School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

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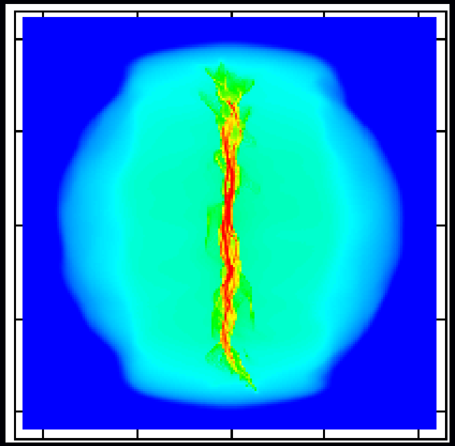
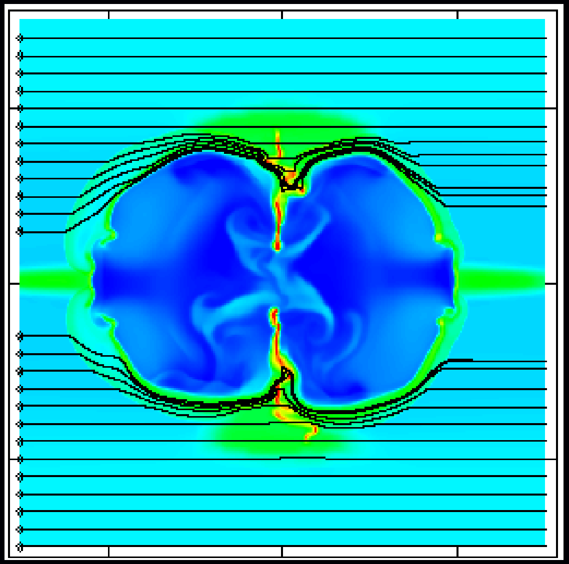
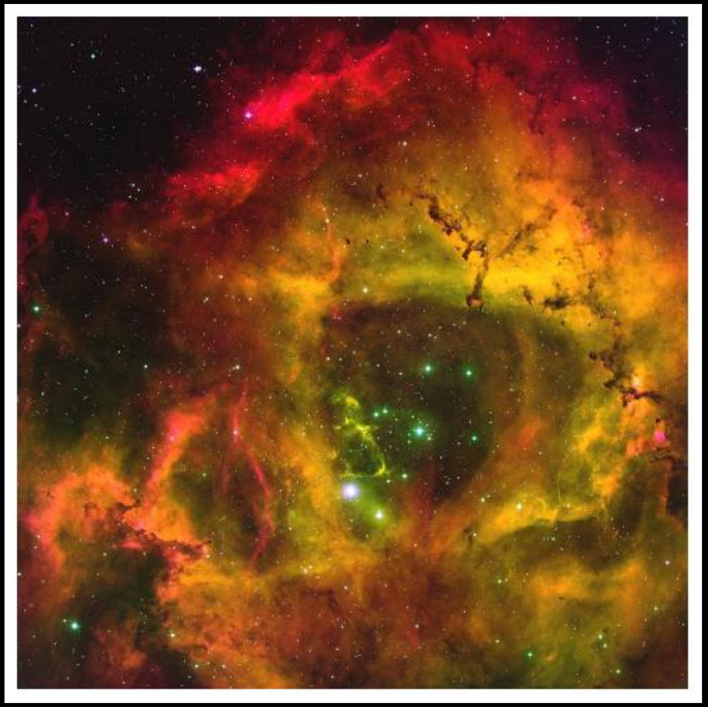
A new massive star feedback model for the Rosette Nebula and its implications for the ISM







Chris Wareing,

Julian Pittard, Sam Falle; Nick Wright (Keele)

EWASS2017 S05; High mass stars, their feedback and massive star clusters

Celebrating Guillermo Tenorio-Tagle’s life-long contribution to Astrophysics

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.
- Prime candidate for triggered star formation.
- RMC shows triggered star formation at the junction of filaments.

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

- D~1.6kpc +/- 250pc
- Central cavity r=6.2pc (Celnik 1985, at 1.4kpc), r~5pc (IPHAS, at 1.53kpc).

NGC 2244
THE ROSETTE NEBULA

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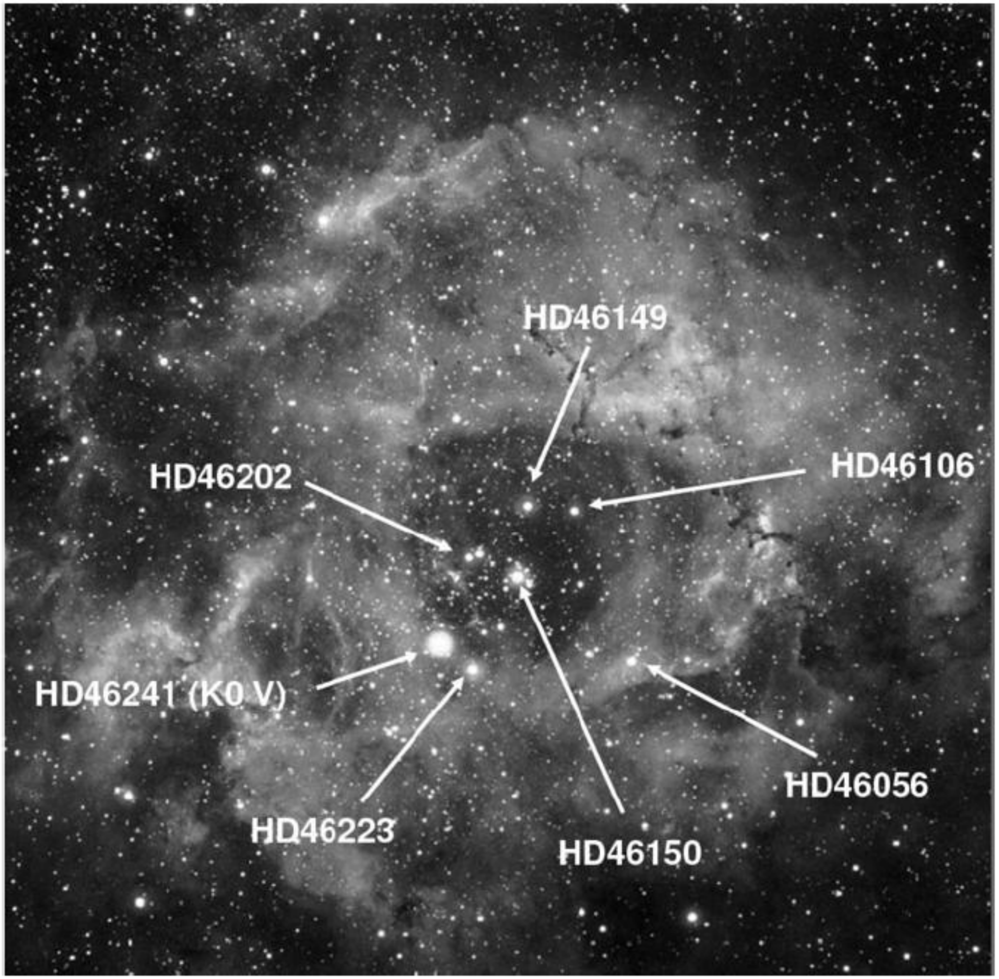
- Central star cluster has 5 O-stars and 1 B-star.
- HD46150 O5 V(f) and HD46223 O4 V(f) have inferred mass-loss rates two orders of magnitude greater than the rest.
- HD46223 (~55 $M_\odot$) is at the edge of central cavity.
- The Rosette Nebula *could* be dominated by a single ~40-50 $M_\odot$ star : HD46150.
- Proper motion analysis in the literature indicates HD46223 may not be part of NGC2244.



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

Dynamical age and missing wind issues

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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.

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

Our physical molecular cloud model

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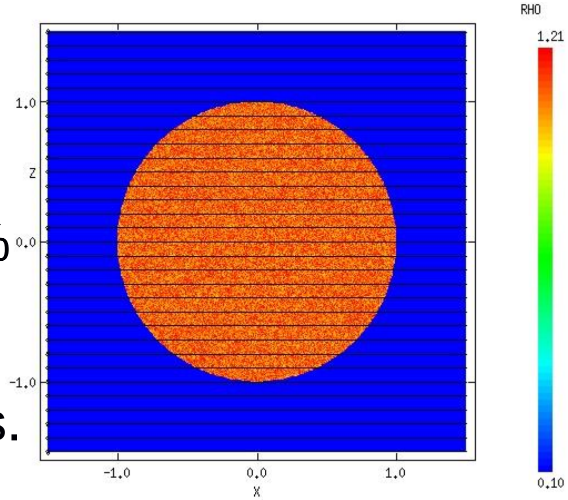
- We wish to start from the simplest set of self-consistent physics for the formation of a molecular cloud and examine what's possible from there. Specifically **3D MHD, self-gravity and multi-phase ISM** (i,e. realistic heating and cooling).
- We used a magnetohydrodynamic version of MG with self-gravity - a parallelised upwind, conservative shock-capturing scheme, with adaptive mesh refinement.
- Three field strengths were considered, all with: $\underline{B} = B_o \hat{\underline{I}}_x$

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

  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 cm^{-3} +/- 10%
- For $\beta = 1$, B_0 = 1.15 μG. For $\beta = 0.1$, B_0 = 3.63 μG
- Pressure equilibrium with low-density surroundings.



Results

INITIAL CONDITION FOR FEEDBACK

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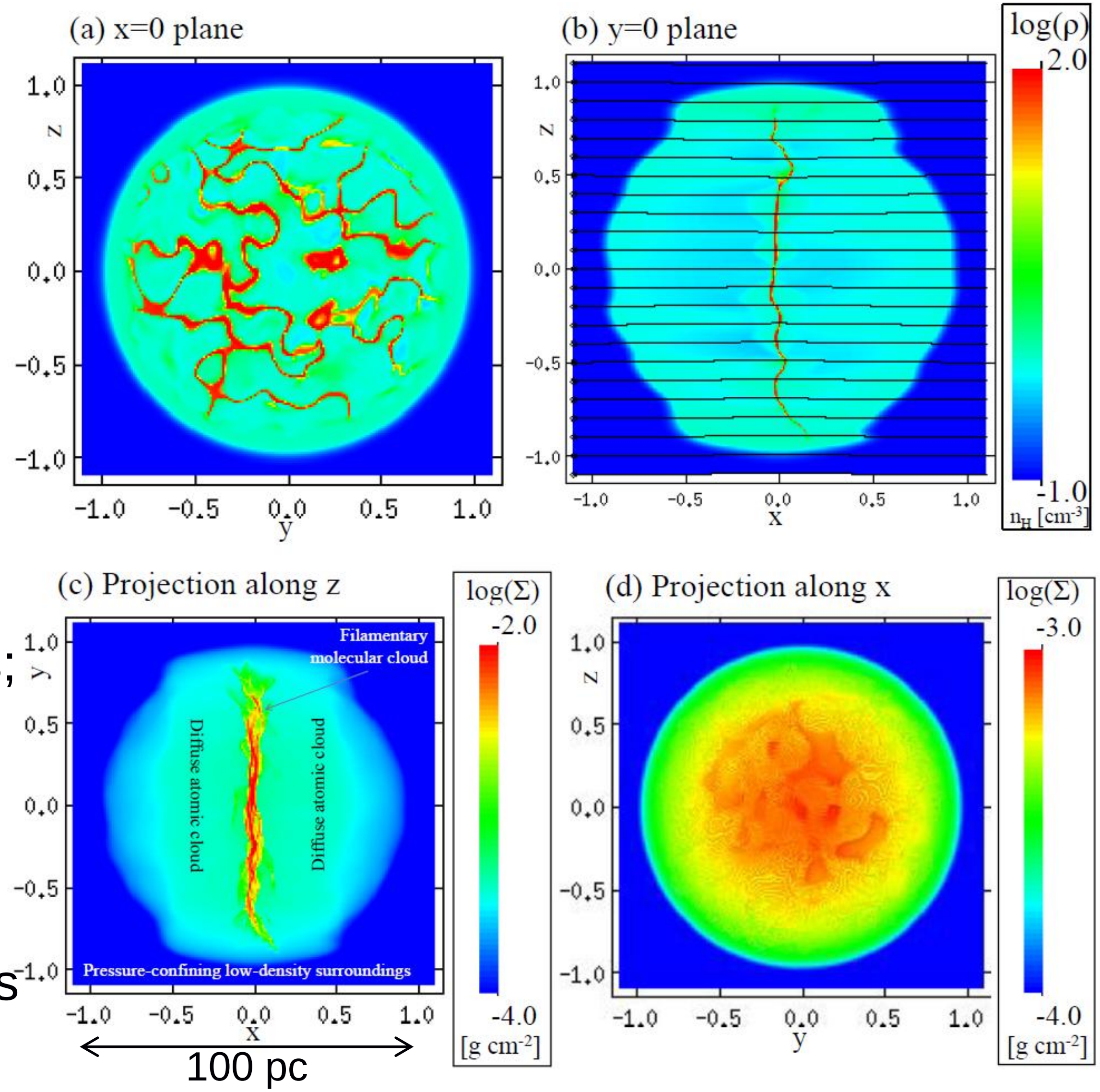
- A 100 pc-diameter 'corrugated' sheet;
- Filamentary in projection;
- 17,000 $M_{\odot}$;
- Density >100 cm^{-3} after 32.9 Myrs of evolution;
- Assume free-fall time of 5.89 Myrs to forms stars;
- Inject stars at t=38.8Myrs;
- Position of central star (-0.025, 0.0, 0.0125);
- Cloud age ~10Myrs;
- Such sheet-like structures are common.



$40M_{\odot}$ star: wind phase

ADDING FEEDBACK

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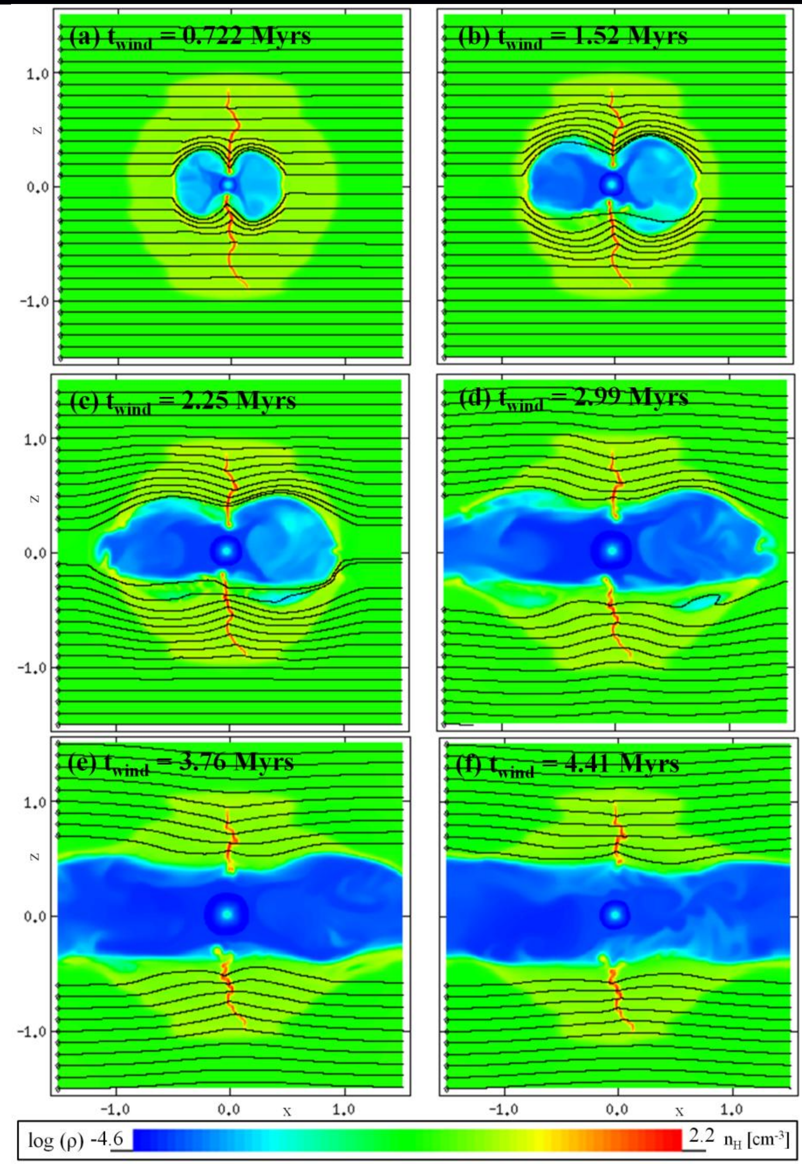
- $40\ M_{\odot}$ star, following non-rotating Geneva 2012 track.
- **For this star, there's a significant impact on the molecular cloud.**
- Large bipolar cavity evolves into a cylindrical cavity (D~40pc) through the centre of the cloud.
- Cavity filled with hot, tenuous wind material moving at up to 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 $27.2\ M_{\odot}$, total energy injected of 2.5×10^{50} erg



A new model...

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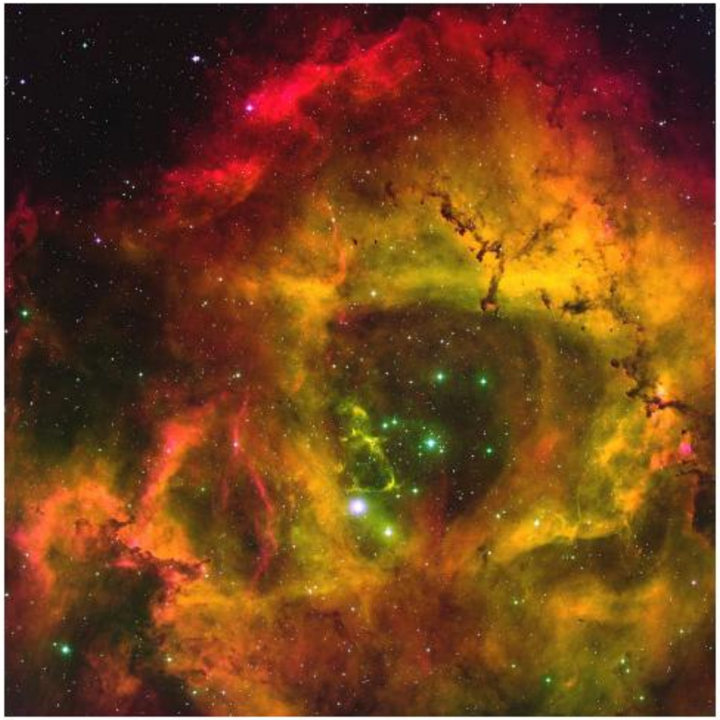
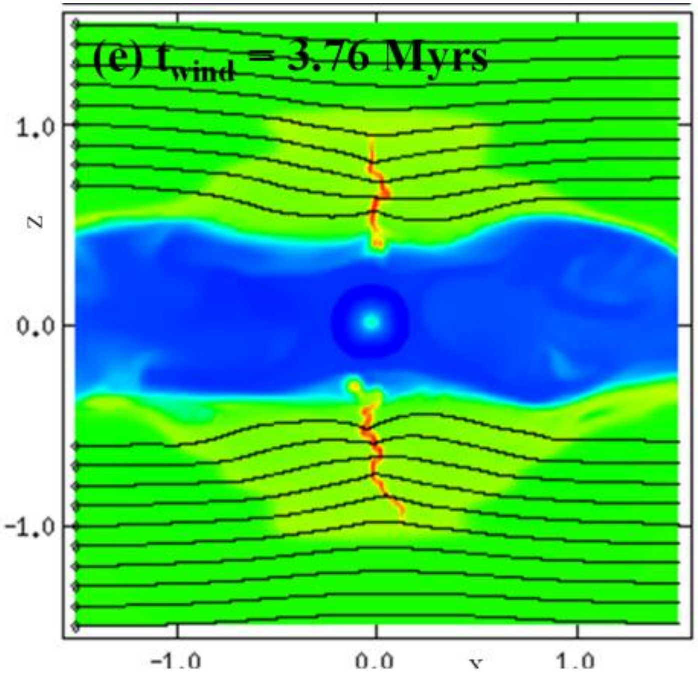
- What if this...



...was formed like this.

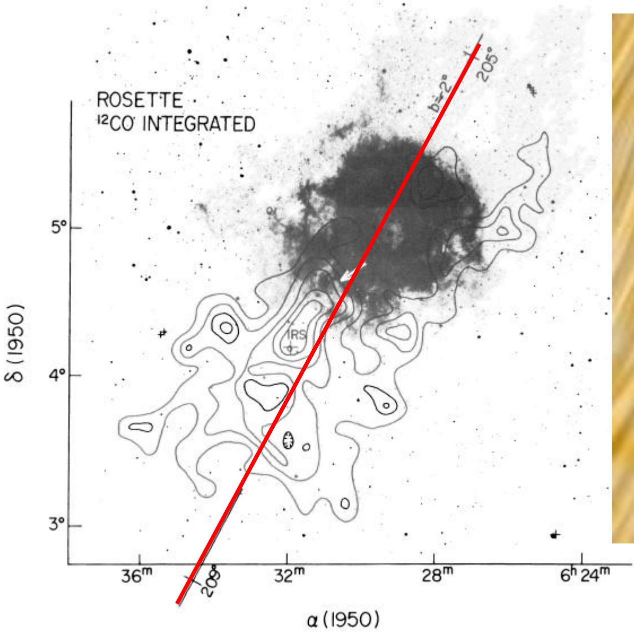


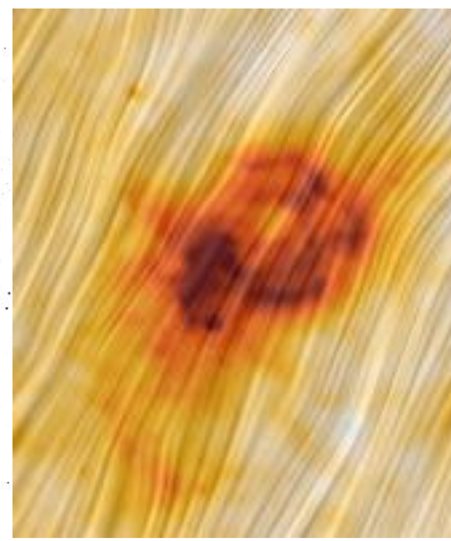
- Our simulations have shown it’s possible to clear a central cavity from a parent molecular cloud.
- **Instantly solve the dynamical age problem!**
- Not an entirely a new idea for the Rosette. (see Meaburn & Walsh 1981 Ap&SS **74** 169)

Background magnetic field

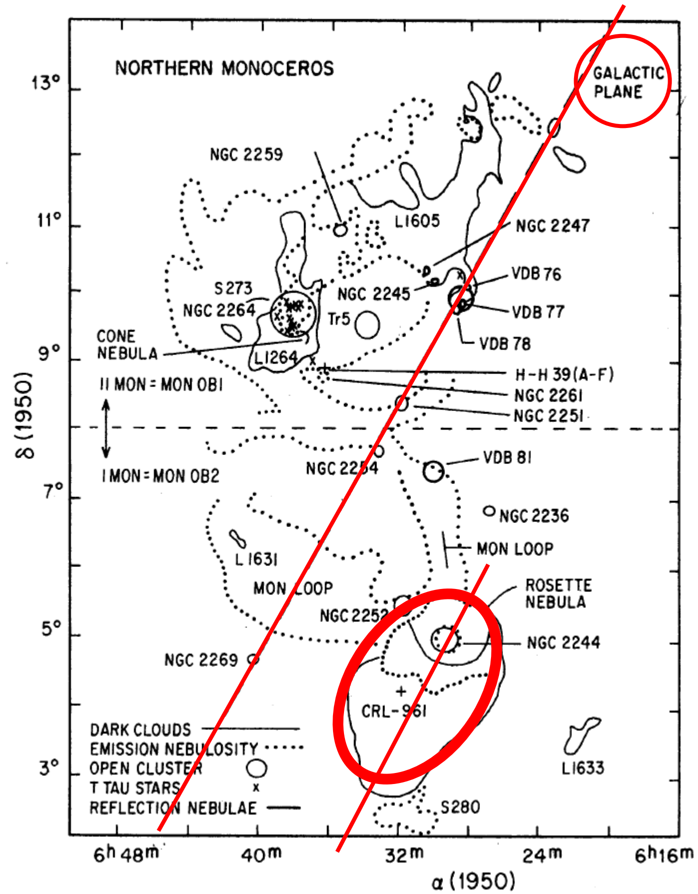
THE ROSETTE NEBULA

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





(Credit: ESA and the Planck Collaboration)



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

New proper motion analysis

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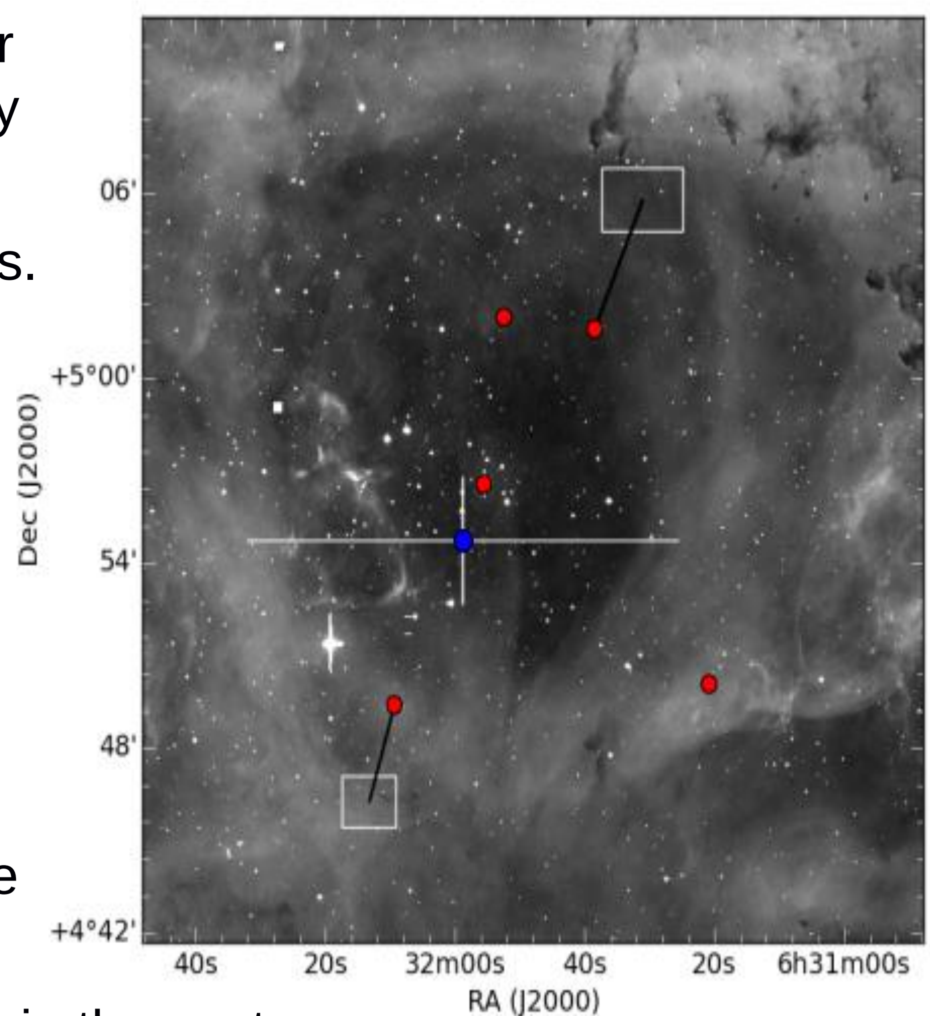
- Our models imply only a single star is required, but does HD46223 play a role? Is it associated?
- New GAIA Data Release 1 analysis.
- Red points: Hipparcos and Tycho members of NGC2244.
- Two runaways detected – HD 46149 and **HD 46223!**
- Black lines show proper motion vectors.
- Best fitting back-traced 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

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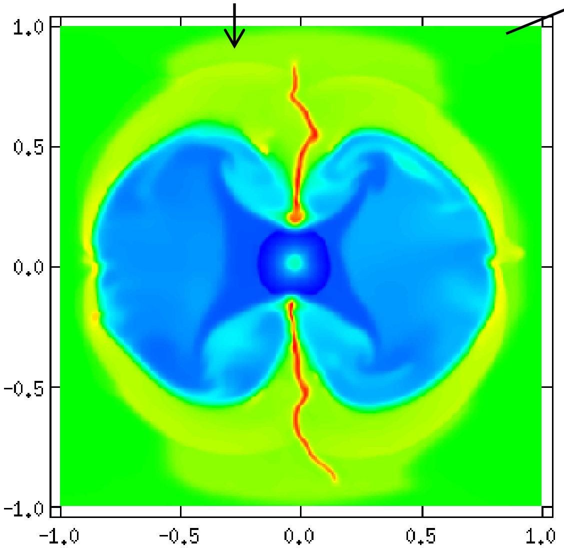
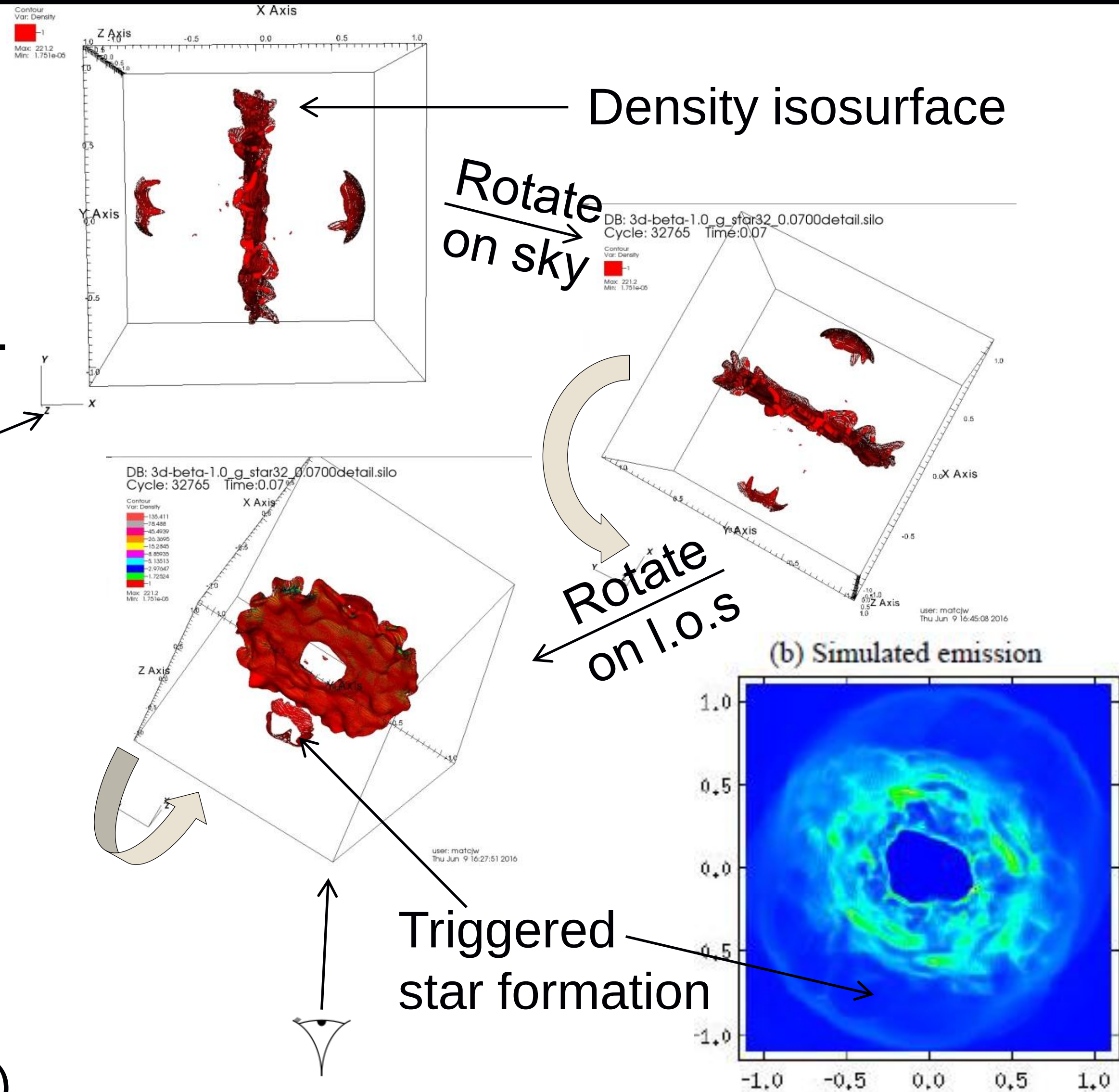
- New simulation of a $60\ M_{\odot}$ star in the same initial condition.
- Evolved for 2 Myrs as implied by proper motion.
- Slice plane at y=0.



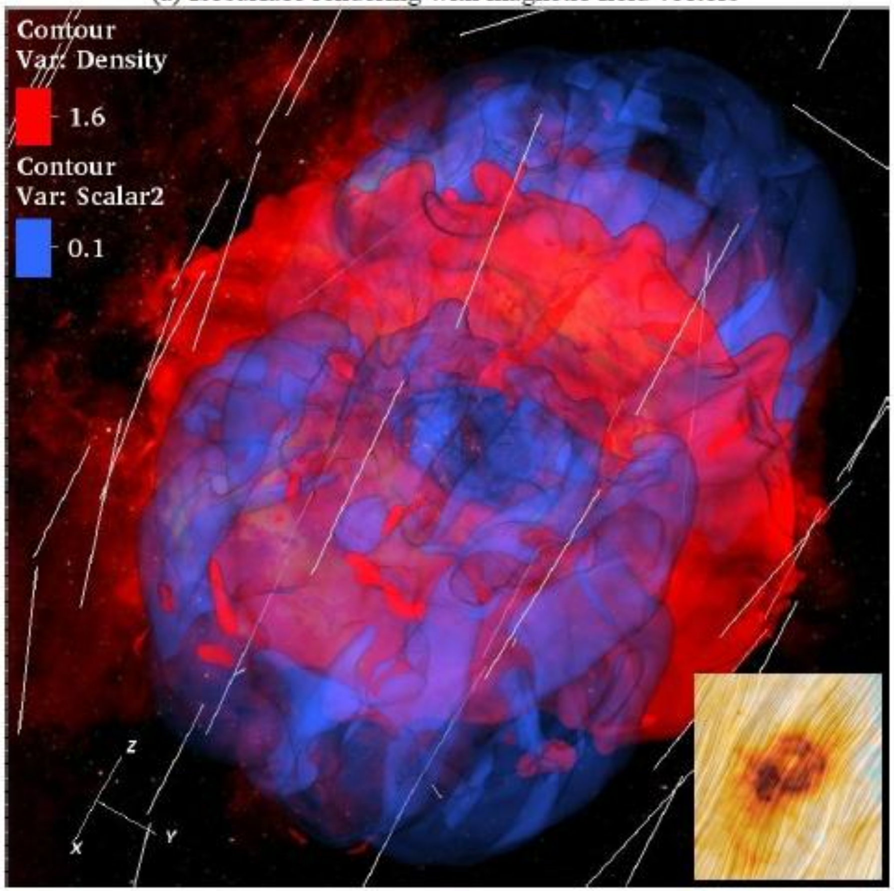
- Central hole: D=18-20pc (c.f. 13pc for the Rosette).



Further refinements...

THE ROSETTE NEBULA

(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 ~1.65e5 $M_{\odot}$ (from CO Measurements)

Further refinements...

THE ROSETTE NEBULA

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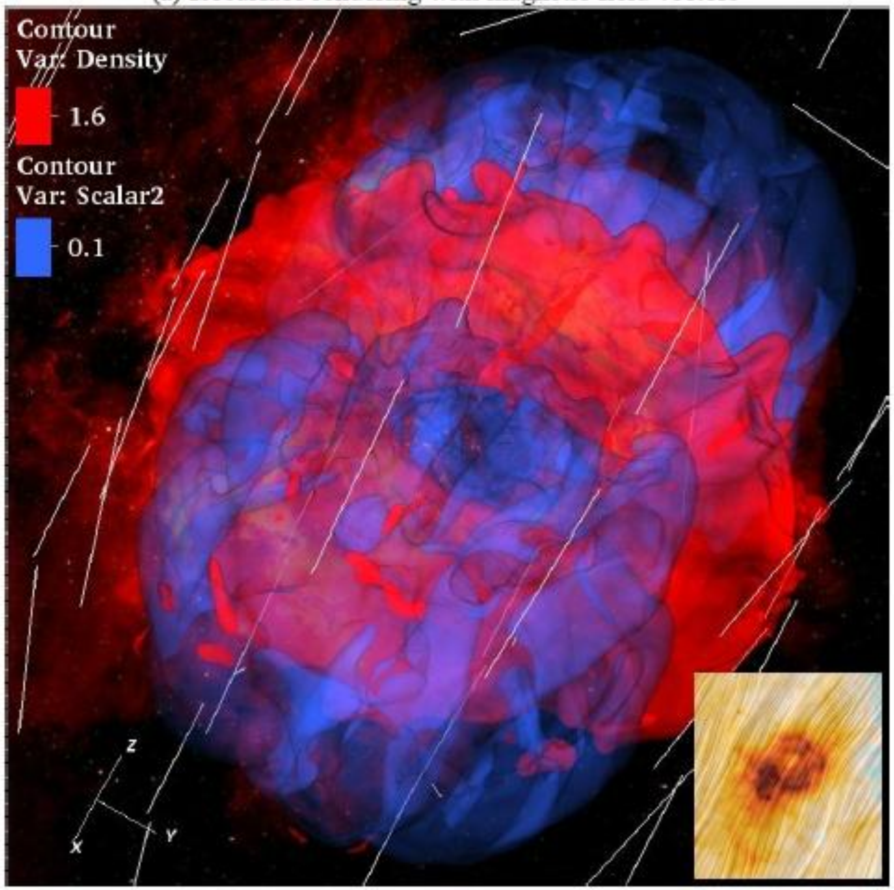
(a) Isosurface rendering with magnetic field vectors



- Refined simulations in a much larger cloud (1.3e5 $M_{\odot}$) 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?

Progress so far

REFINED SIMULATIONS OF THE ROSETTE NEBULA

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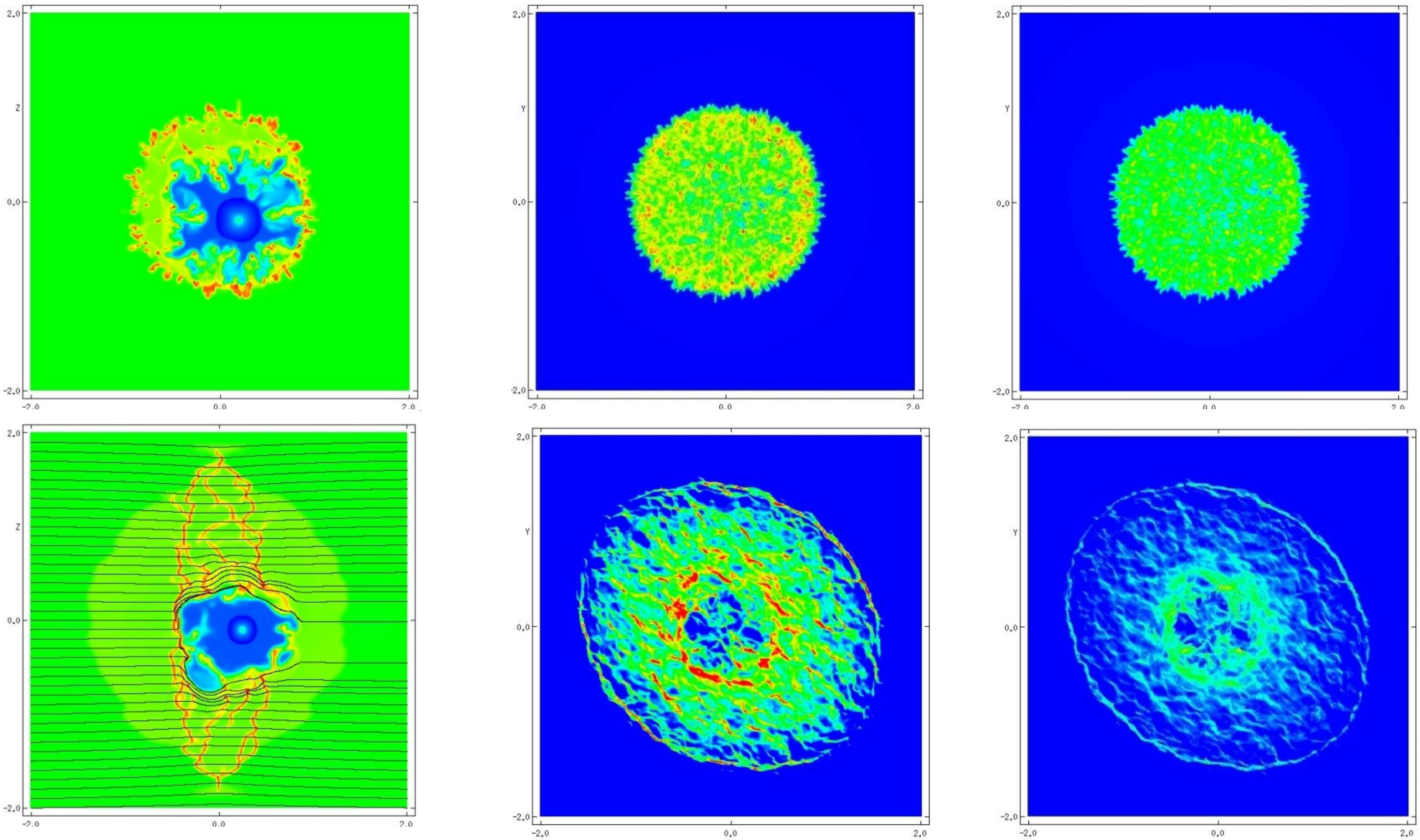
Density on plane y=0 | Column density | Naive emission

Test 1: No magnetic field

Test 2: Single star, B field



- Magnetic field is required (subject to initial position of star).
- The effect of HD46223 may also be required.

Test 3 underway...

Implications for the ISM from our work

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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.