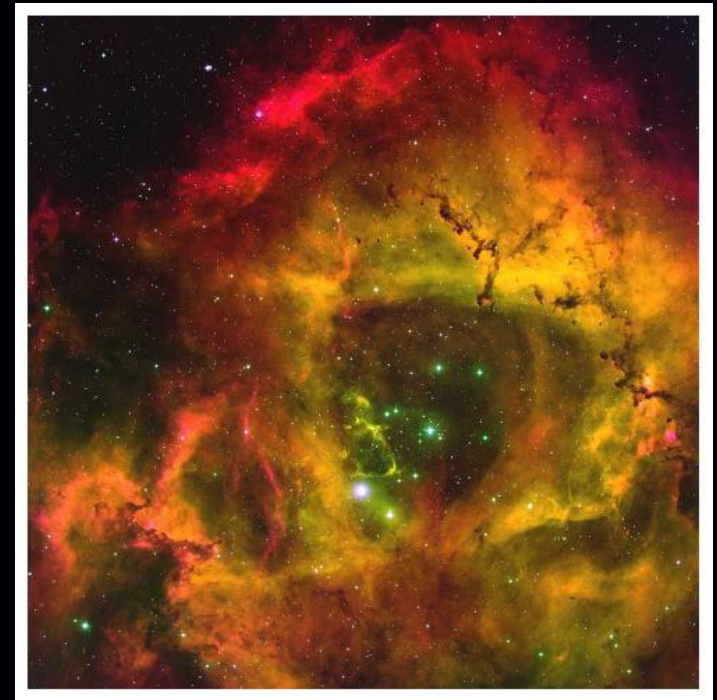
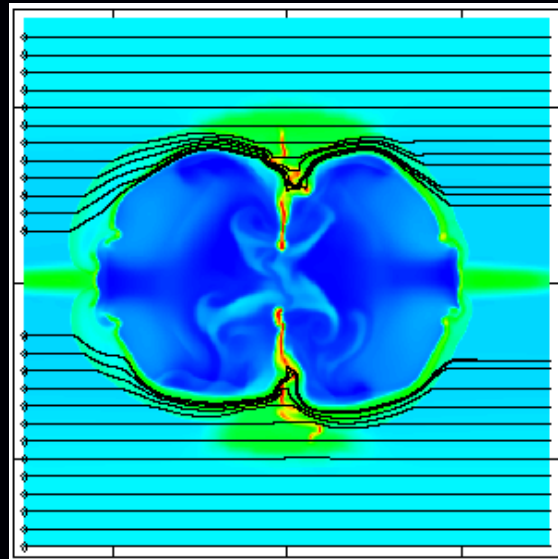
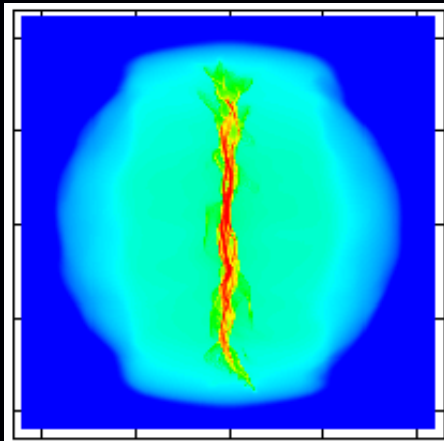


A new massive star feedback model for the Rosette Nebula and its implications for the ISM



Chris Wareing,
Julian Pittard, Sam Falle; Nick Wright (Keele)

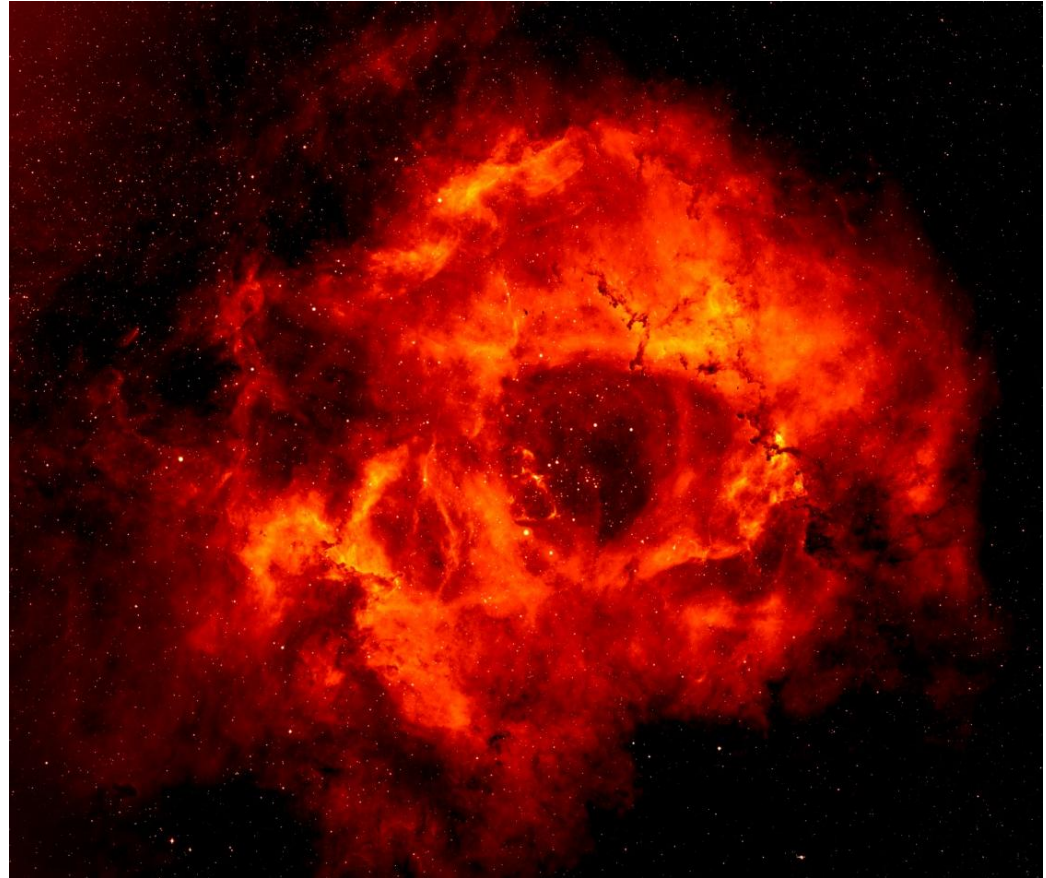
Northern Stars Meeting,
7th & 8th September, Astrophysics Research Institute, LJMU

The Rosette Nebula



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- Large HII region in the Monoceros GMC complex.
- Shocked high velocity cloud?
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.
- Prime candidate for triggered star formation.
- 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)

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

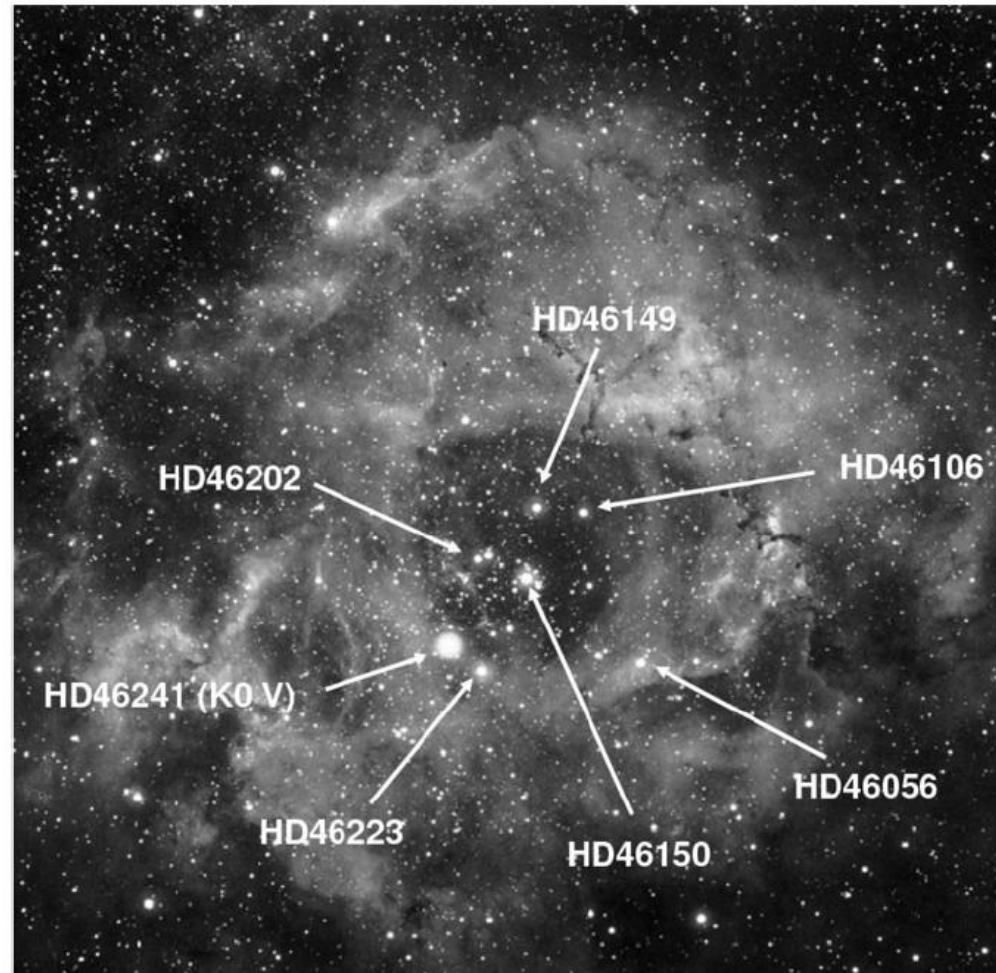
NGC 2244

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 indicates HD46223 may not be part 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 expansion velocity point to a dynamical 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.
 - Bruhweiler et al postulate “an ejection event formed the cavity”.
 - But they “uncomfortably” emphasize that an asymmetric cavity where the much larger axis is directed toward observer cannot be ruled out (axis ratio required > 17), explaining the small radius seen in the plane of the sky.
-
- Turbulence in low mass clouds may confine radiative feedback, but mechanical feedback requires very high levels of turbulence ($M \sim 10!$)

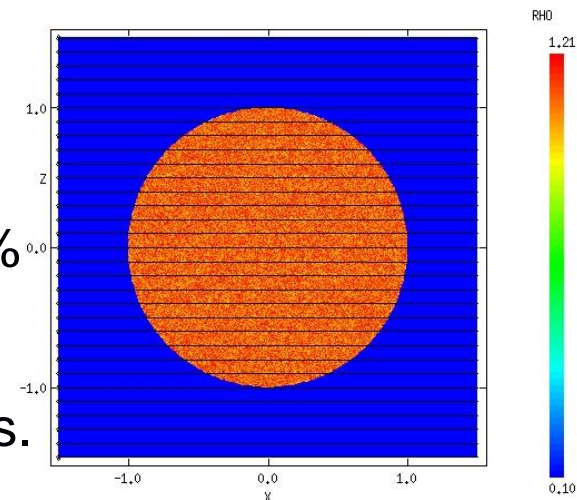
Our physical molecular cloud model



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- 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. Specifically **3D MHD, self-gravity and multi-phase ISM** (i.e. realistic heating and cooling) leading to thermal instability.
- We used a magnetohydrodynamic version of MG with self-gravity
 - a parallelised upwind, conservative shock-capturing scheme, with adaptive mesh refinement.
- Three field strengths were considered, all with: $\underline{B} = B_o \hat{\underline{I}}_x$
 - The hydrodynamic case: $\beta = \infty$
 - Pressure equivalence: $\beta = 1$ - commonest.
 - Magnetically dominated regime: $\beta = 0.1$
- 100-pc diameter diffuse cloud, $n_H = 1.1 \text{ cm}^{-3} \pm 10\%$
- For $\beta = 1$, $B_o = 1.15 \mu\text{G}$. For $\beta = 0.1$, $B_o = 3.63 \mu\text{G}$
- Pressure equilibrium with low-density surroundings.
- Thermally unstable initial condition.

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



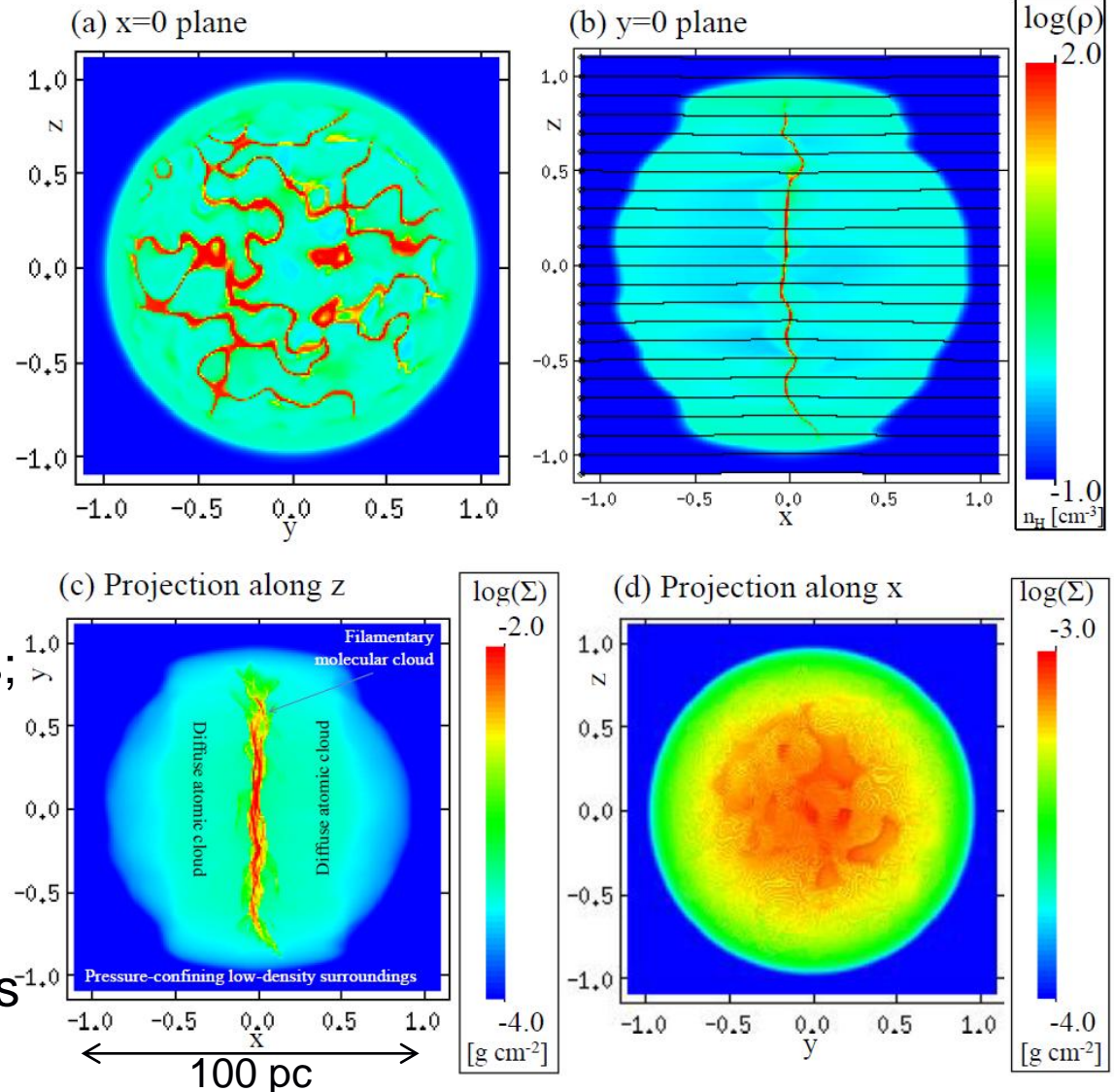
Thermal instability driven results

INITIAL CONDITION FOR FEEDBACK



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- A 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 $(-0.025, 0.0, 0.0125)$;
- Cloud age $\sim 10 \text{ Myrs}$;
- Such sheet-like structures are common.



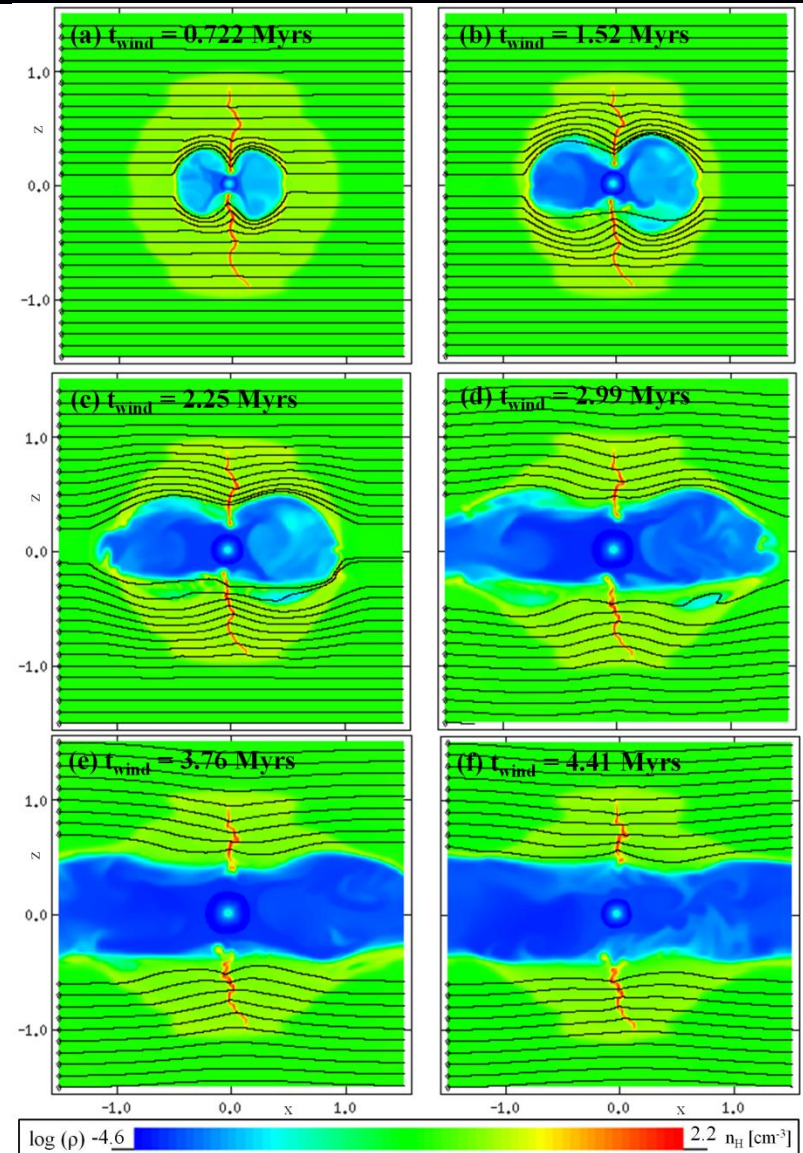
40M_⊙ star: wind phase

ADDING FEEDBACK



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- 40 M_⊙ star, following non-rotating Geneva 2012 track.
- **For this star, there's a significant impact on the molecular cloud.**
- Large bipolar cavity evolves into a cylindrical cavity (D~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.
- Total mass injected 27.2 M_⊙, total energy injected of 2.5×10^{50} erg



A new model...

THE ROSETTE NEBULA

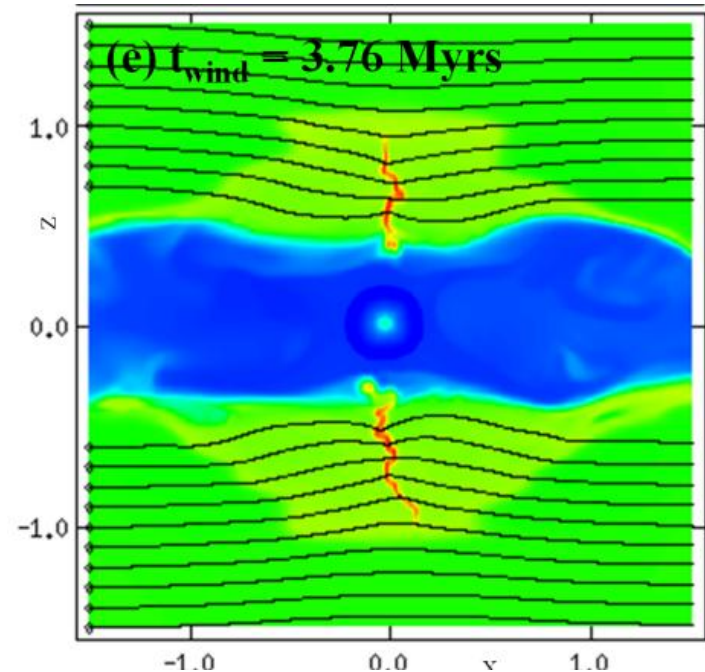


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- What if this...



...was formed like this.



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

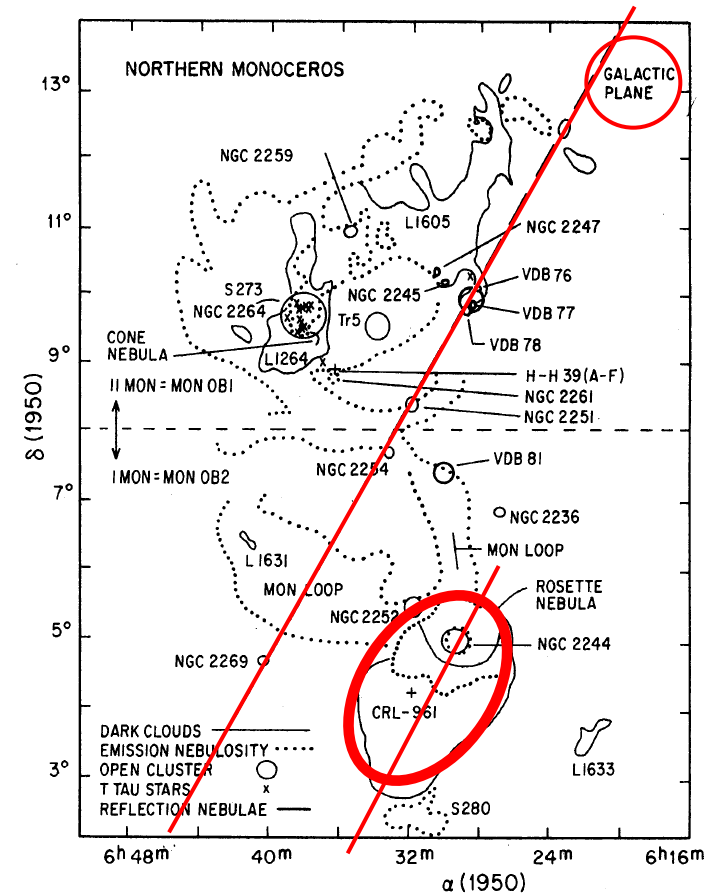
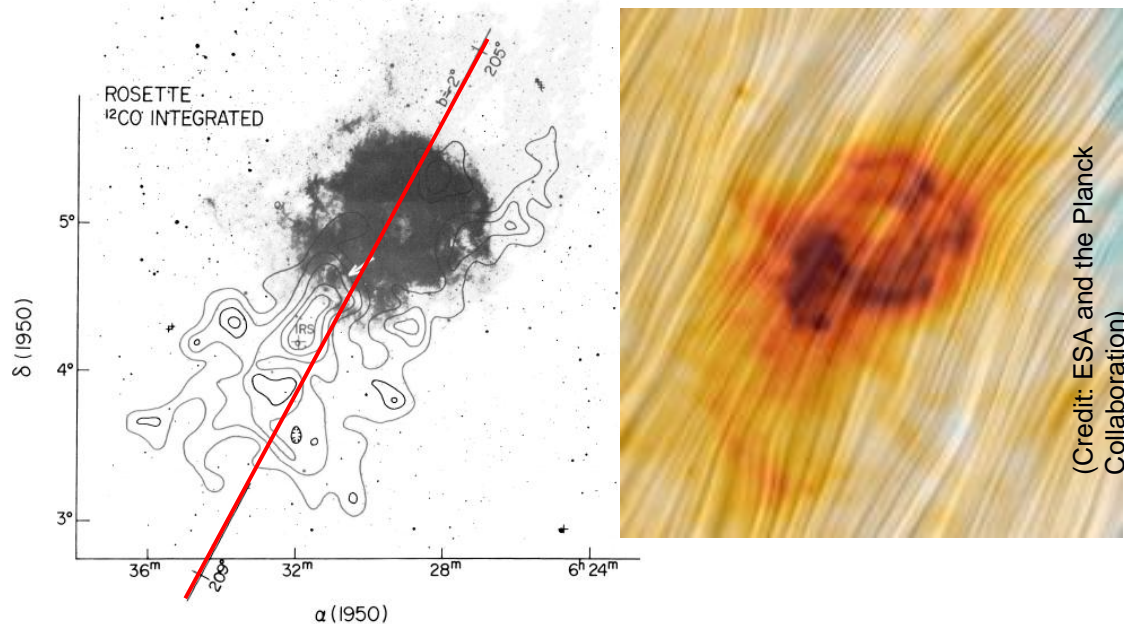
Background magnetic field

THE ROSETTE NEBULA



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



- Naively, wind ejection is **a perfect fit** for the triggered star formation.
- Planck observations combined with rotation measure suggest 45° angle to line of sight.

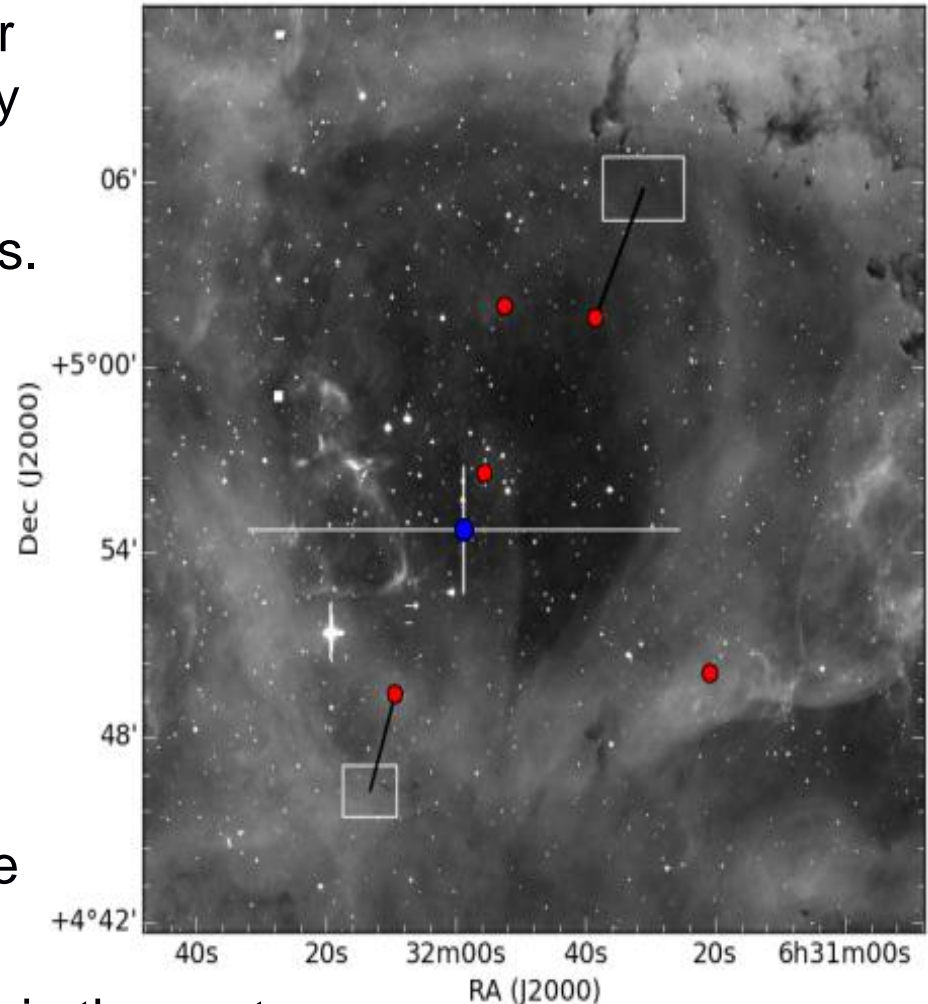
New proper motion analysis

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.
- 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.



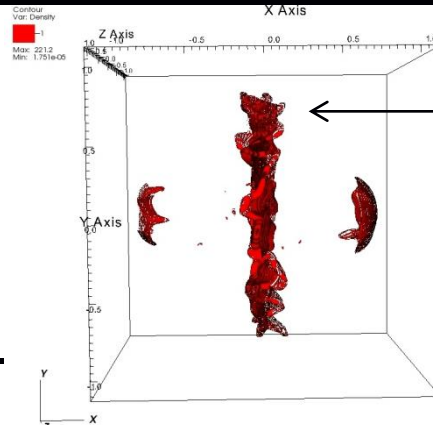
New tuned model

THE ROSETTE NEBULA



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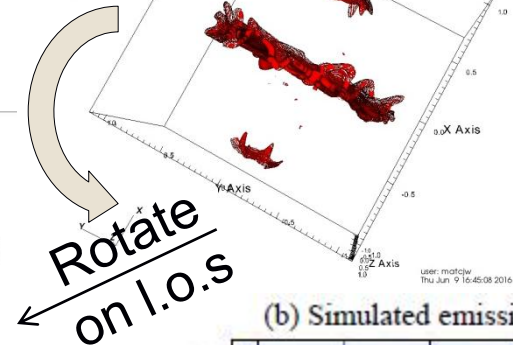
- New simulation of a $60 M_{\odot}$ star in the same initial condition.
- Evolved for 2 Myrs as implied by proper motion.
- Slice plane at $y=0$.



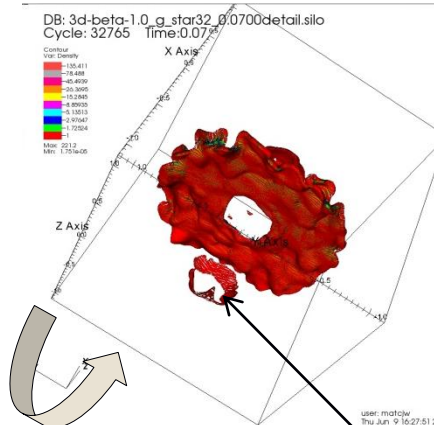
Density isosurface

Rotate
on sky

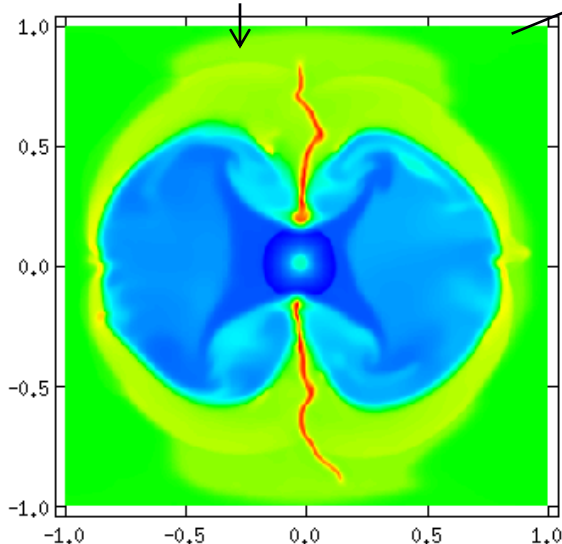
DB: 3d-beta-1.0_g_star32_00700detail.silo
Cycle: 32765 Time: 0.07



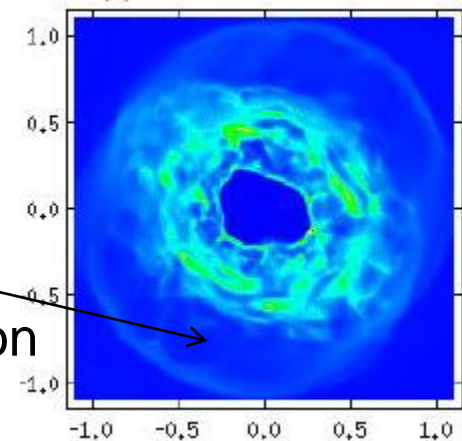
Rotate
on I.O.S



Triggered
star formation



(b) Simulated emission



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

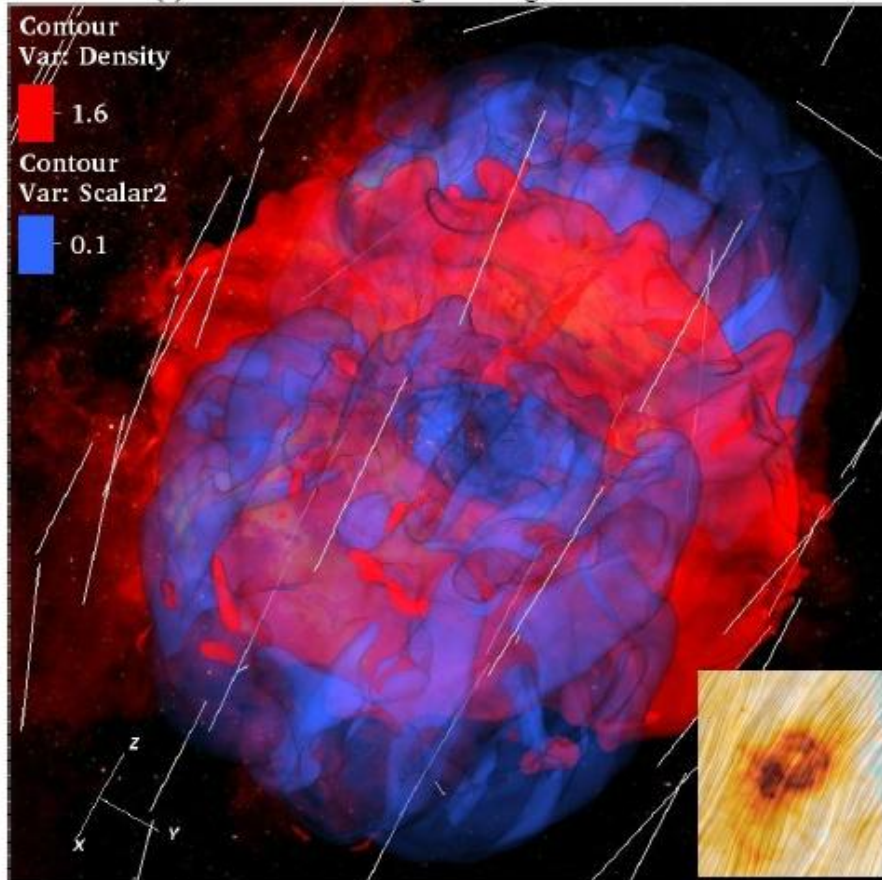
Further refinements...

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.

But...

- Low mass cloud ($17,000 M_{\odot}$)
- Rosette estimates are $\sim 1.65 \times 10^5 M_{\odot}$ (from CO Measurements).

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

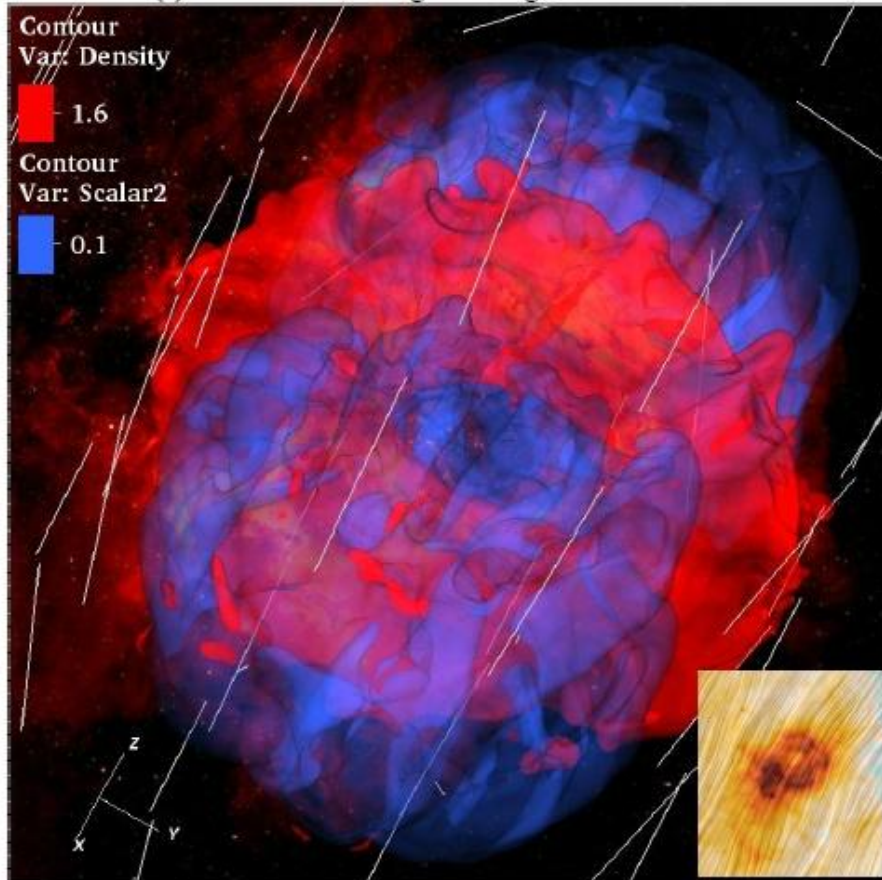
Further refinements...

THE ROSETTE NEBULA



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(a) Isosurface rendering with magnetic field vectors



- Refined simulations in a much larger cloud ($1.3 \times 10^5 M_{\odot}$) are now underway.
- Three tests: hydro ($\beta = \infty$), pressure equivalence ($\beta = 1$) & $\beta = 1$ double star.
- We consider isolated evolution. Could be shocked/compressed clouds?

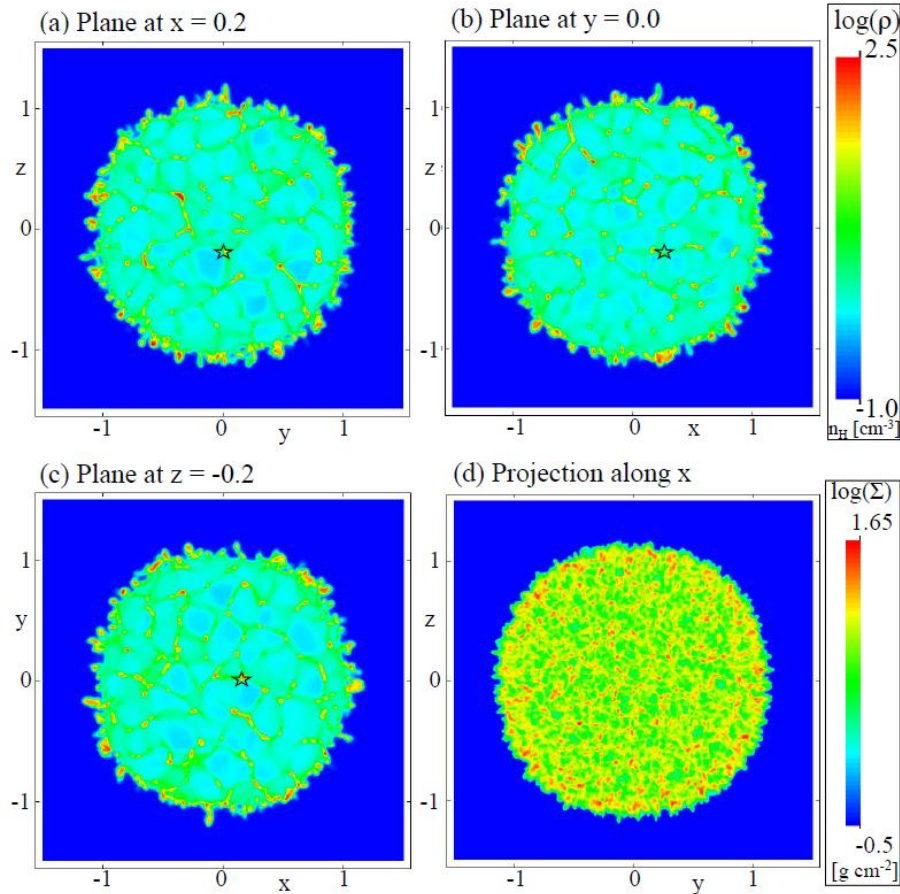
Initial conditions – 135,000 M_{\odot} cloud

REFINED SIMULATIONS OF THE ROSETTE NEBULA

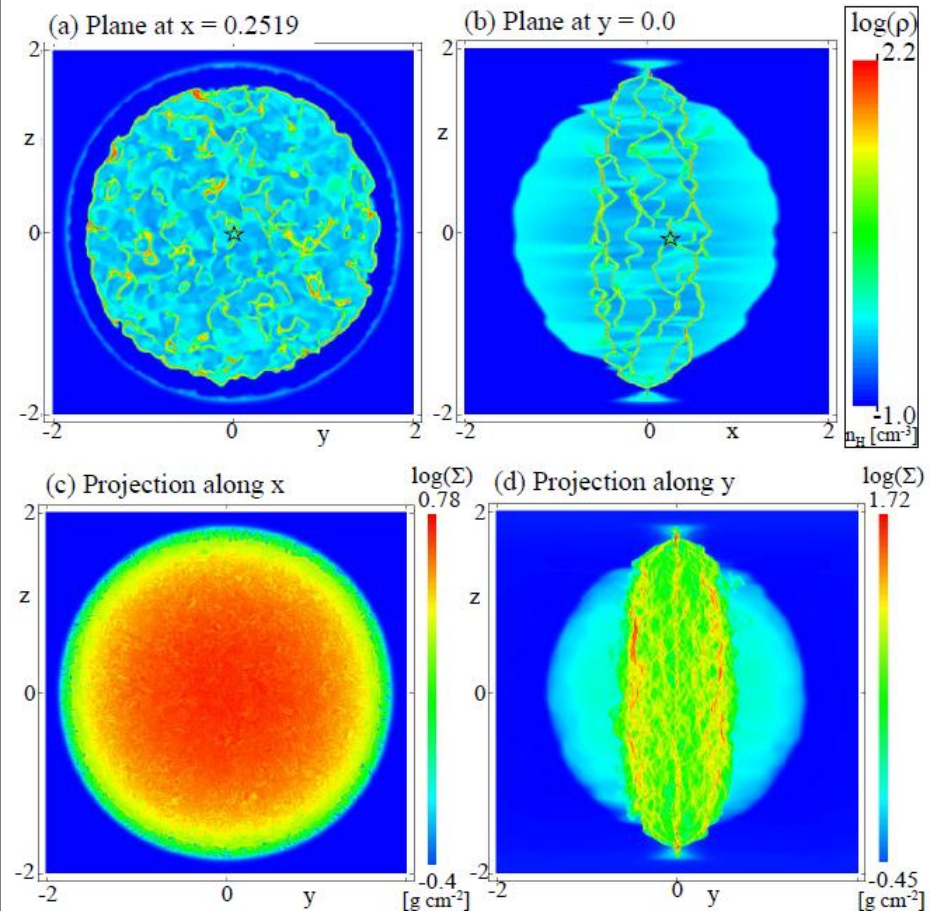


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Hydrodynamic case



Magnetic field case



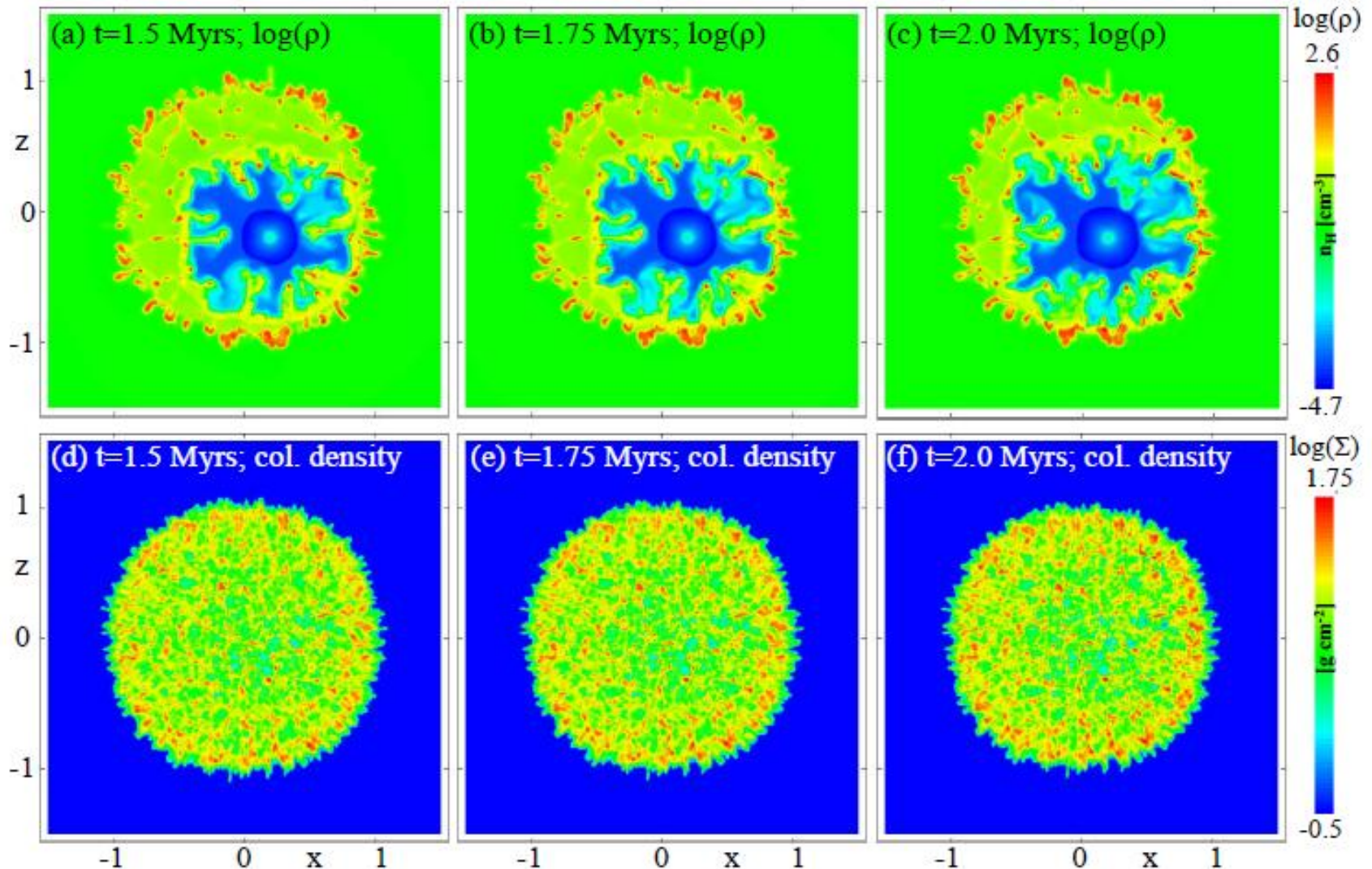
- In both cases, thermal instability drives the evolution on these large scales.

Results: Hydrodynamic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



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- Hydrodynamic case does not reproduce the Rosette nebula

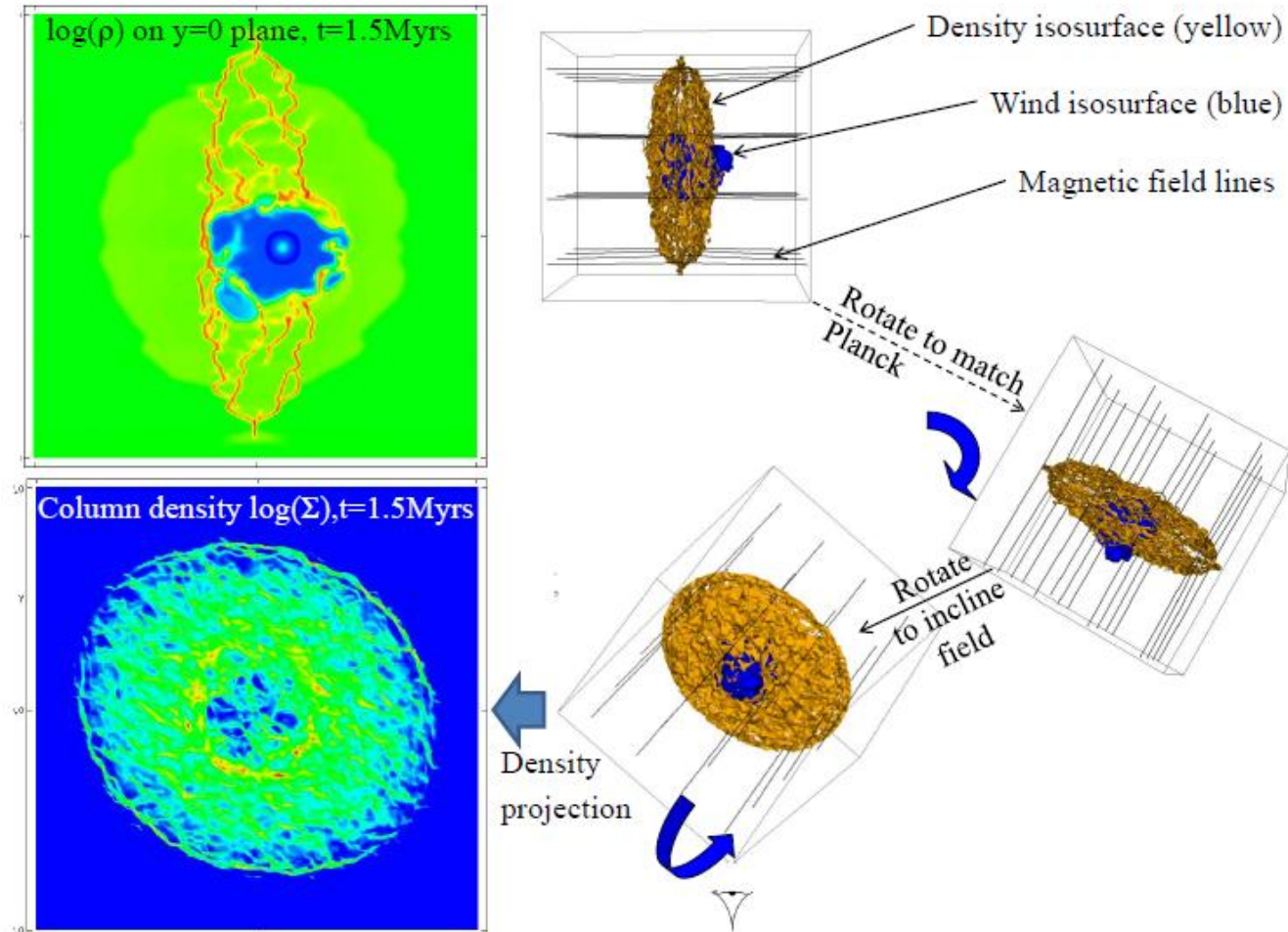
Results: Magnetic case

REFINED SIMULATIONS OF THE ROSETTE NEBULA



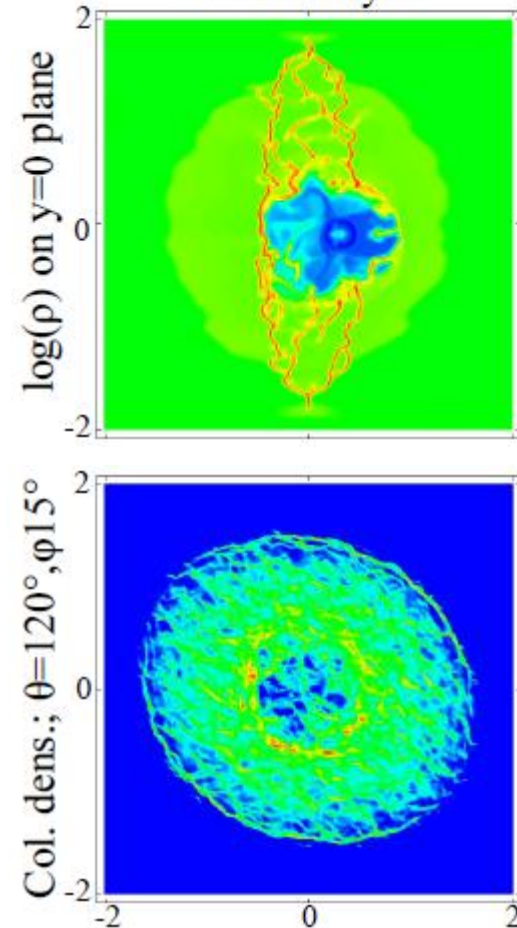
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Magnetic field case with a single star



Double star

$t = 1.5$ Myrs



- Model still works, even in a much higher mass cloud!

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.

Thank you for listening. Any comments or questions?

For information on generalised cloud-wind-SNe interaction, please see our other papers:-

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, DOI:10.1093/mnras/stx1417

Rosette special case: Wareing, Pittard & Falle, 2017, MNRAS in prep.