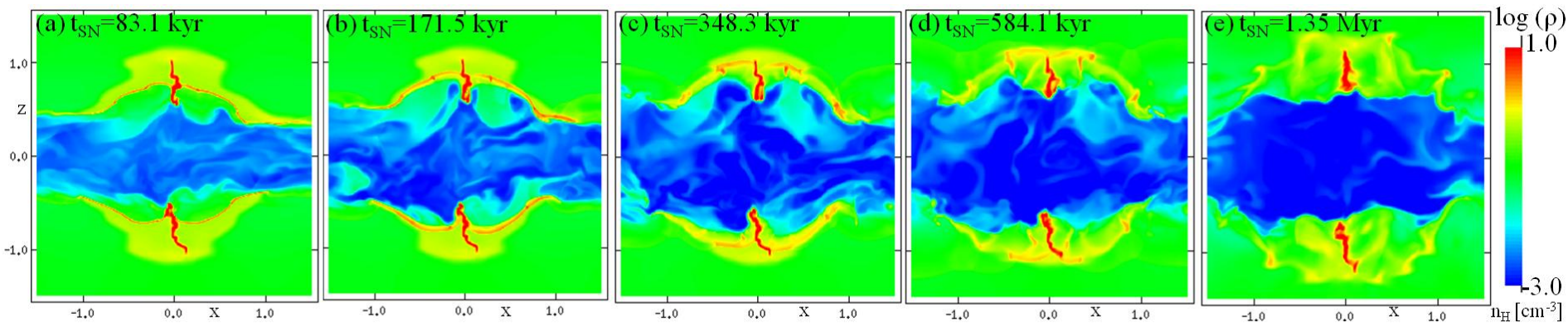
- Final LBV phase results in a high-density environment around star.
- WR wind sweeps this up into a $D=25\text{pc}$ shell, in which the SN explodes.
- Spherical SN remnant until it reaches the cavity wall (8 kyrs).
- SNR then accelerates away through the cavity, whilst slowing into the denser diffuse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

40M_⊙ 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.

- 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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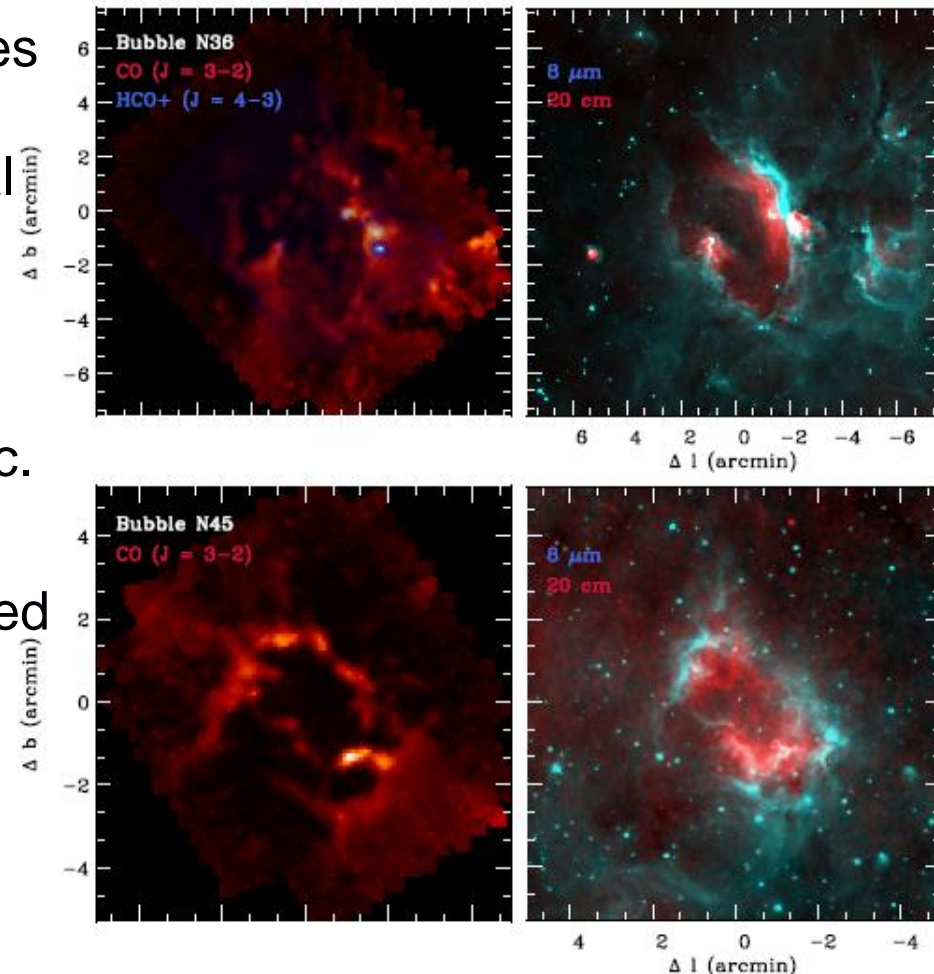
- There's agreement with other authors regarding:
 - Lower mass stars have little effect on parent cloud.
 - Mass-loss rates below $10^{-7} M_{\odot} \text{ yr}^{-1}$ have little effect on the parent cloud.
- High levels of turbulence have been shown to resist shaping effects of winds.
 - Are these appropriate? 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 \sim pc.
- Our work naturally produces such structures, along field line dominated evolution.
- Bipolar HII regions would form if we had included photoionization (when!).

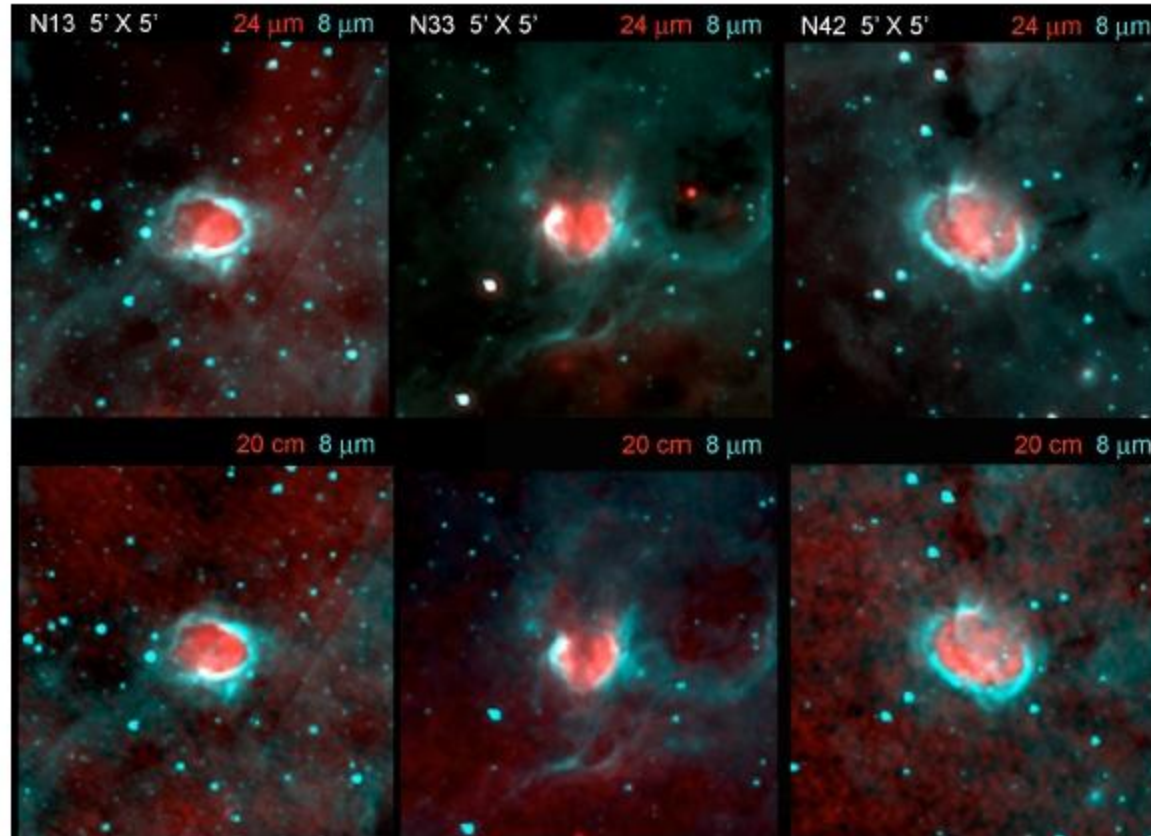


Beaumont & Williams 2010, ApJ, 709, 791-800

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.

Serendipity...



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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.
- Central cavity $r=6.2\text{pc}$ (Celnik 1985, at 1.4kpc), $r\sim 5\text{pc}$ (IPHAS, at 1.53kpc).



IPHAS H α image (Credit: N.Wright/IPHAS)

• $D\sim 1.6\text{kpc} \pm 250\text{pc}$

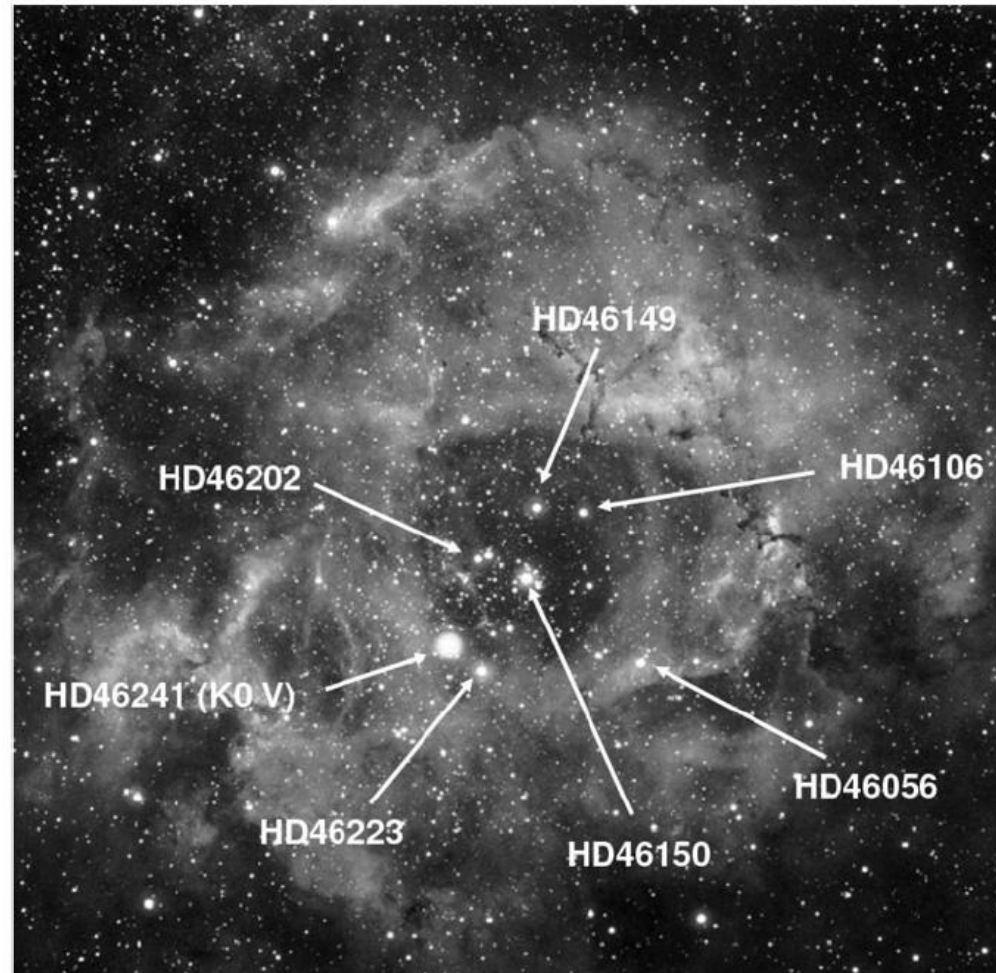
NGC 2244

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 ($\sim 55 M_{\odot}$) 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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- 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 (2-4Myr)**, 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 ($M \sim 10!$)

64,000 years!?

THE ROSETTE NEBULA



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Properties: $r \sim 6.7$ 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 $6.2\text{pc} / (43+13 \text{ km/s}) = 110,000$ 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?

- 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, $V_{\text{exp}} \sim 13$ km/s leads to an age estimate of $\sim 450,000$ yrs, $>4x$ less than 2-6 Myr NGC2244 estimate.

↙ **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...

THE ROSETTE NEBULA

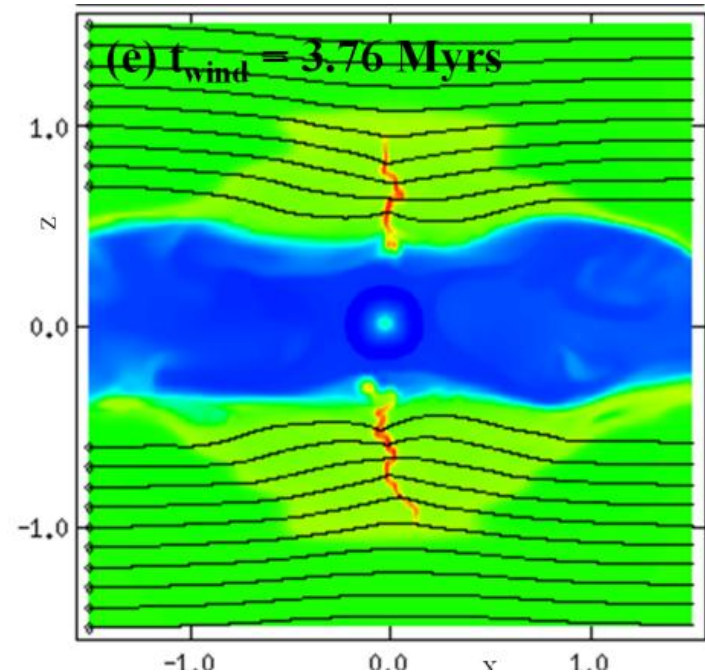


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- What if this...



...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)

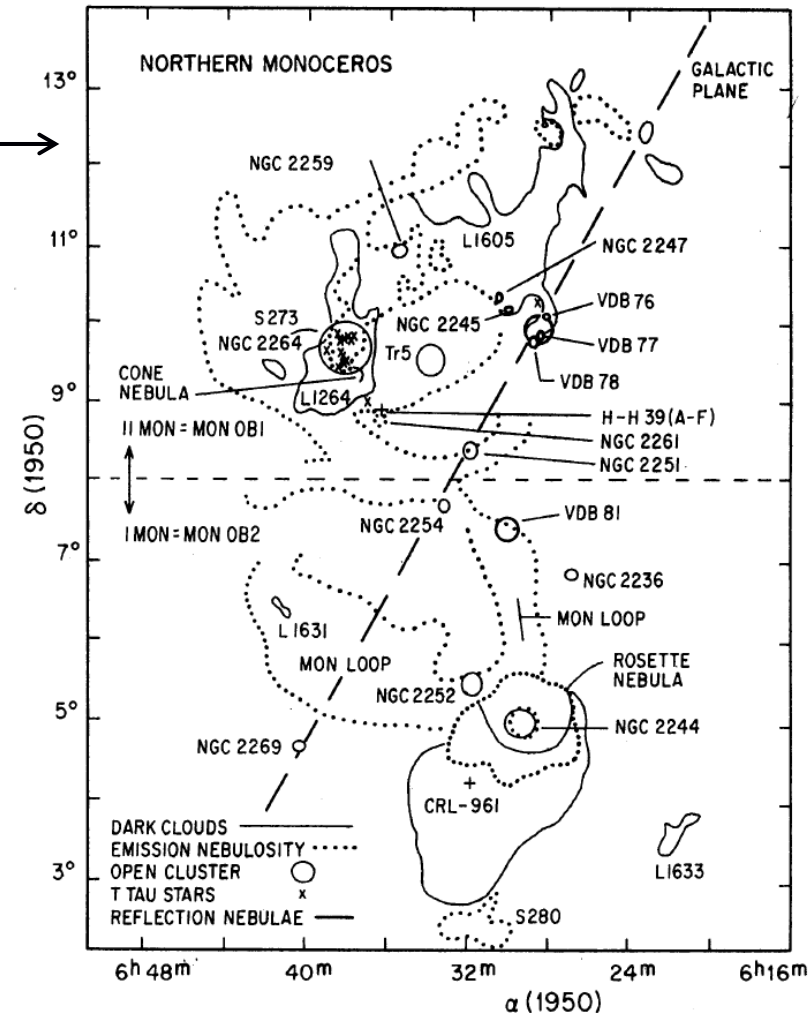
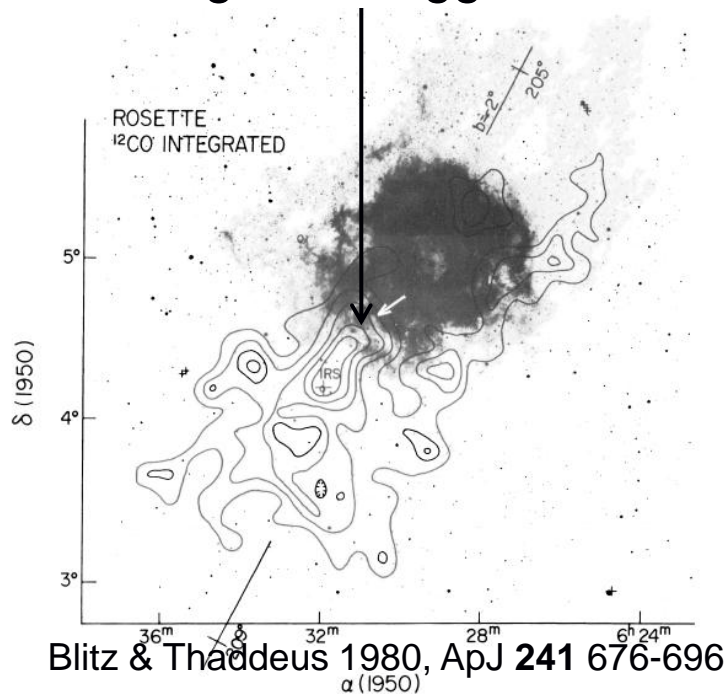
Rosette surroundings

THE ROSETTE NEBULA



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



- So, triggered star formation appears localised.

Pérez 1991 RMxAA 22 99-111

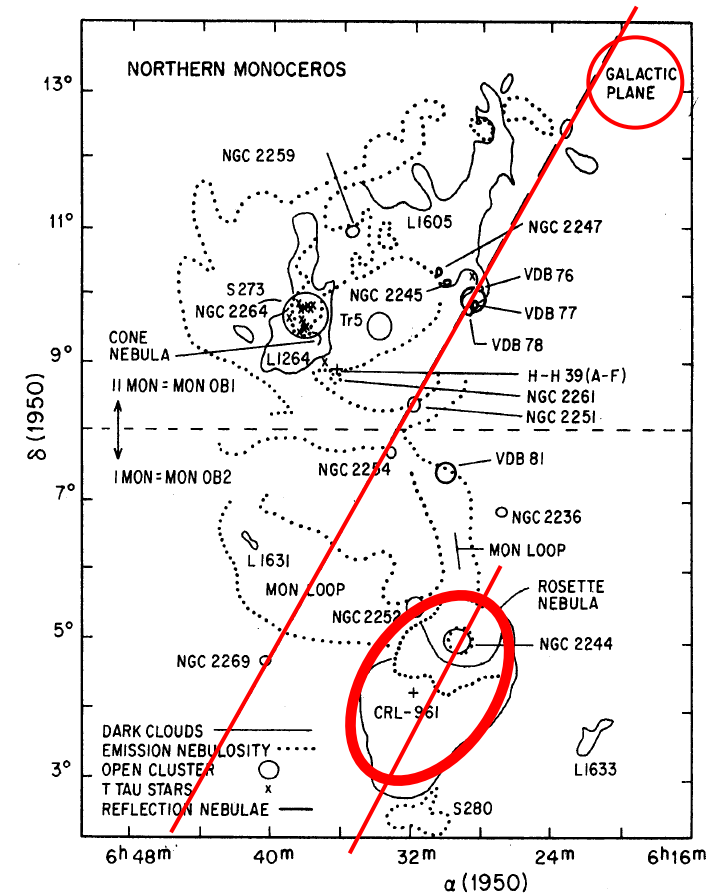
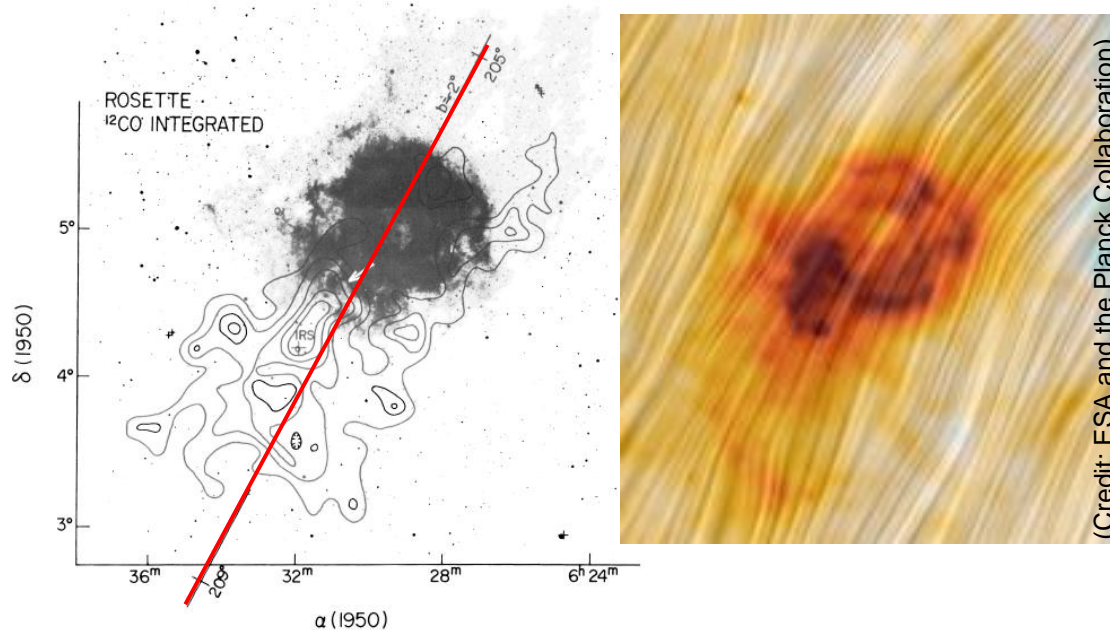
Background magnetic field

THE ROSETTE NEBULA



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



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

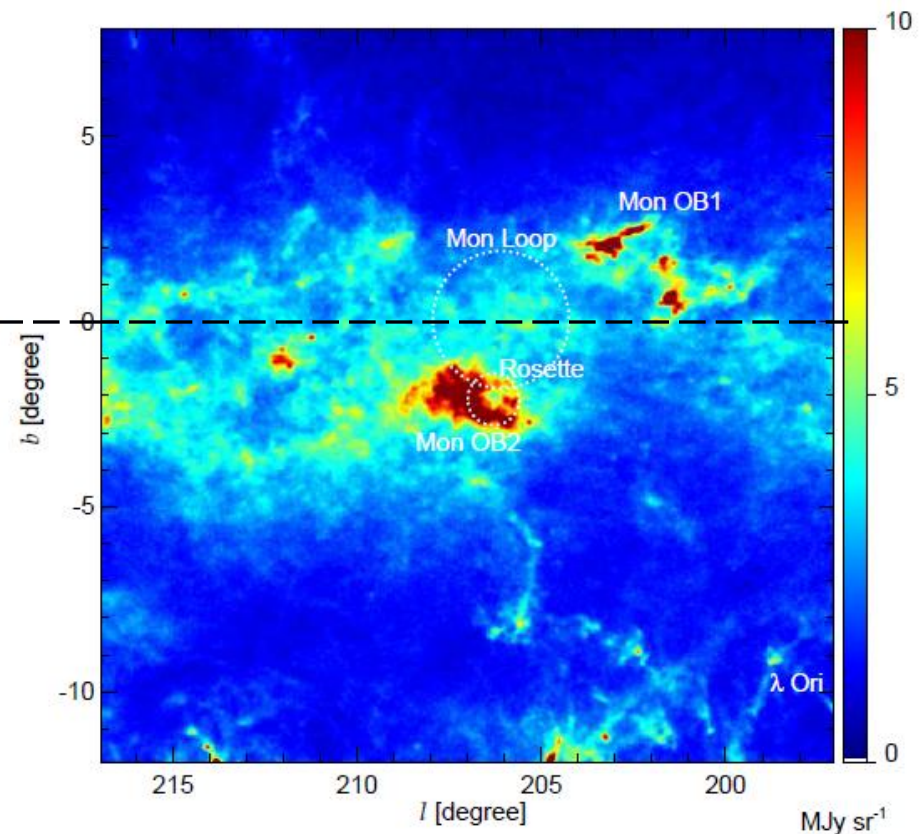
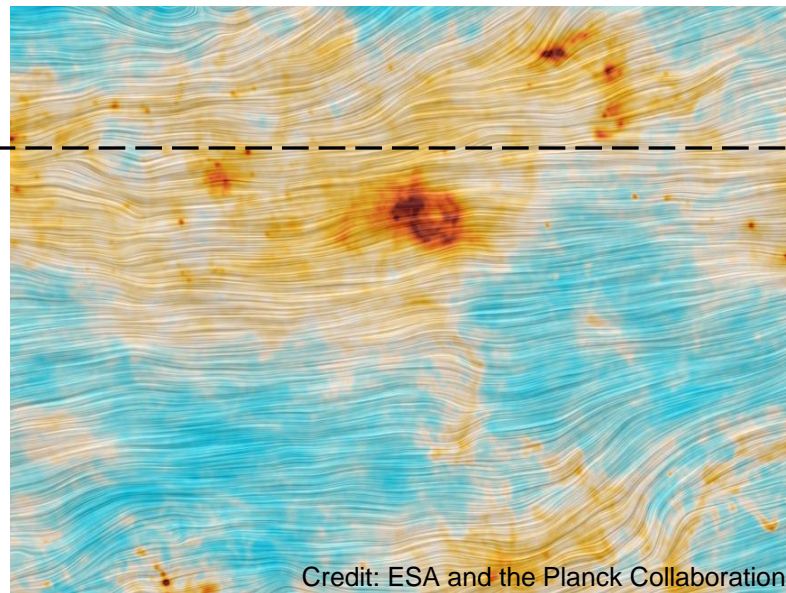
Magnetic field prediction: Planck

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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)



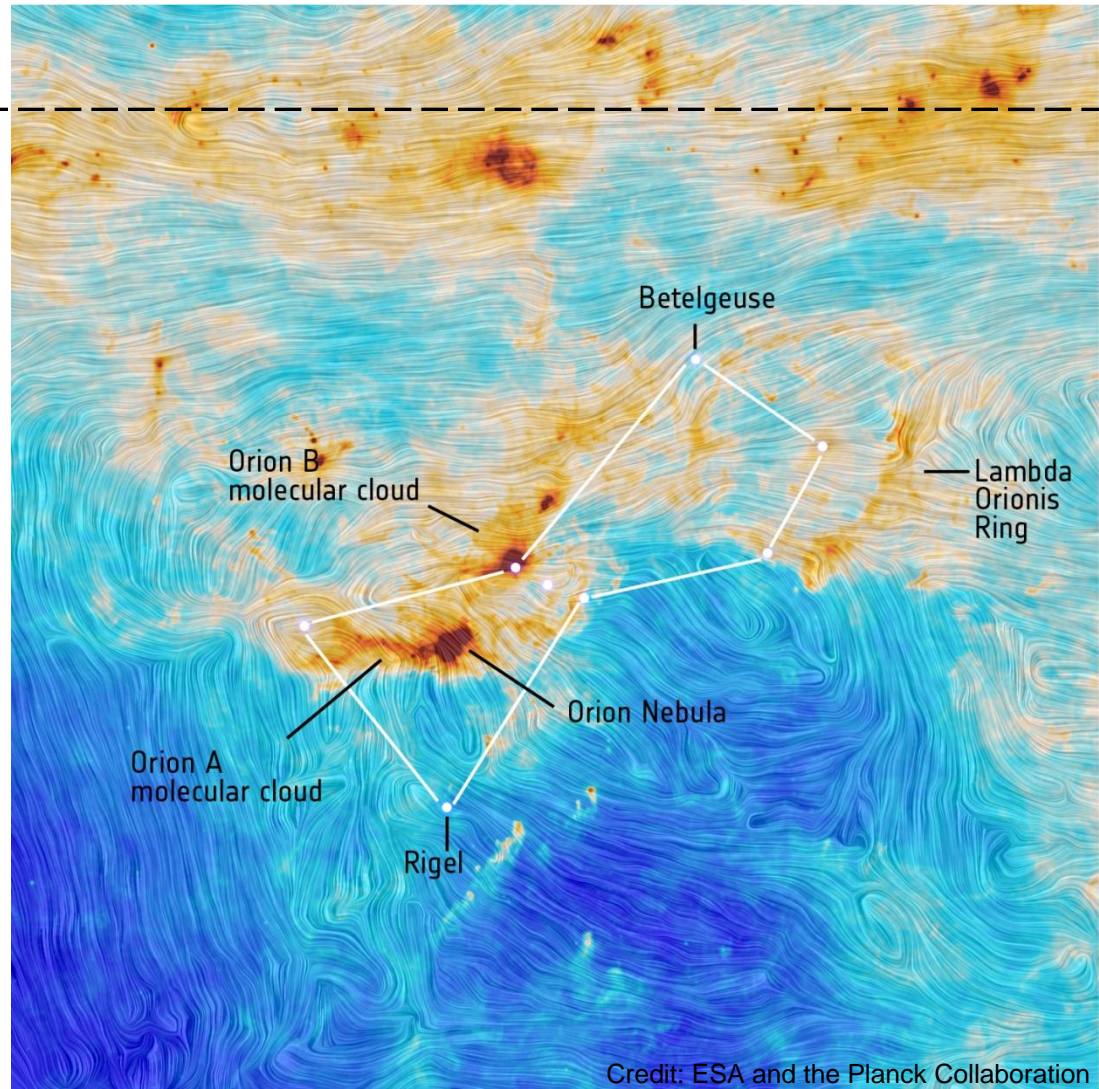
Aside: wider field around Orion

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- Note also the complexity of the magnetic field in and around Orion.
- Away from the plane (dashed line), the field is far more complex.
- Most interestingly is the tendency of the field to be *perpendicular* to the apparently filamentary structures.



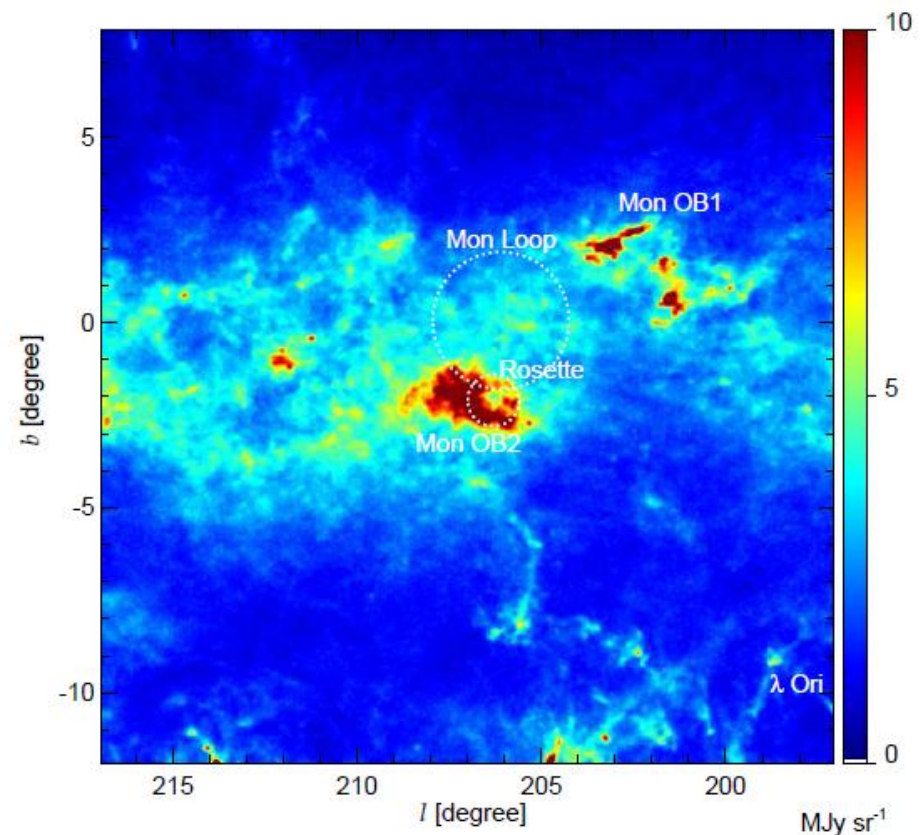
Recent Planck+starlight results

THE ROSETTE NEBULA



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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 45° of angle to line of sight.**
- In good agreement with what our model would require...



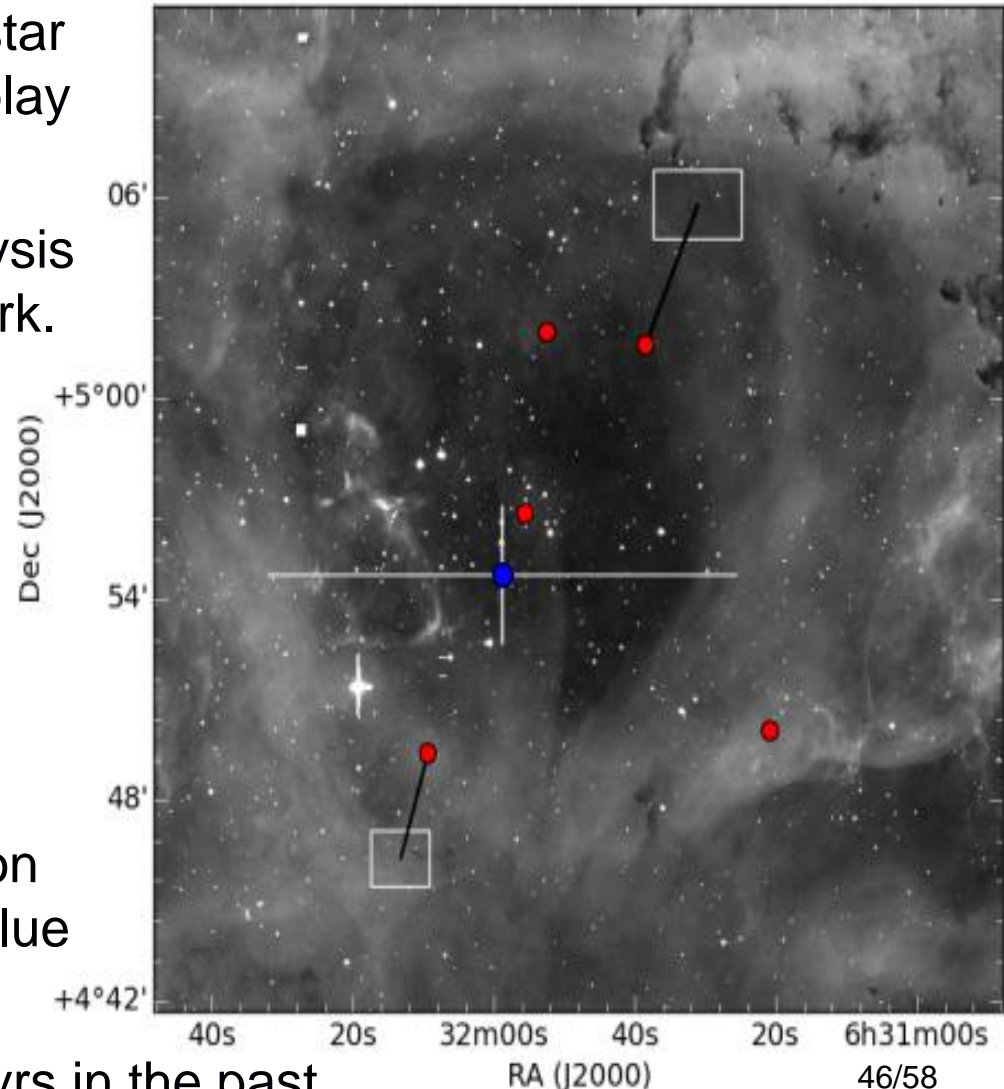
New proper motion analysis

THE ROSETTE NEBULA



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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.



Column density variations?

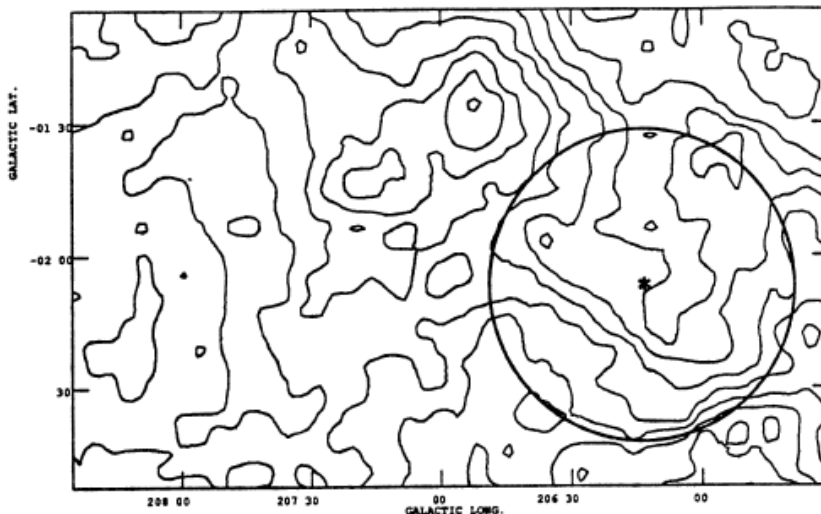
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- Column density through Rosette nebular gas should (naively) be constant across the nebula, if this is a 'disc' or increasing toward centre if spherical.
- Nothing seems to indicate increasing density towards centre

FIGURE 1: H I Integrated Intensity



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

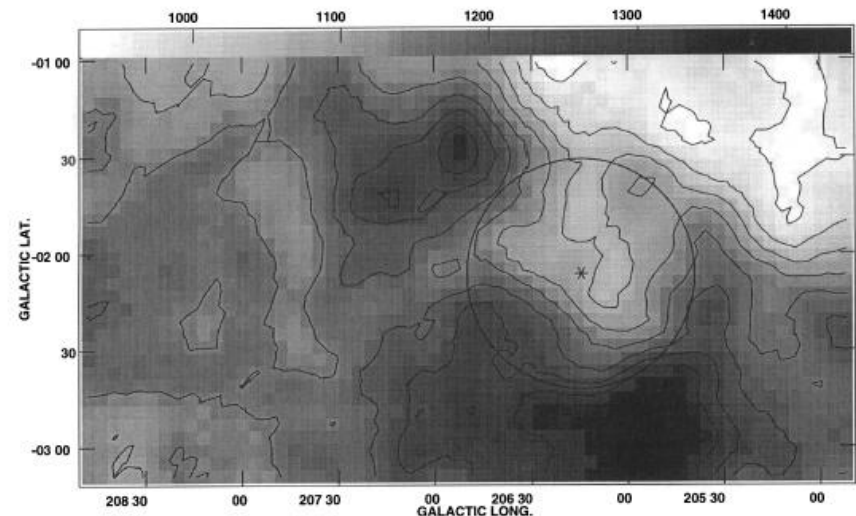


FIG. 1.—Velocity integrated H I intensity map $\int T_a dv$, where T_a is expressed in antenna temperature units (brightness temperature, $T_b = 1.37 T_a$). The integration was performed over $V_{LSR} = 3.1\text{--}24.2 \text{ km s}^{-1}$. The contours range from 950 to 1450 K km s^{-1} and are spaced 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 H I 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 ($R = 38'' = 17.7 \text{ pc}$ 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.

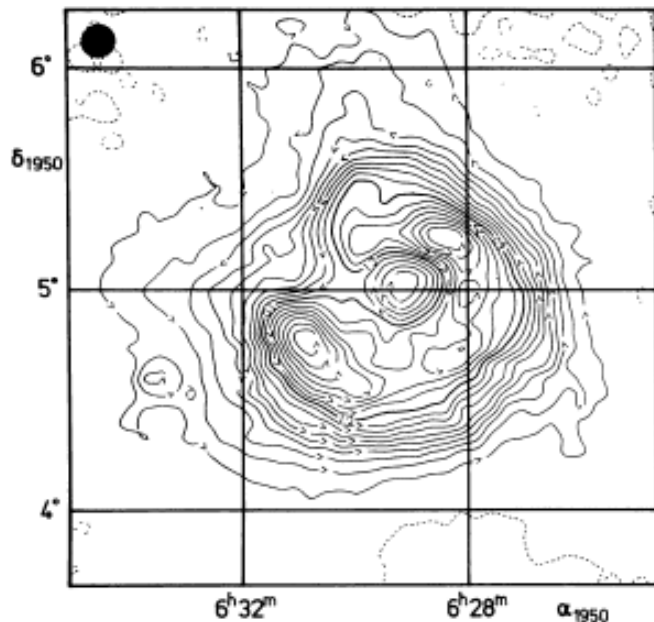


Fig. 1. Distribution of brightness temperature across the Rosette nebula at 1410 MHz, lowest (dashed) contour line at 0, line No. 10 at 8.0 K, thin lines at 0.8 K intervals, lines with arrows indicating clock wise rotation enclose decreasing temperature values, angular resolution is $9'24''$

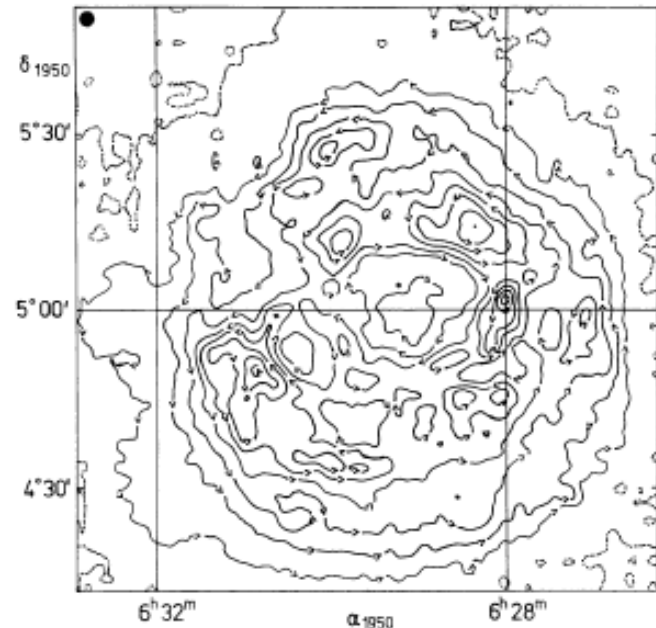


Fig. 2. Distribution of brightness temperature across the nebula at 4750 MHz, lowest (dashed) contour line at 0.1 K, contour lines at 0.2 K intervals, lines with arrows indicating clock wise rotation enclose decreasing temperature values, angular resolution is $2'43''$

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

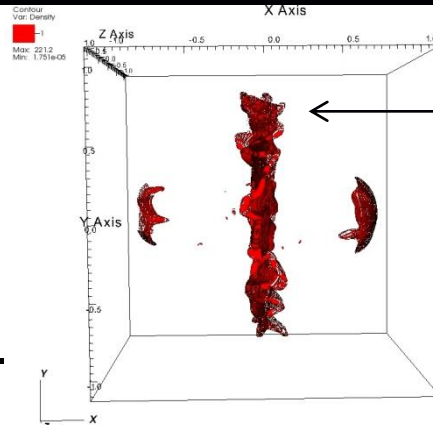
New tuned model...

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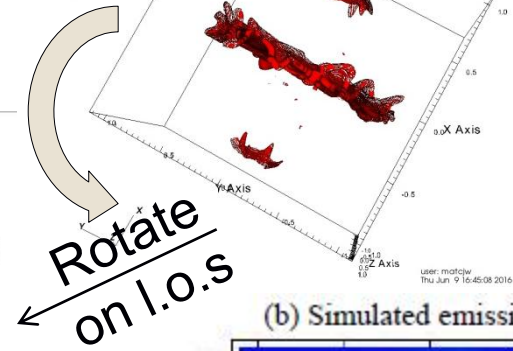
- New simulation of a $60 M_{\odot}$ star in the same initial condition.
- Evolved for 2 Myrs as implied by proper motion.
- Slice plane at $y=0$.



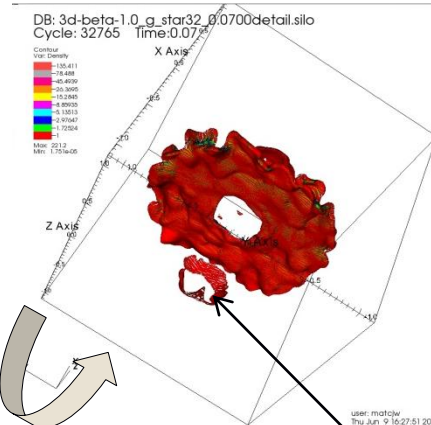
Density isosurface

Rotate
on sky

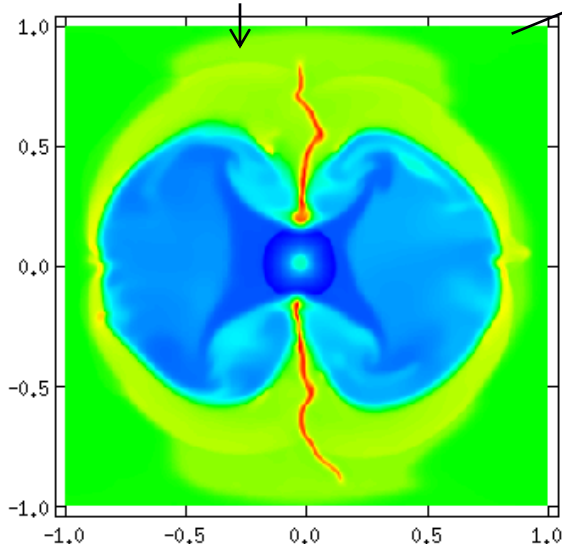
DB: 3d-beta-1.0_g_star32_0.0700detail.silo
Cycle: 32765 Time: 0.07



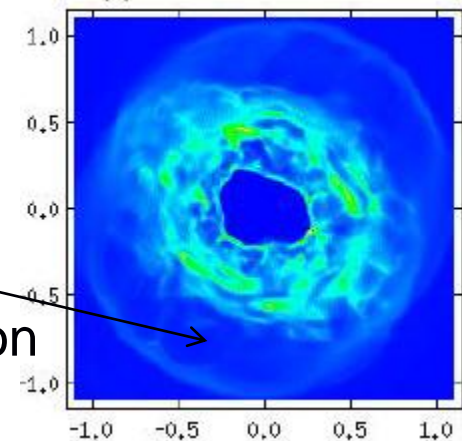
Rotate
on I.O.S



Triggered
star formation



(b) Simulated emission



- Central hole: $D=18-20\text{pc}$
(c.f. 13pc for the Rosette).

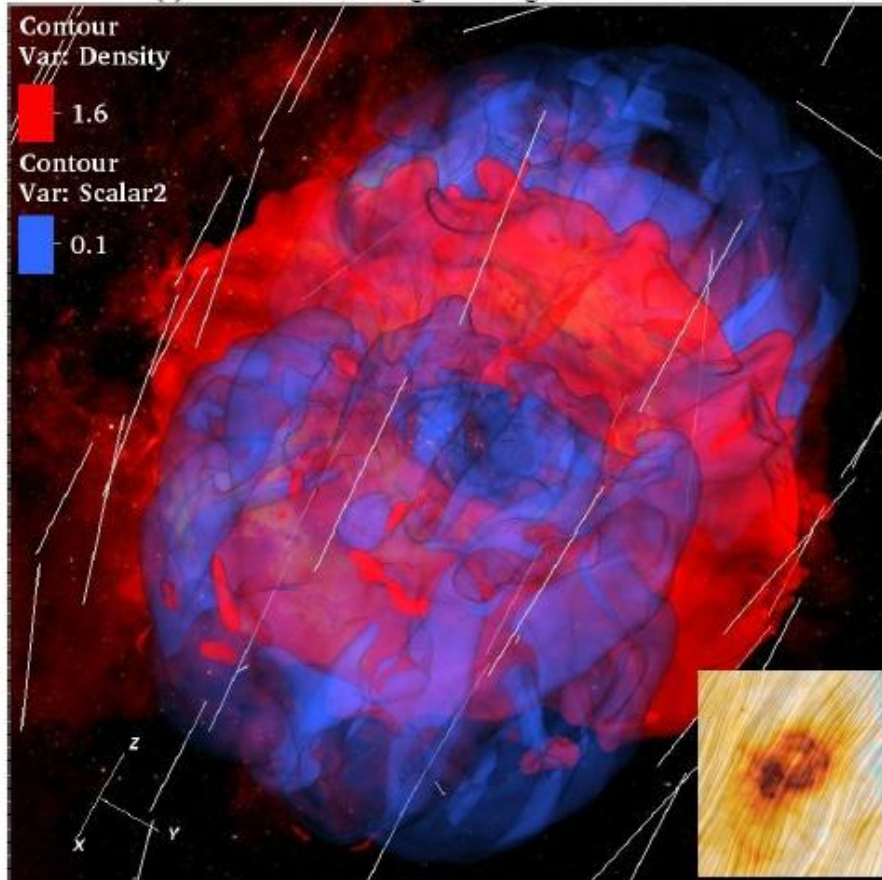
...provides a solution!

THE ROSETTE NEBULA



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(a) Isosurface rendering with magnetic field vectors



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.

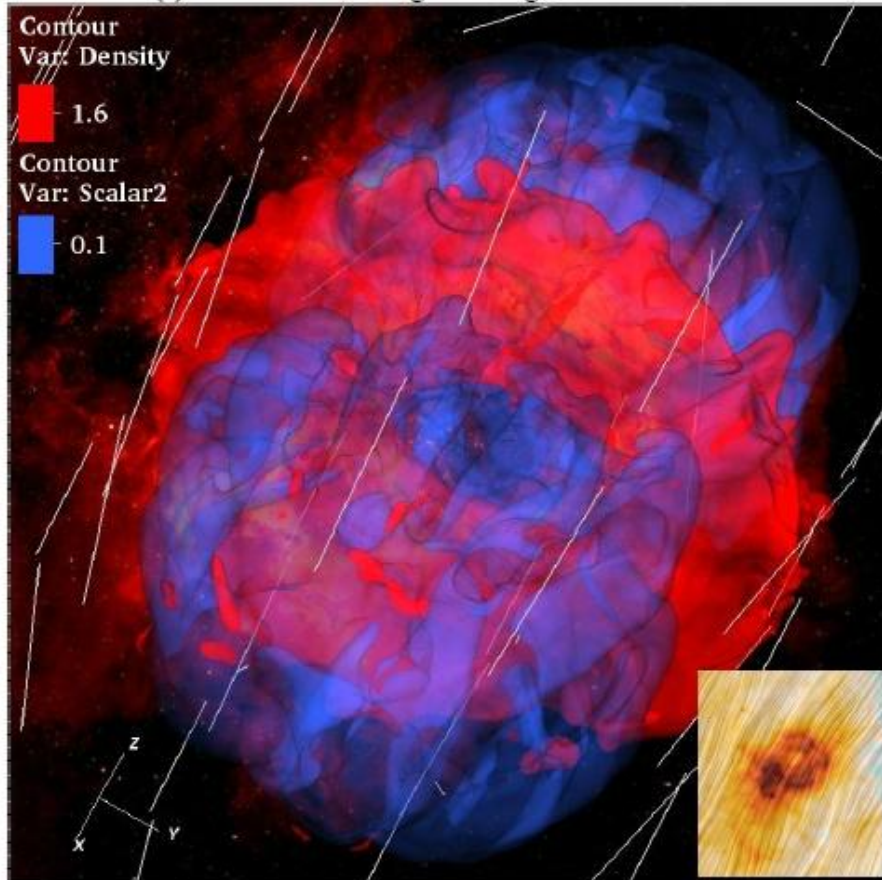
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THE ROSETTE NEBULA



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We have a solution for:-

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- Magnetic field alignment and the angle to the line of sight.
- Ejection of HD46223 from the cluster.

But...

- Low mass cloud ($17,000 M_{\odot}$)
- Rosette estimates are $\sim 1.65e5 M_{\odot}$ (from CO Measurements).

(The Rosette lies at one end of the cloud so local conditions may have less mass)

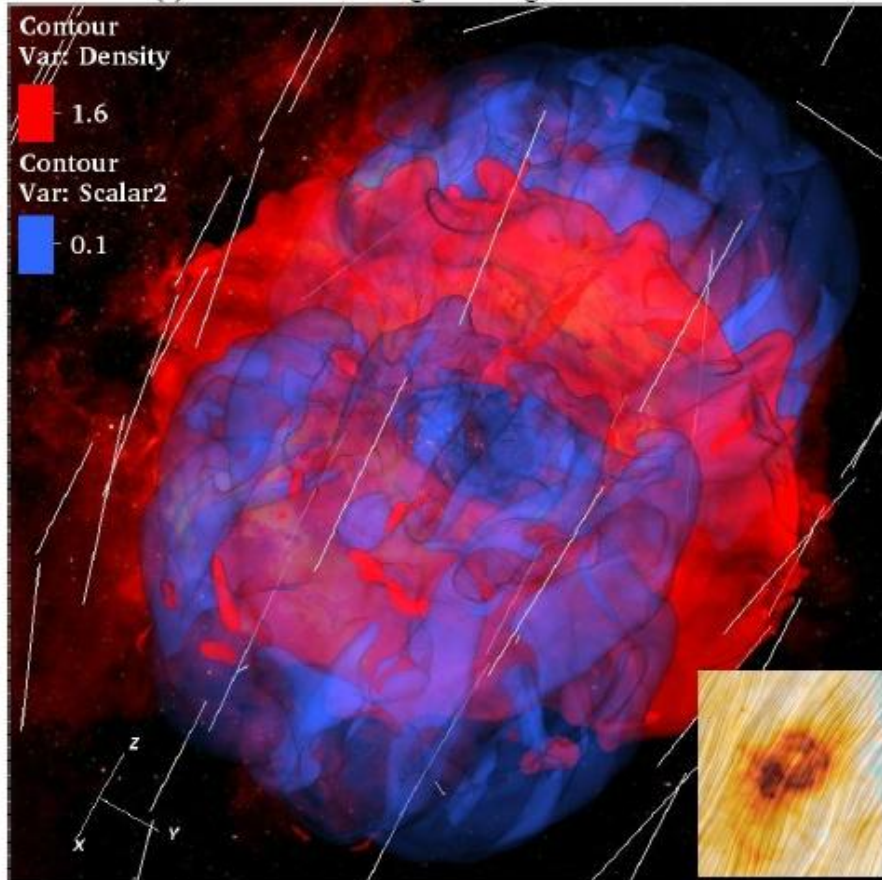
Further refinements...

THE ROSETTE NEBULA



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(a) Isosurface rendering with magnetic field vectors



- Refined simulations in a much larger cloud ($1.35 \times 10^5 M_{\odot}$):
 - $60 M_{\odot}$ 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.

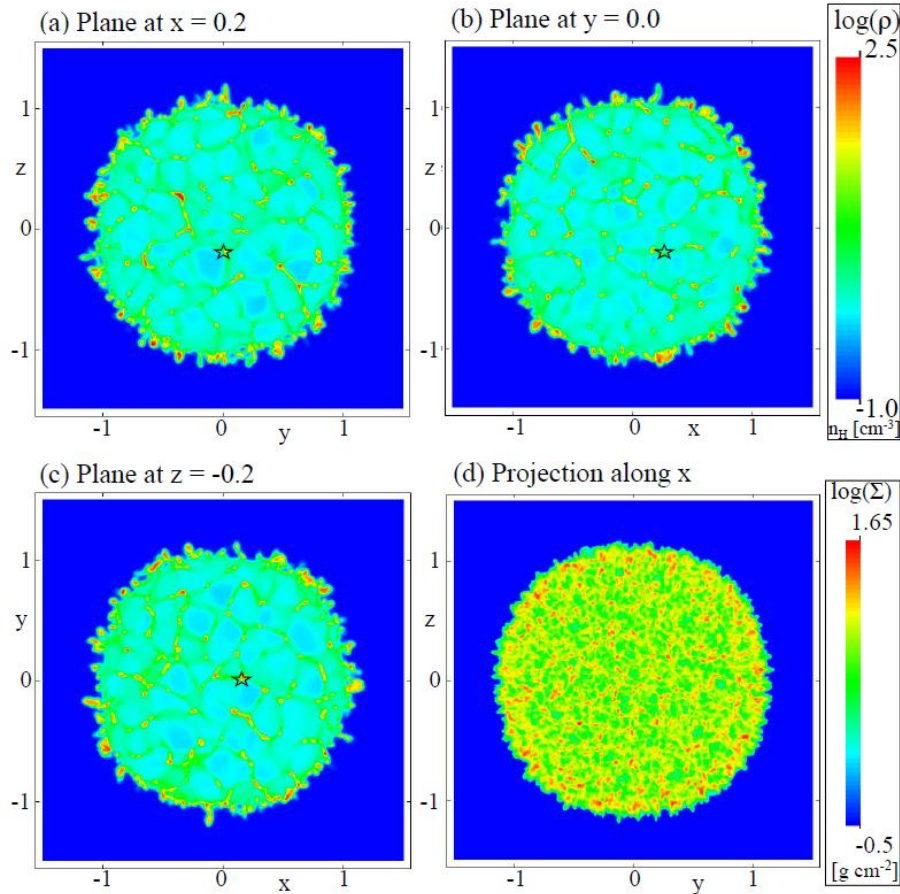
Initial conditions – 135,000 M_{\odot} cloud

REFINED SIMULATIONS OF THE ROSETTE NEBULA

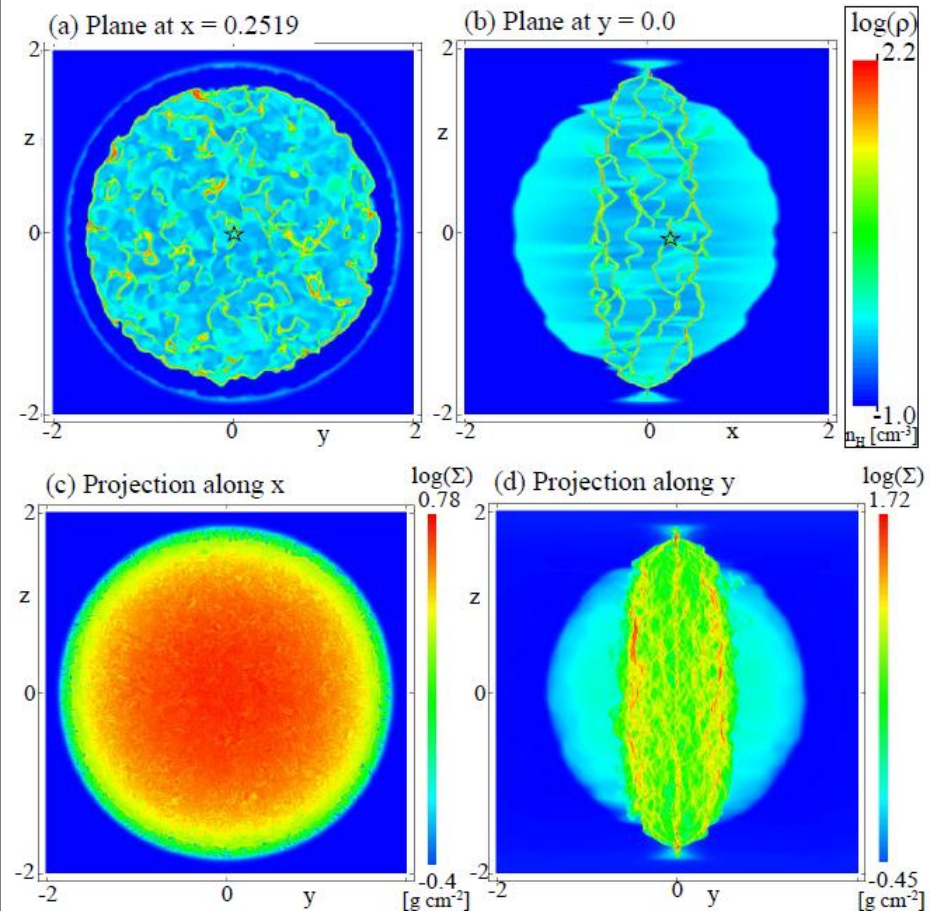


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Hydrodynamic case



Magnetic field case



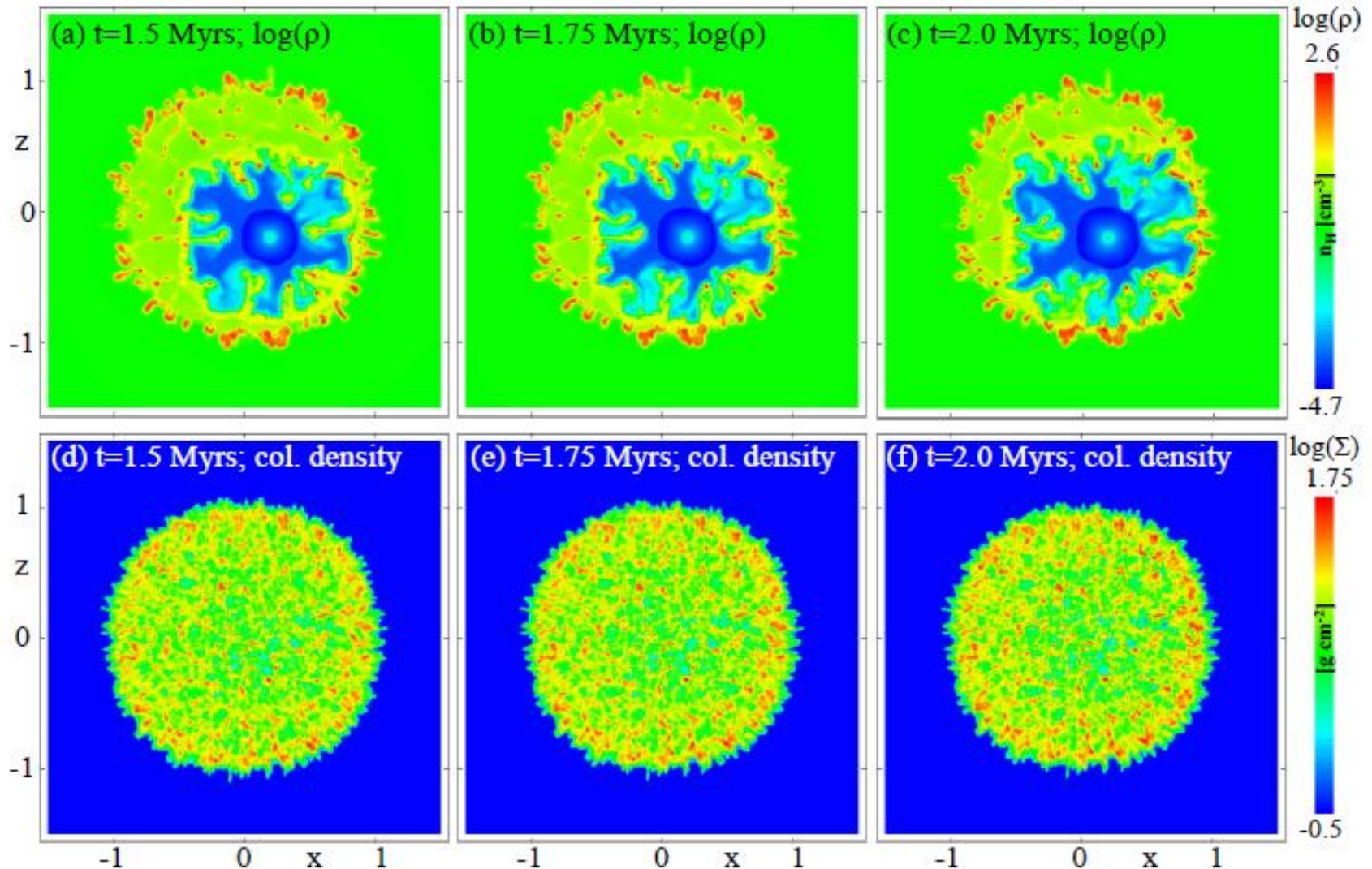
- In both cases, thermal instability drives the evolution on these large scales.

Results: Hydrodynamic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



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- Hydrodynamic case does not reproduce the Rosette nebula

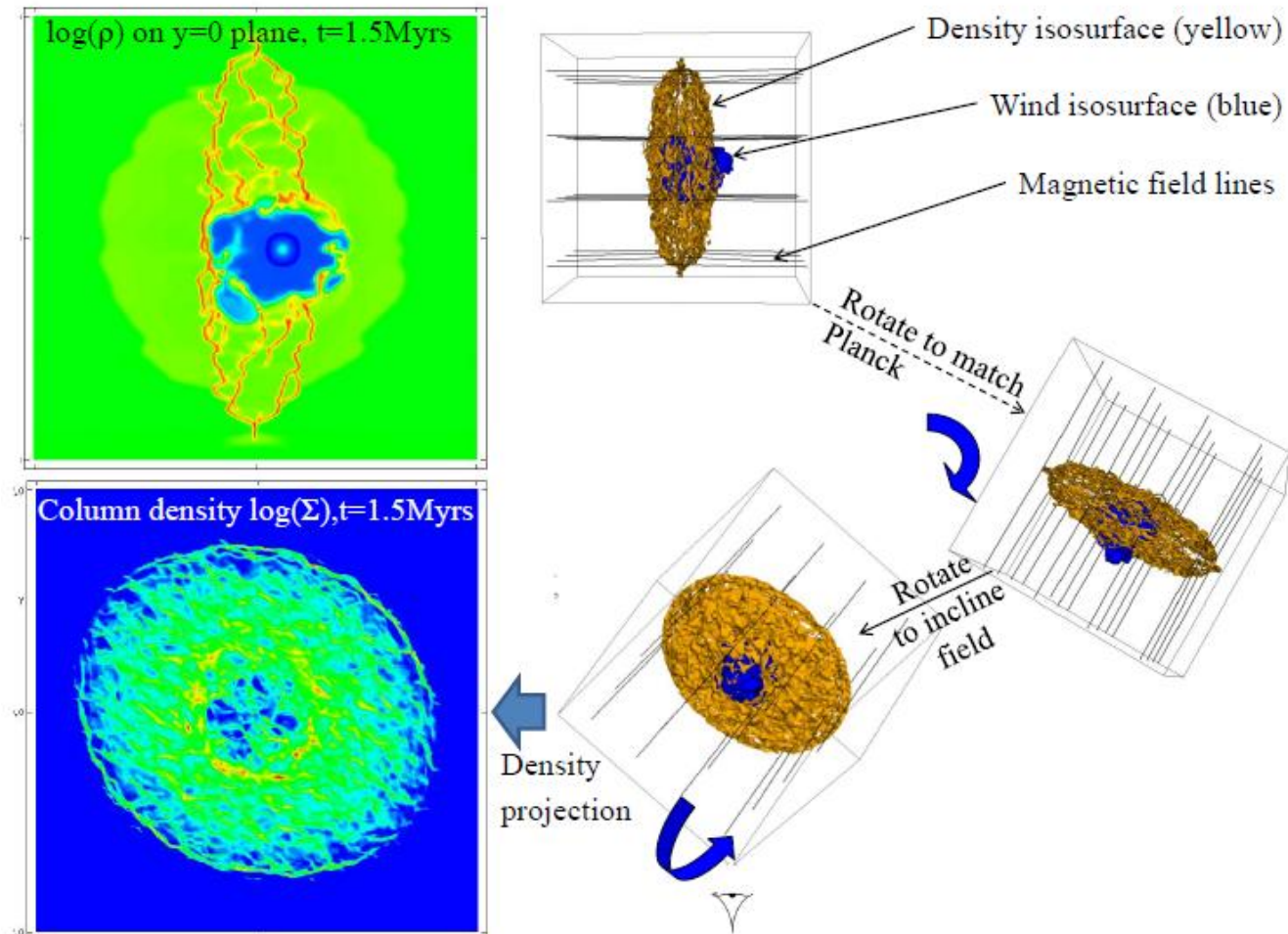
Results: Magnetic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



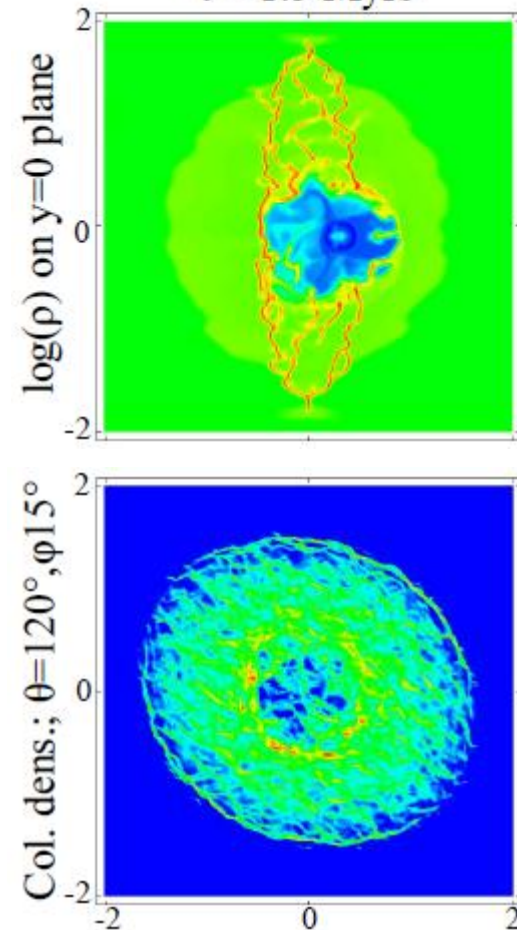
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Magnetic field case with a single star



Double star

$t = 1.5$ Myrs



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

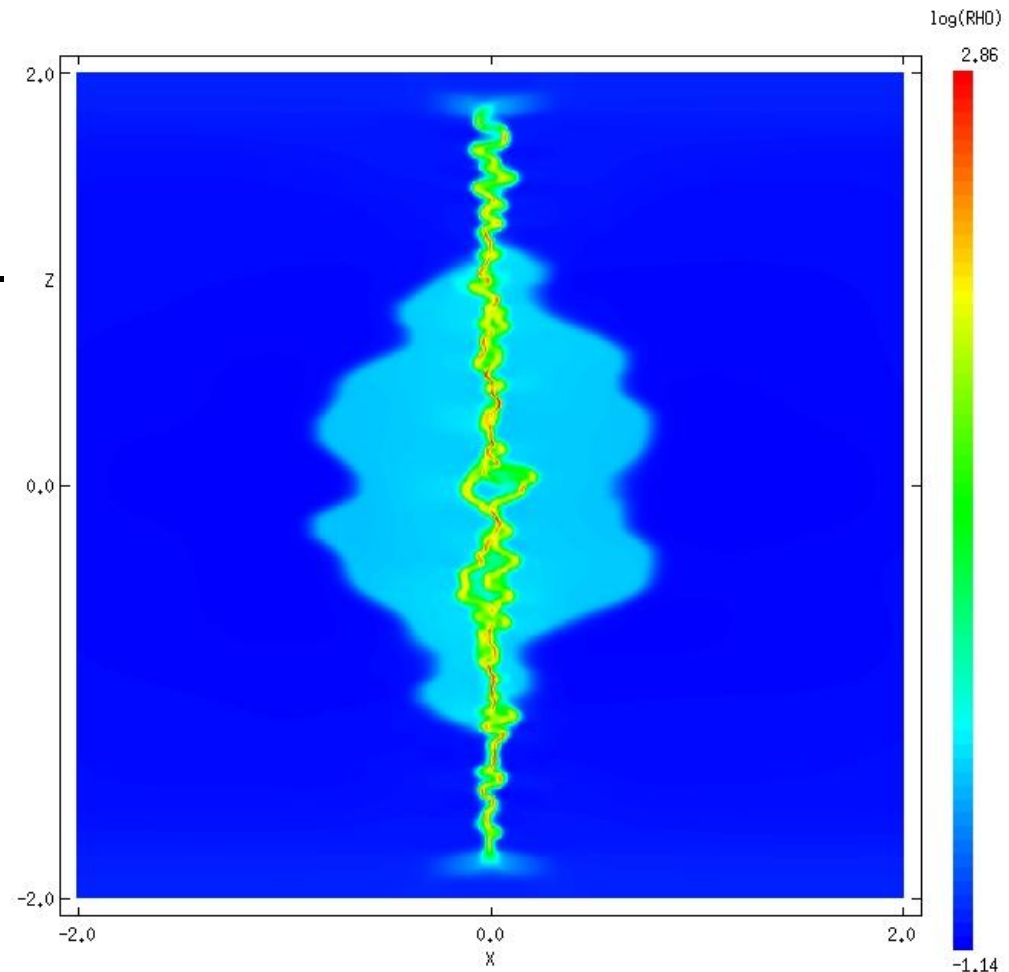
Thin disk magnetic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



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- 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.



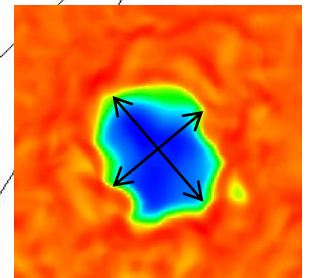
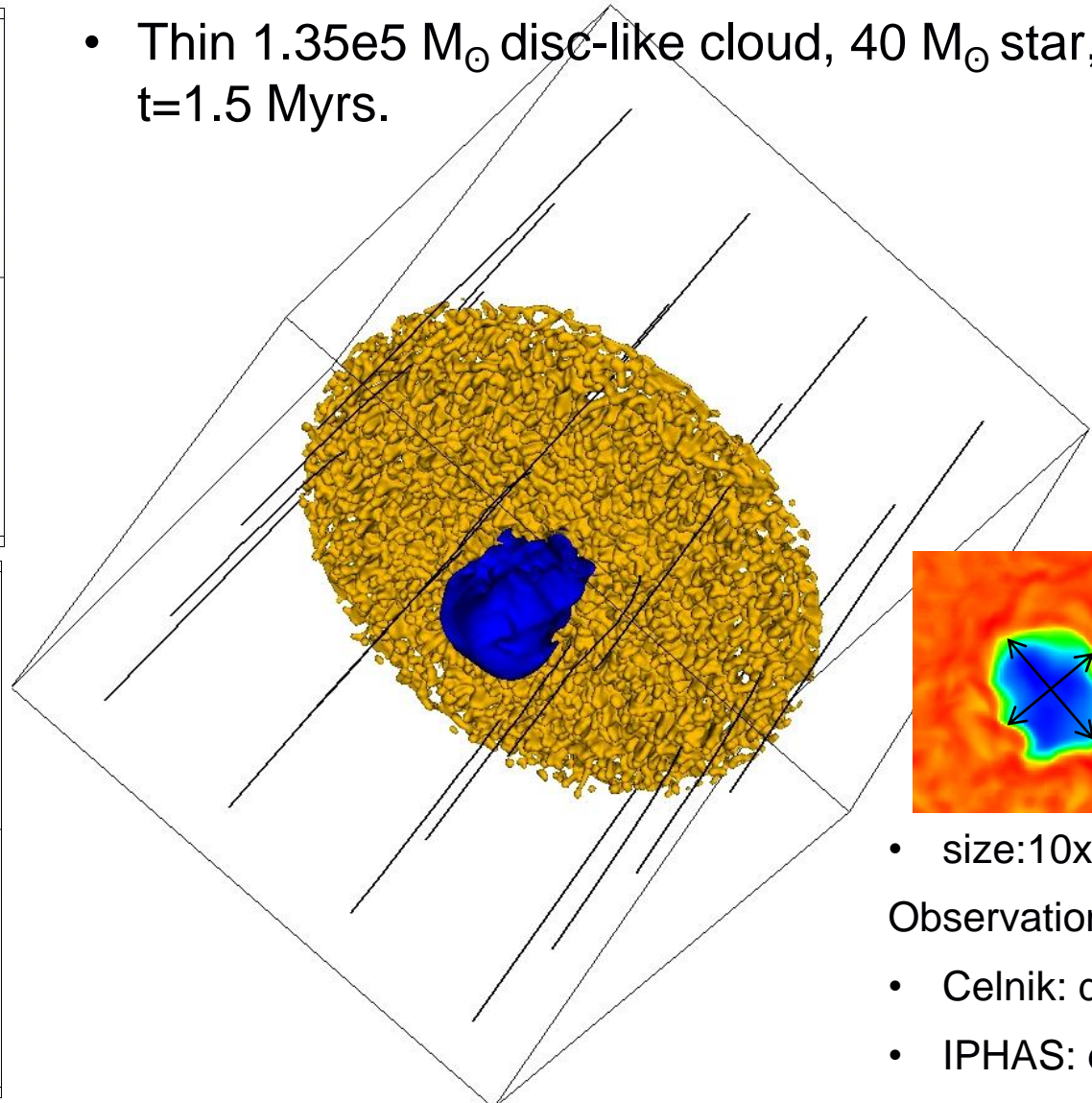
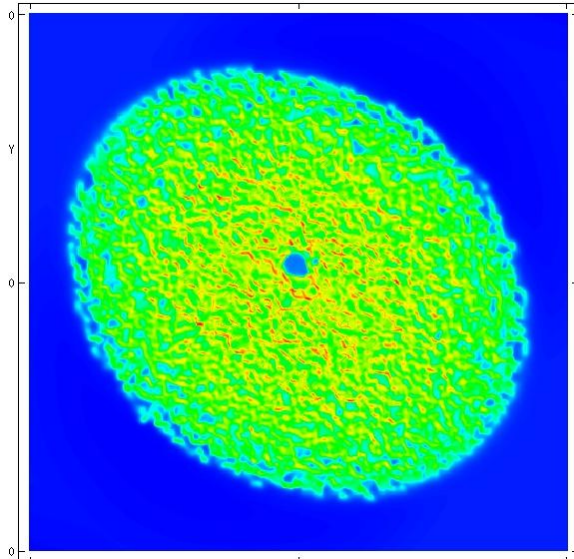
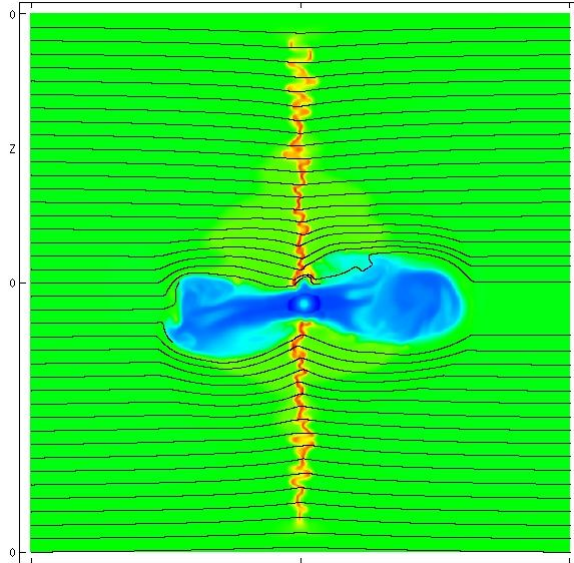
Results: Thin disk magnetic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



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- Thin $1.35 \times 10^5 M_{\odot}$ disc-like cloud, $40 M_{\odot}$ star, $t = 1.5$ Myrs.



- size: 10×7.5 pc

Observations:

- Celnik: $d \sim 13$ pc
- IPHAS: $d \sim 10$ pc

Implications for the ISM from our work

THE ROSETTE NEBULA



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- Background magnetic field can have a strong effect on thermal instability driven evolution of molecular clouds, forming corrugated sheets that are filamentary in projection.
- Winds from stars $<15 M_{\odot}$ have little effect on their parents clouds.
- Winds from high mass stars can carve channels and destroy clouds.
- SNe disrupt parent clouds, returning cold material to the ISM, but only in the very highest mass cases ($120 M_{\odot}$) do they return all the material to the thermally unstable phase.
- An extended but thin molecular cloud can host the Rosette Nebula.

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, 2017, MNRAS in prep.