Lost into Space

The Fate of our Sun

or ‘Revealing the mass-loss history of a star’

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11th July 2012 – Leeds AstroSoc

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Overview

- Where's our Sun going in life?

- Modelling evolved stars:-
  - planetary nebula and their progenitors
  - mira stars
  - neutron stars

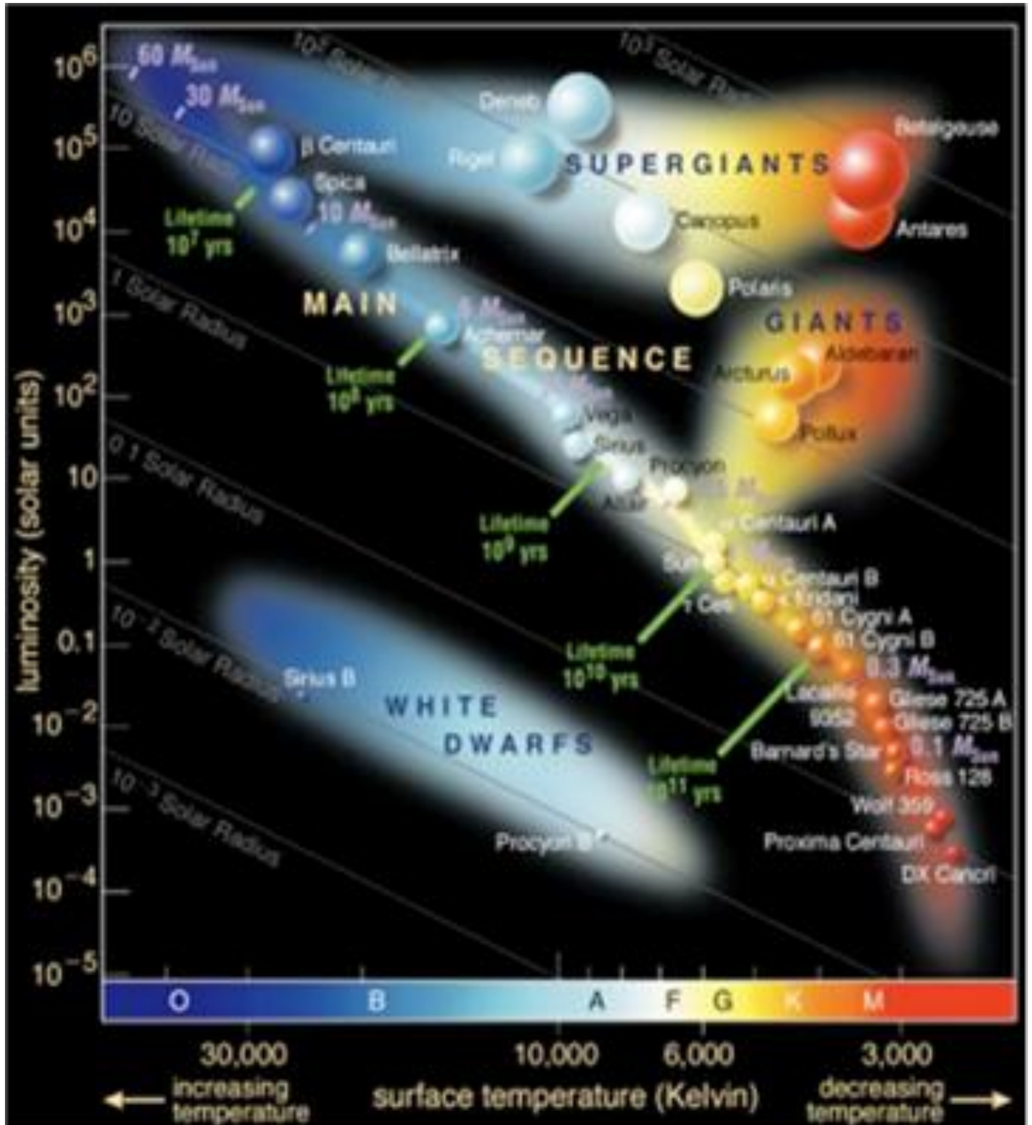
Motivations

- What's my motivation?

- Towards understanding the evolution of our Sun…
  - will our Sun explode in a giant fireball?
  - or will it fizzle out and fade into obscurity?
  - or is it something in between?
  - what will happen to the Earth?

- Stellar mass-loss is the motor that makes stars and galaxies change over time.
  - If only we could see how it changed over time!
  - Could we disentangle the effects of the surrounding interstellar space and reveal the mass-loss history of a star for the first time!

Where are we now…



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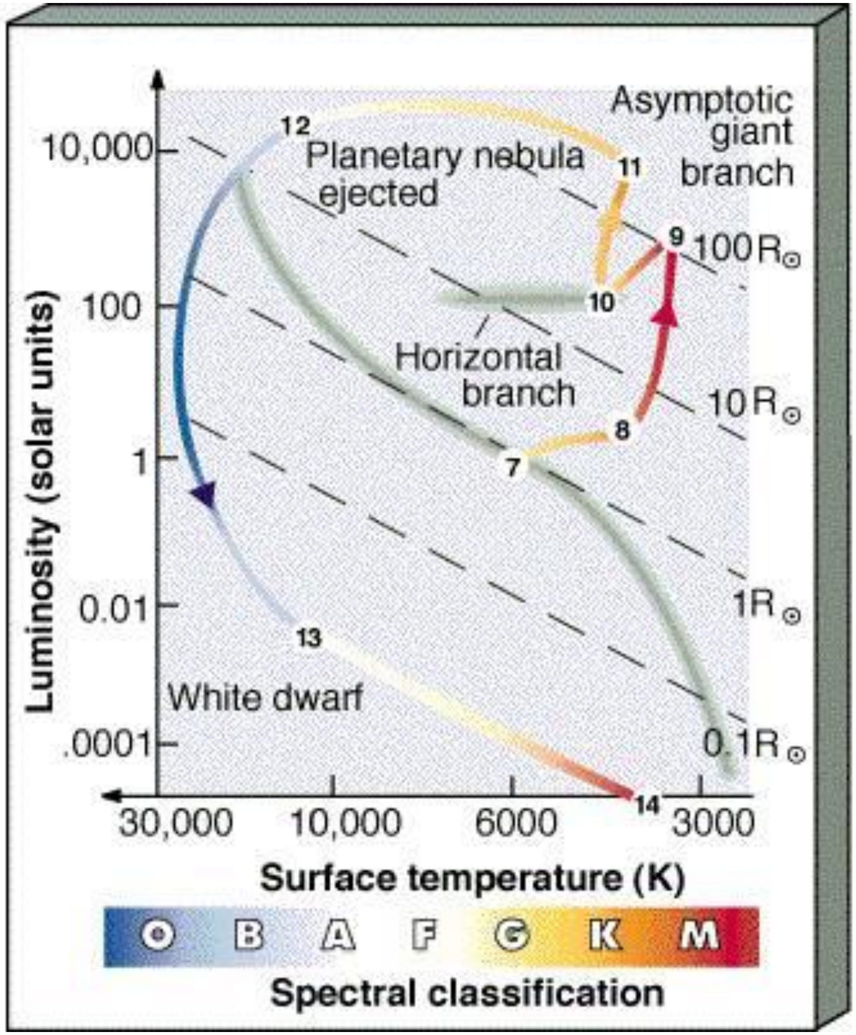
…and where are we going?



To answer these questions, astronomers must study planetary nebulae

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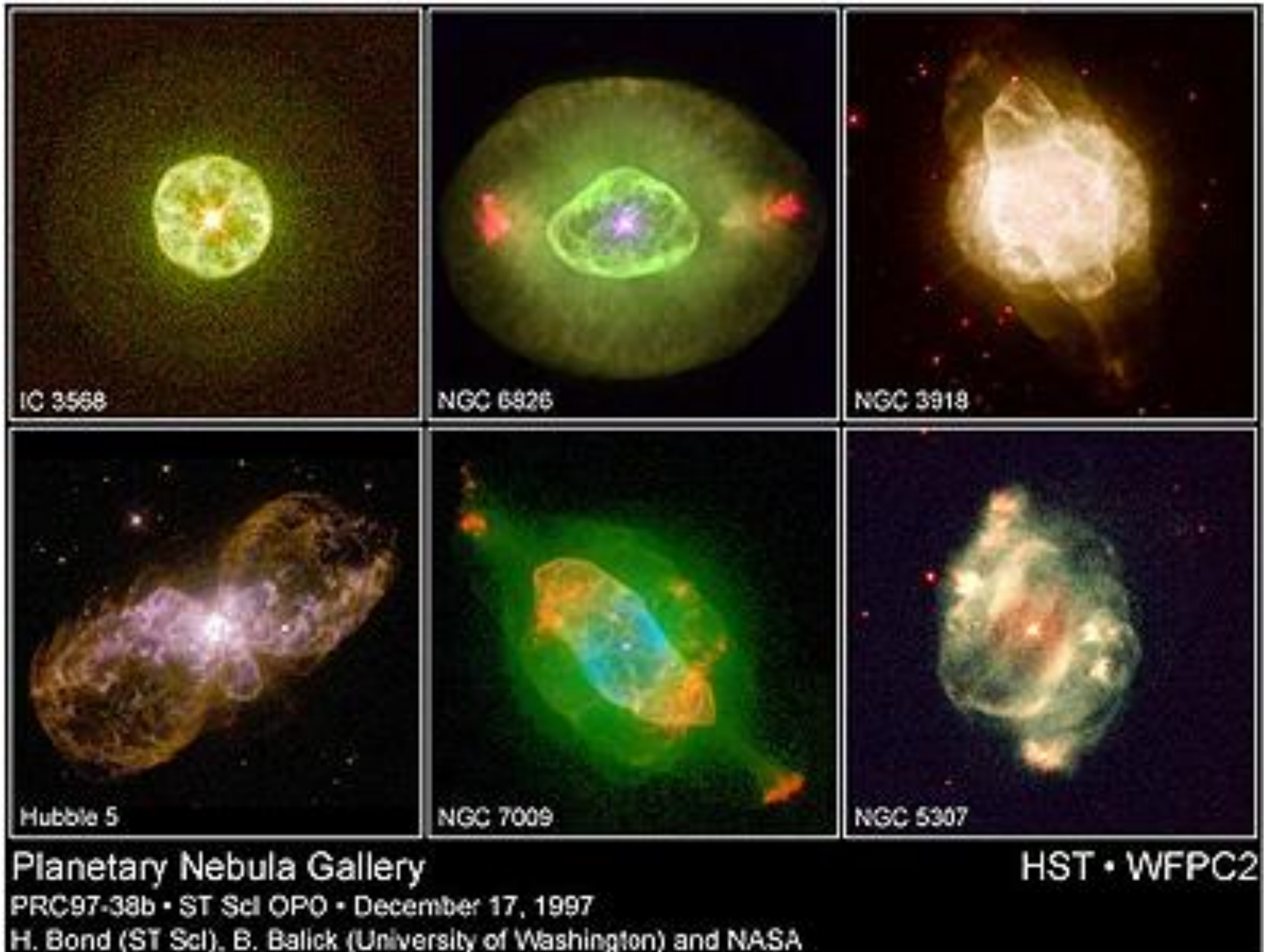
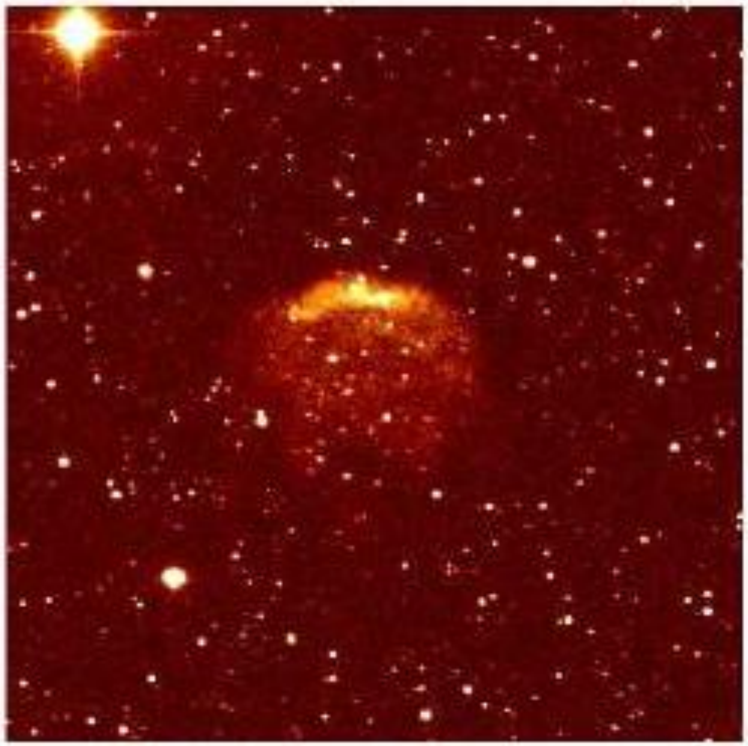
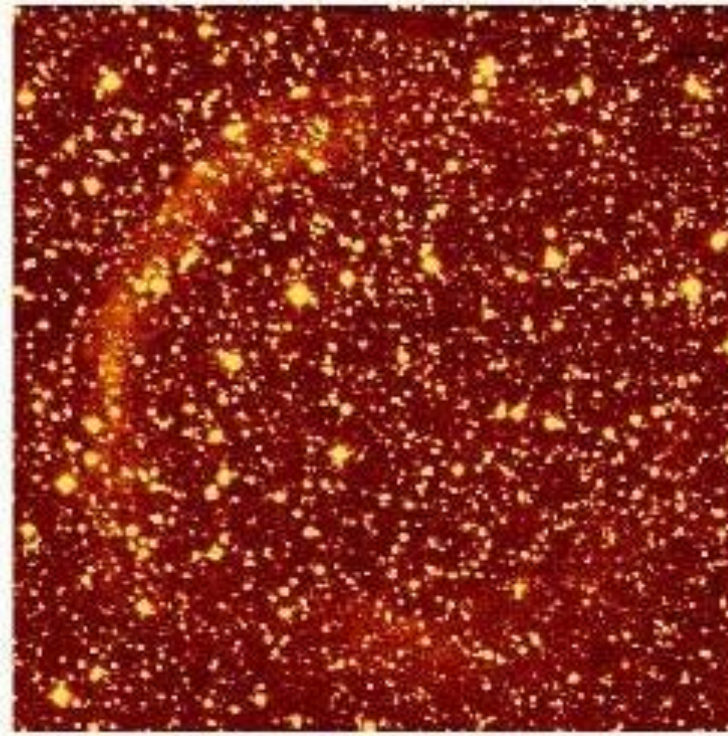
Some of the beautiful images…



PNe from the recent IPHAS survey

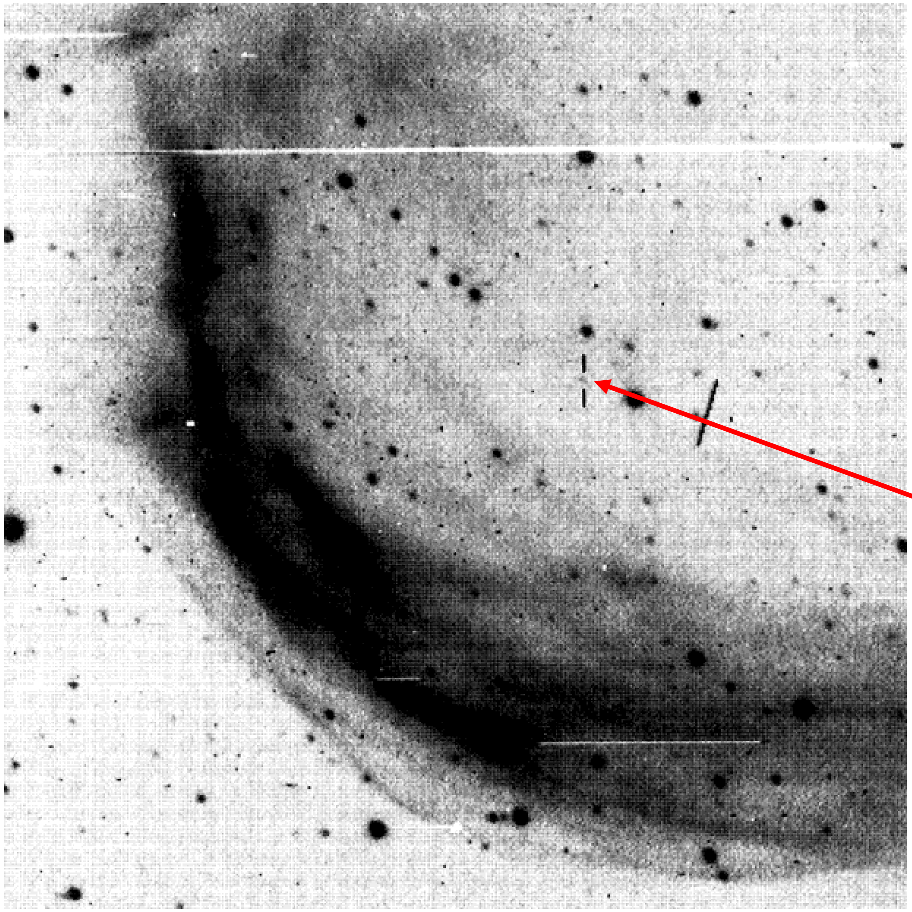




Some PNe show only interactions at their extreme edges.

What are they interacting with?
Where has this material come from?
Might this material contain details of mass-loss history?

Example: the PN Sh 2-188



Filamentary one-sided nebula.

3600s Hα exposure. Image is 5.7' on a side.

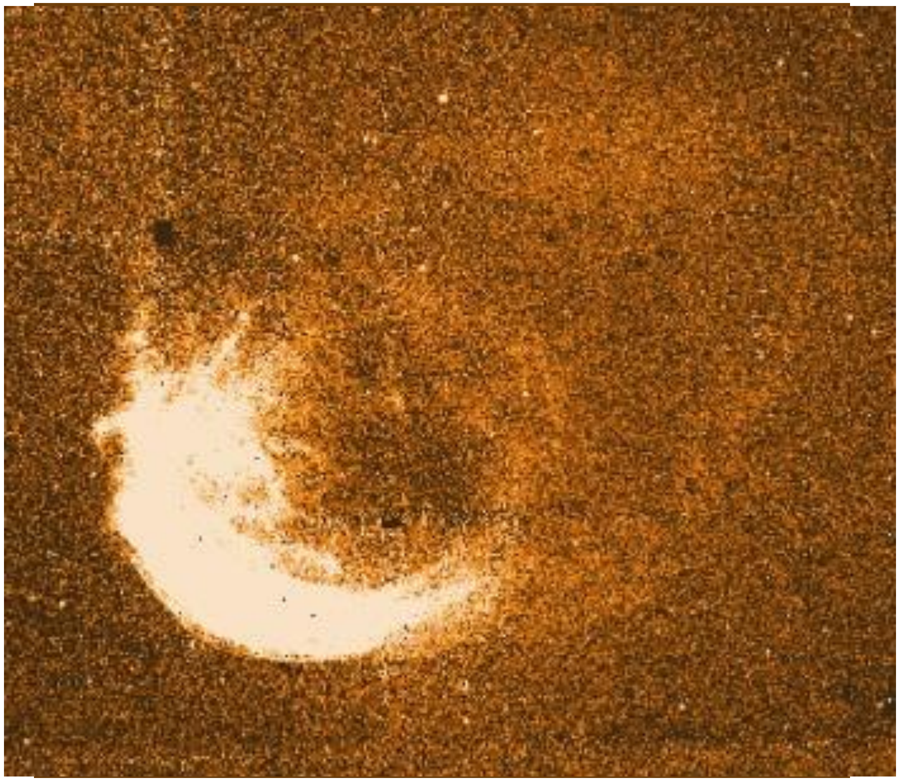
Central star candidate.

Kwitter, Jacoby and Lydon, AJ, (1988), 96, 997.

Sh 2-188: vital statistics

- Flat (thermal) radio spectrum precludes supernova origins.
- Galactic Plane PN.
- Interaction with ISM suggests highly evolved object.
- One-sided appearance has been attributed to an highly inhomogeneous ISM.
- Filamentary structure is particularly unusual.
- Distance unclear:
  - D = 600pc, d = 1.75pc, age = 12,100yr
  - D = 965pc, d = 2.8pc, age = 22,000yr

Sh 2-188: IPHAS observation



Hα mosaic image from INT Photometric Hα survey of the Northern Galactic Plane (IPHAS).

Drew et al. MNRAS 362 753

Note the filamentary structure, the closed ring and the long tail.

Sh 2-188: IPHAS observation

RGB merged image from IPHAS data.

Red/yellow: Hα
Green: i’
Blue: r’

Central star candidate marked

Image credit
N. Wright, UCL

Model

Developed a ‘triple-wind’ model (in the frame of reference of star):-

- slow, dense AGB stellar wind,
- fast, rarefied post-AGB stellar wind sweeping up AGB wind into a PN,
- third wind representing motion through the ISM.

500,000 years of AGB evolution, 30,000 of post-AGB evolution.

Wind ejection achieved in a spherical region at the position of the central star, radius 5 ¾ cells.

ISM ‘wind’ flows in at x=0 boundary. Remaining boundaries are free-flow.

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Hydrodynamic Scheme

- 3D 2nd order Godunov-type scheme, Riemann solver according to Falle (1991).
- Parallelisation using MPI.
- Efficient over large numbers of processors (standard methods, MPE).
- Radiative cooling down to 8000 K according to Raymond, Cox & Smith (1976).

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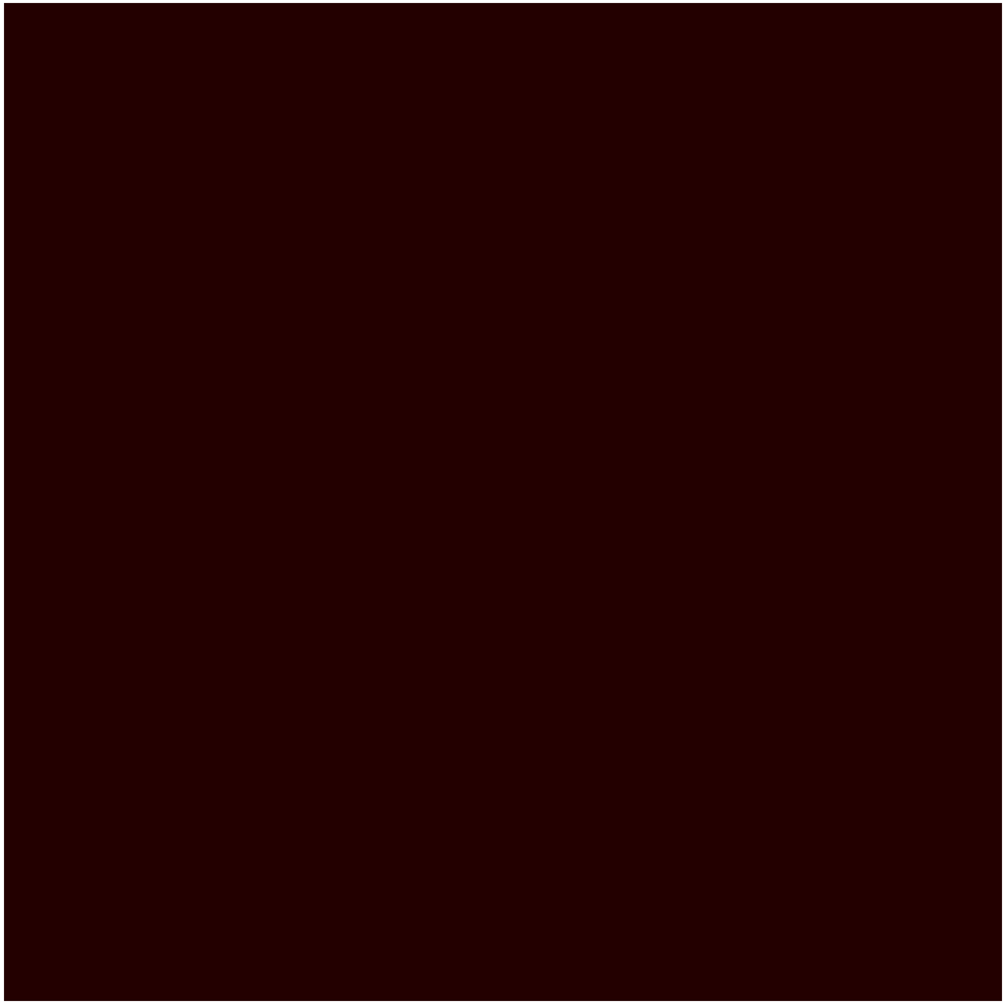
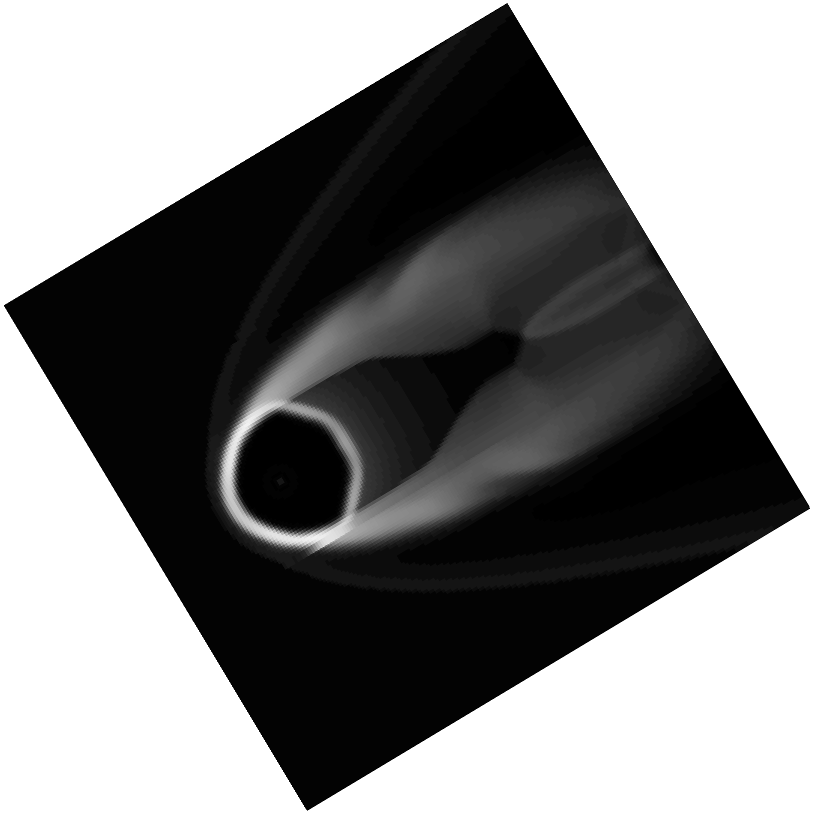
Hydrodynamic simulations



- space isn't empty, albeit very close.
- we simulate space as a very low density fluid
- the equations for the motion of fluids are well known (if still unsolved!)
- we use an approximation and a model like a boat passing through water; we move a star through the fluid

N.B. – there are 5 times more frames per unit time during the post-AGB phase

Sh 2-188: post-AGB evolution



Best fit of model implies a velocity of 125 kilometres per second!

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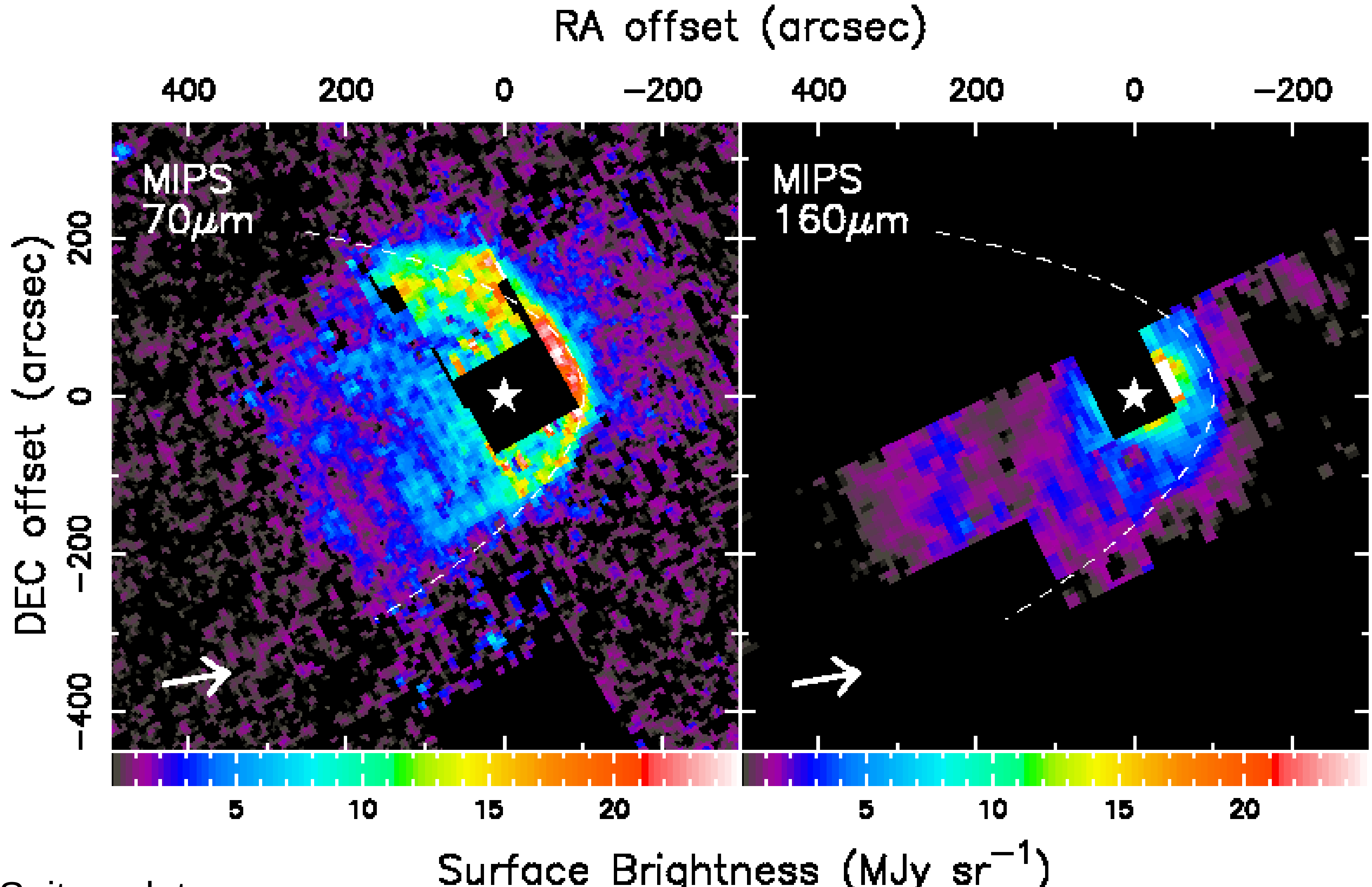
Prediction 1

There must exist bow shocks around the *progenitors* of planetary nebulae.

New observations of R Hydrae



Spitzer data

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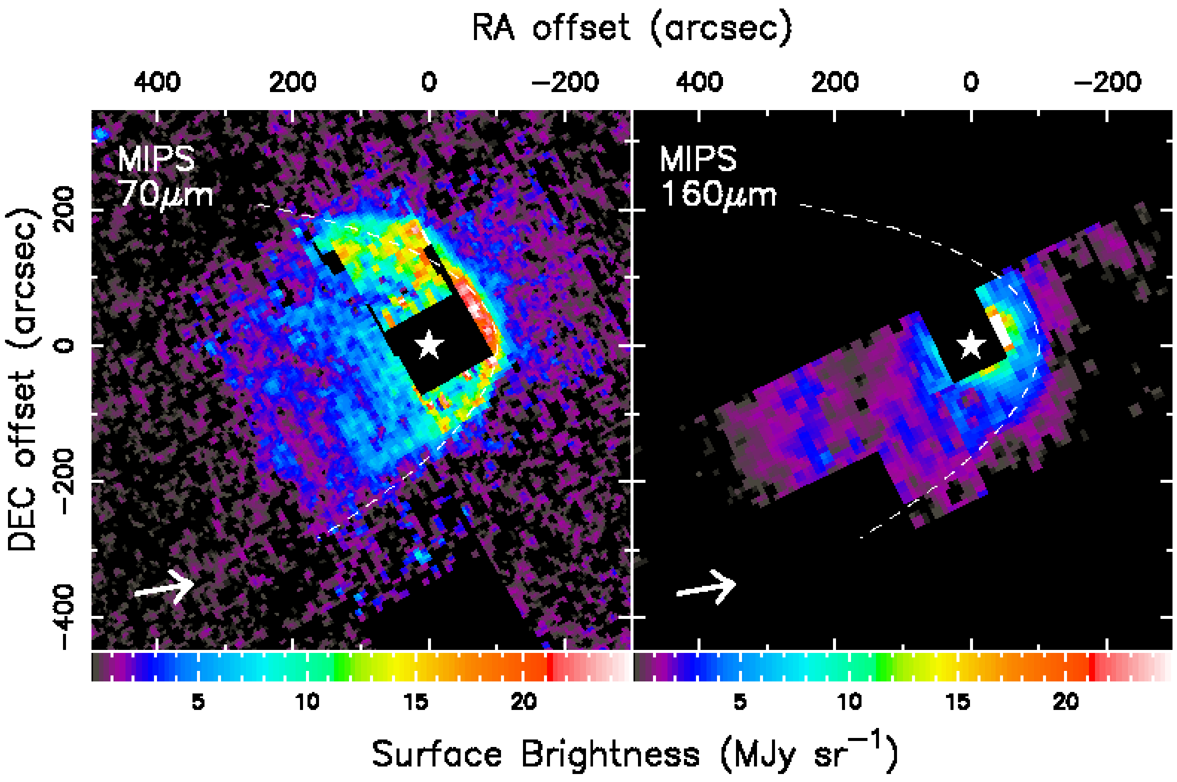
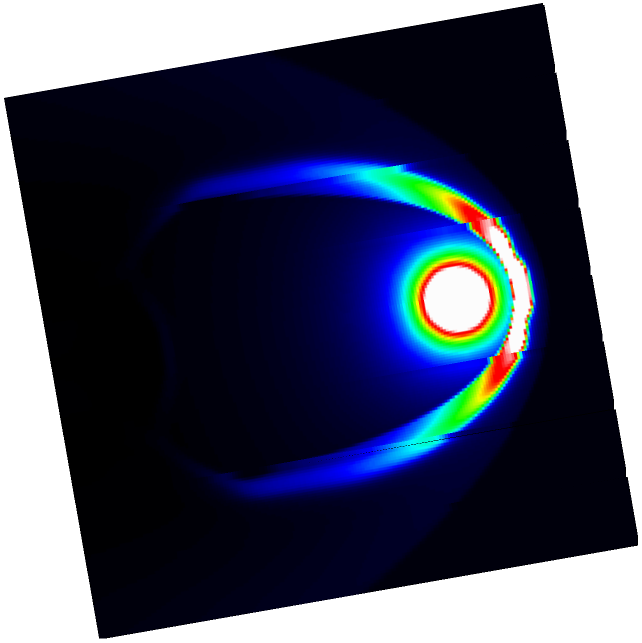
New observations of R Hydrae



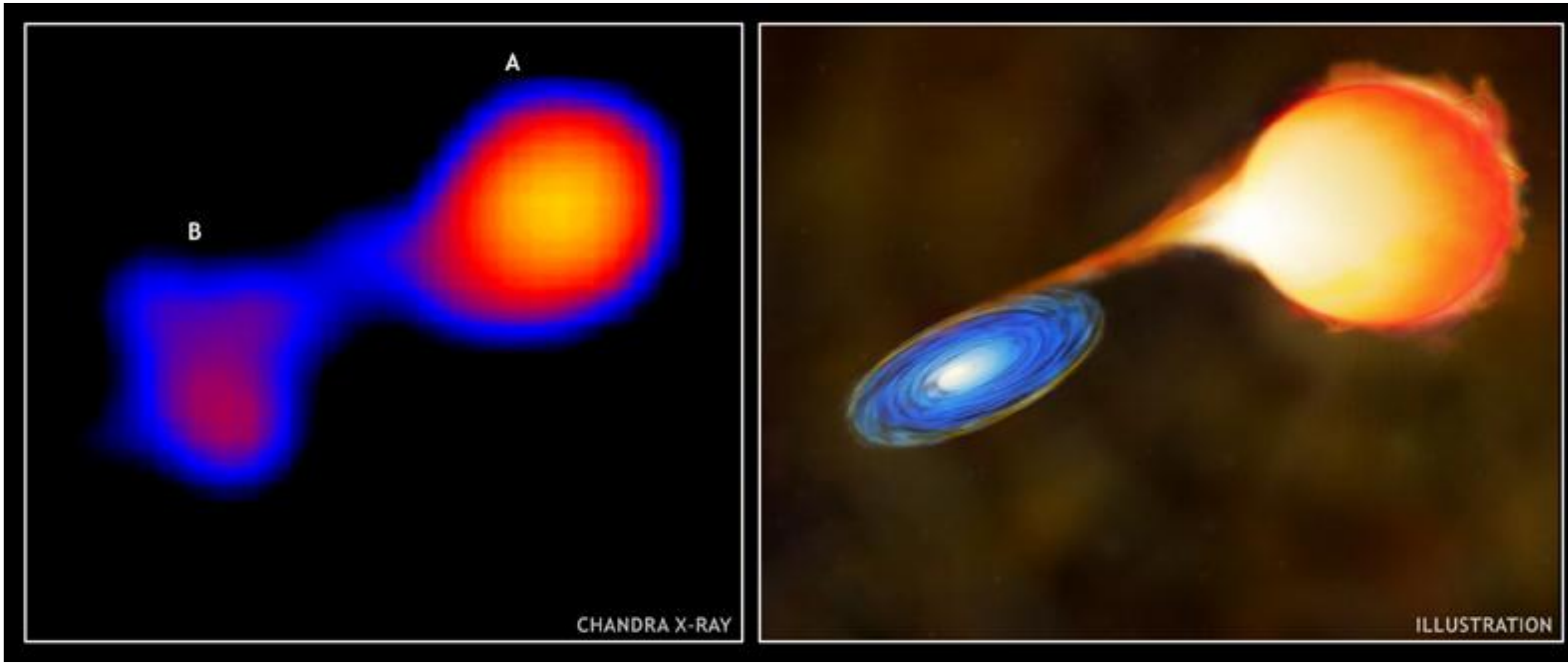


Motion of the star is in the right direction for the arc-like structure ahead of the star being a bow shock.

Prediction 2

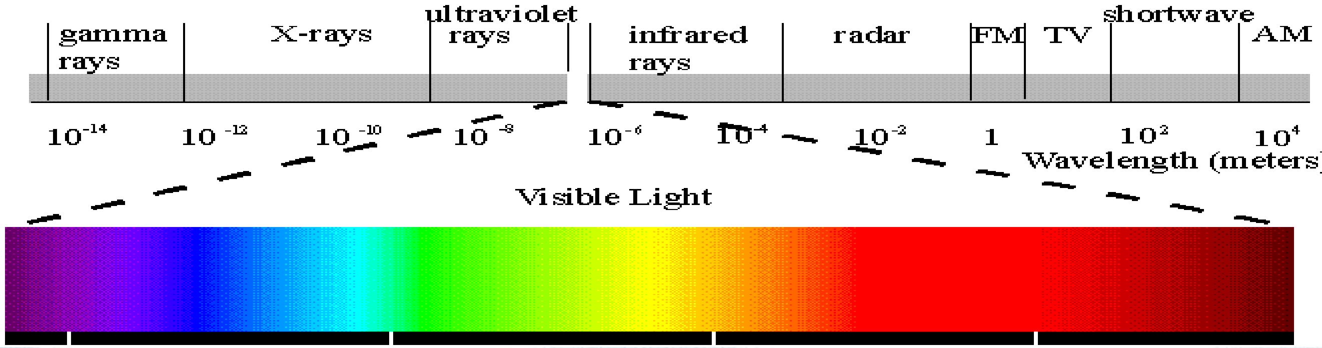
If bow shocks exists around the progenitors of planetary nebulae, *tails* of material must also exist.

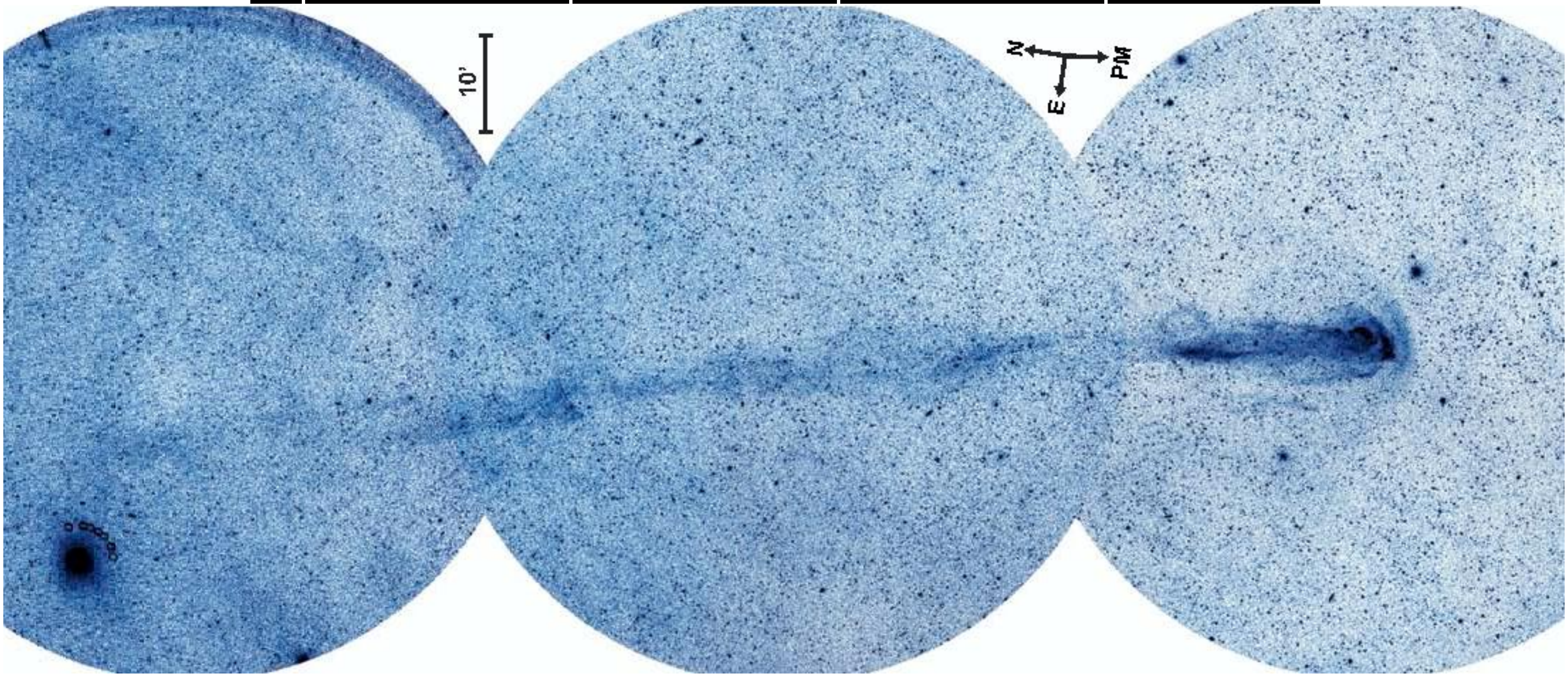
The binary star system Mira



- Mira A: planetary nebulae progenitor.
- Mira B: possibly a white dwarf.

Ultra-violet GALEX observation





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Ultra-violet vs. visible light

Ultra-violet

Visible light

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Mira

An animation of Mira's movement through the ISM
Credit: NASA/JPL-Caltech

The mass loss history of Mira

- Martin et al concluded:-

  - the structures are a bow shock and ram-pressure-stripped tail of material.

  - directionality is in agreement with the proper motion of the system.

  - spatial extent of the tail is 12 light years implying the tail represents 30,000 years of mass-loss history.

  - density variations along the tail are the result of mass-loss variations.

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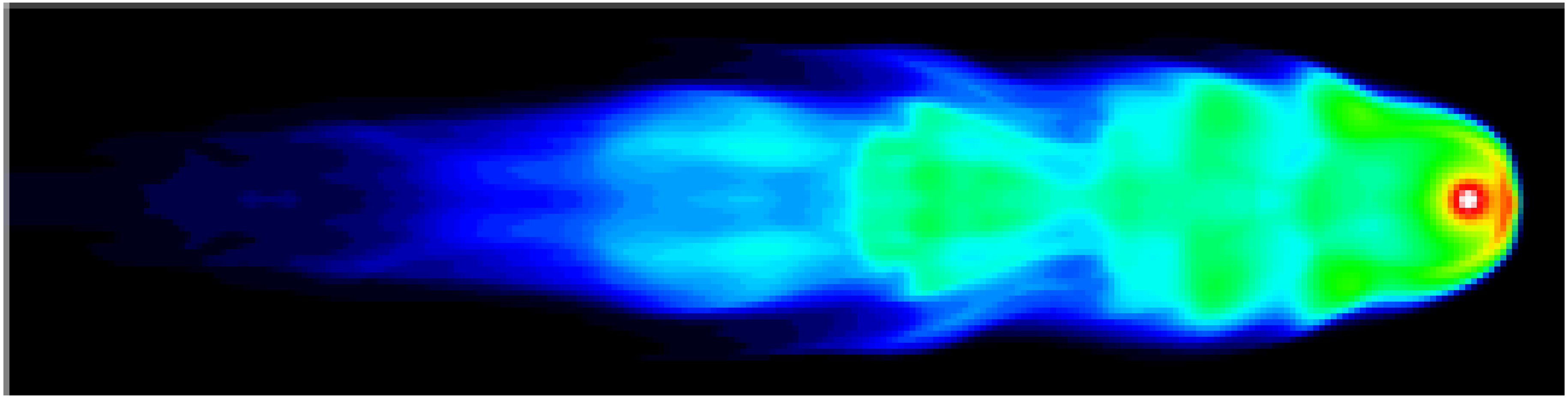
Simulations



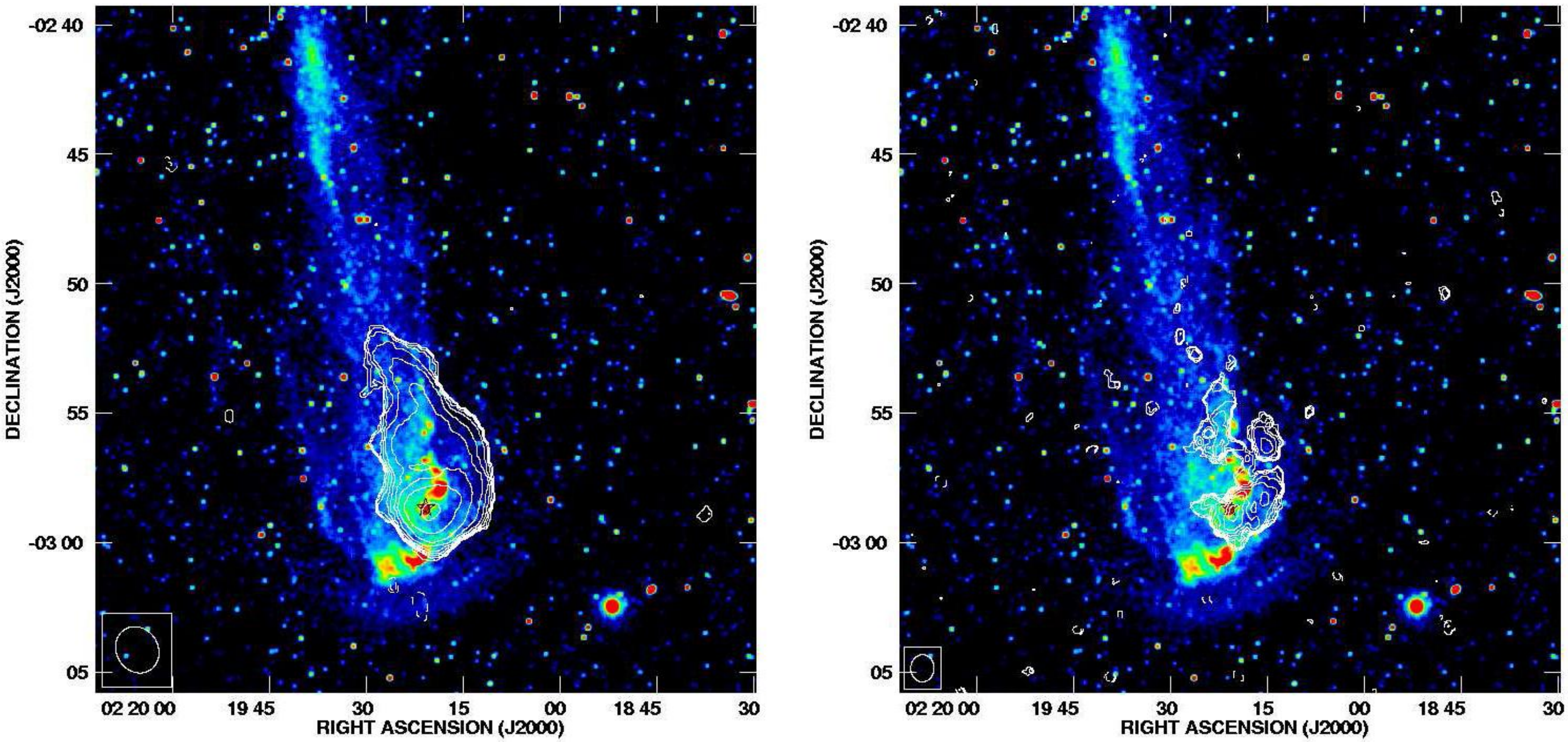
450,000 years to form a 4pc tail!

Prediction 4

Material entering the tail behind Mira does not immediately deccelerate to zero, instead it gradually deccelerates along the tail.

Much older material 'keeps up' with Mira and the tail is in fact far older than 30,000 years.

Radio observations



- H1 emission (VLA observation) overlaid on GALEX observation.

Further radio mapping with Nancay Radio Telescope reveals a clear slowing-down of the material in the tail with increasing distance from Mira.

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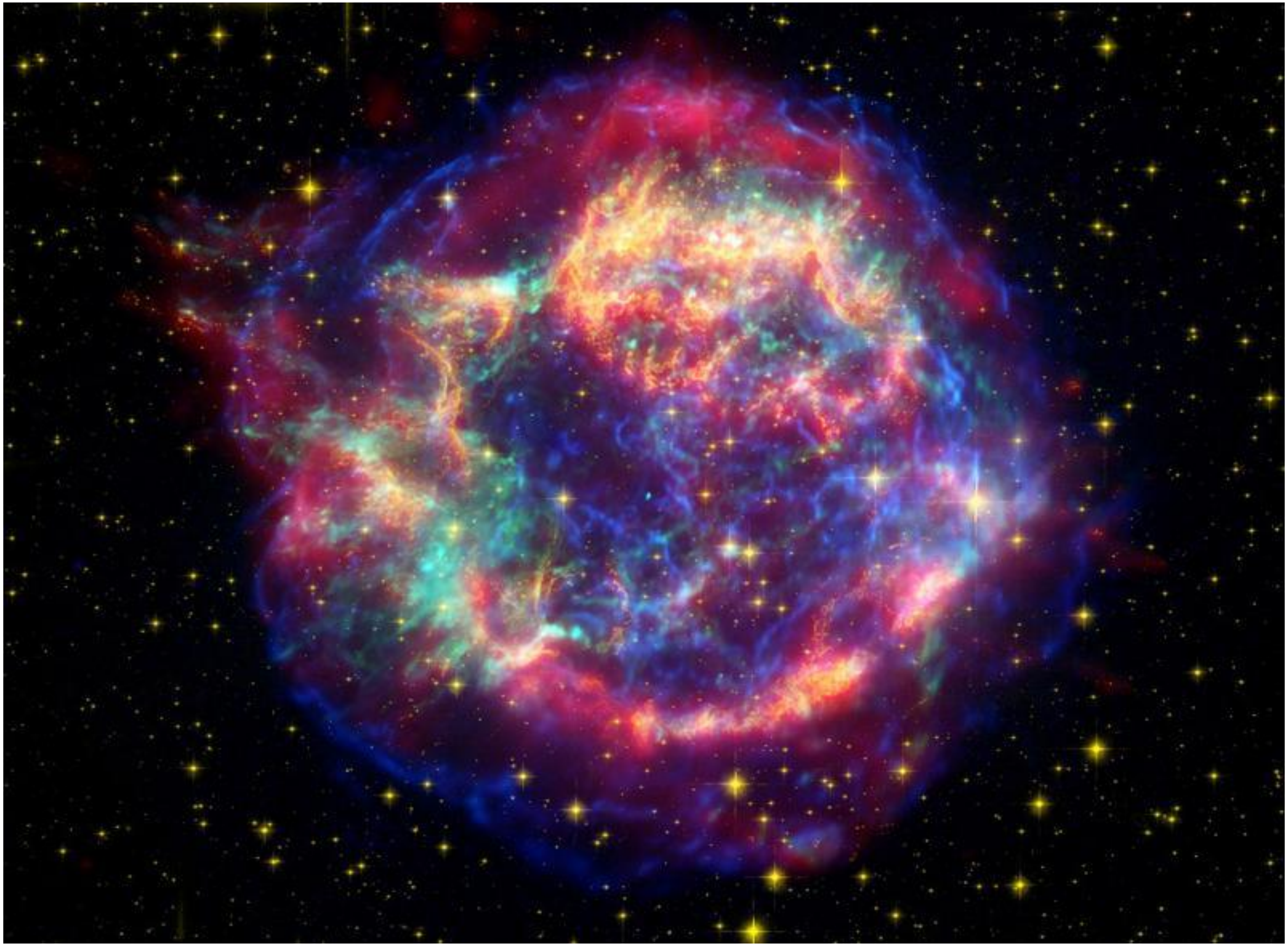
Gaps in the tail?

Why is there a recent gap in the tail?
Why is the tail kinked at the same place?

- Mira is in the right direction at the right distance to have *possibly* recently entered the local bubble.

Might this have something to do with it?

The local bubble is a supernova remnant...



...maybe.

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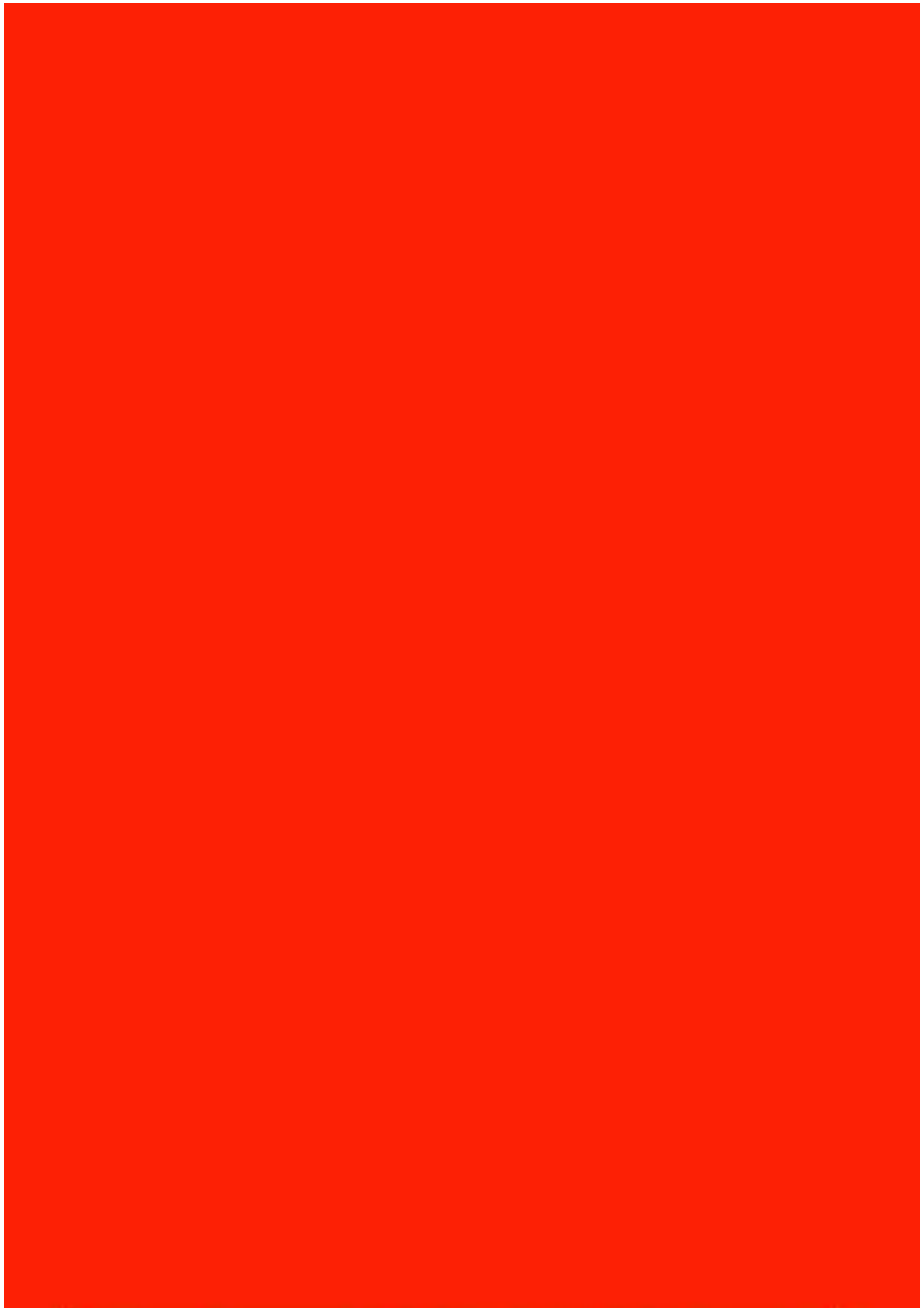
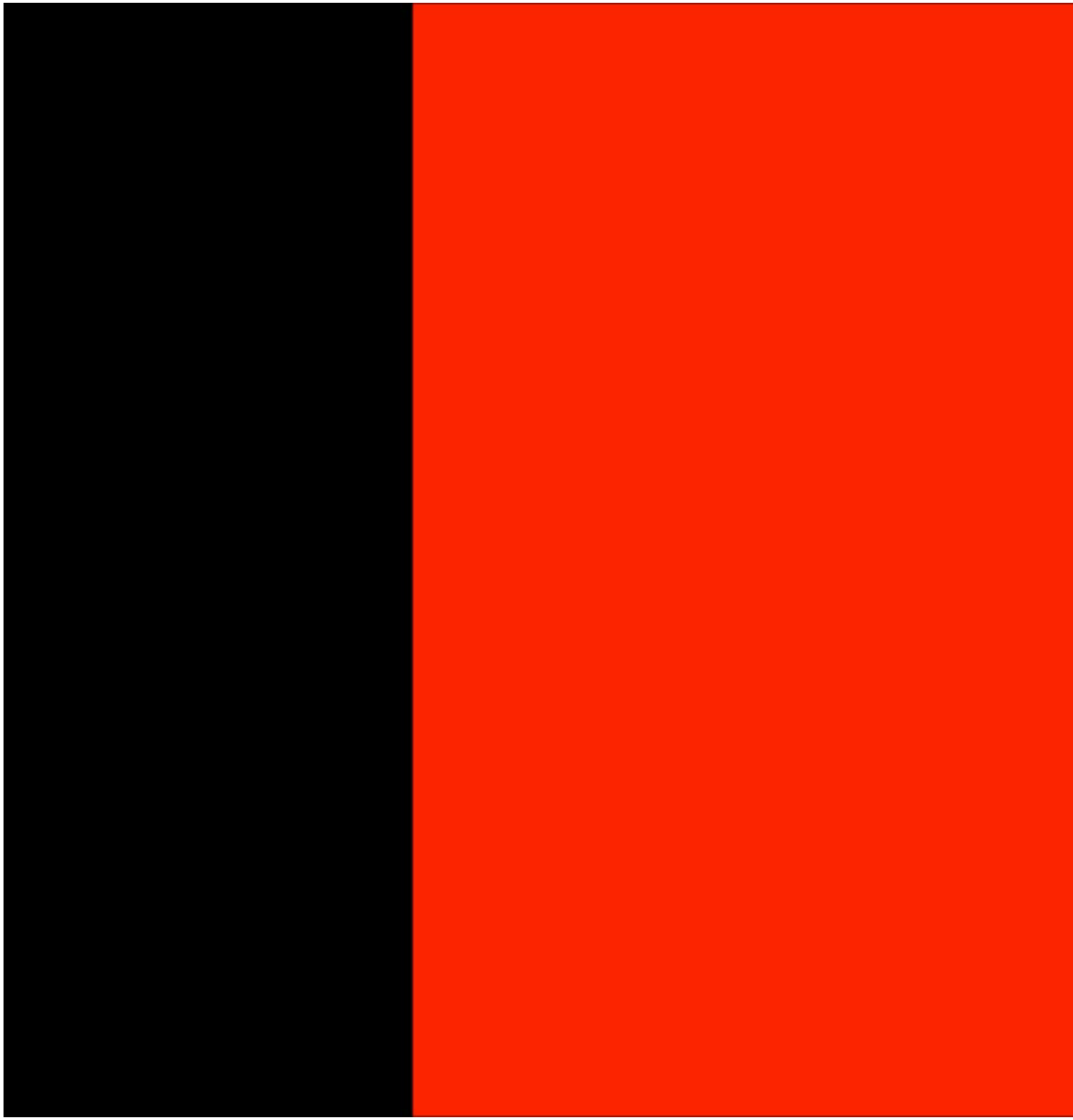


- Whatever the origins, what happens if Mira passes from a high density environment to a low density one?



Great, so now we have a bow shock in the right place and a narrow tail.

- Now, what if the high density region had a cross flow?

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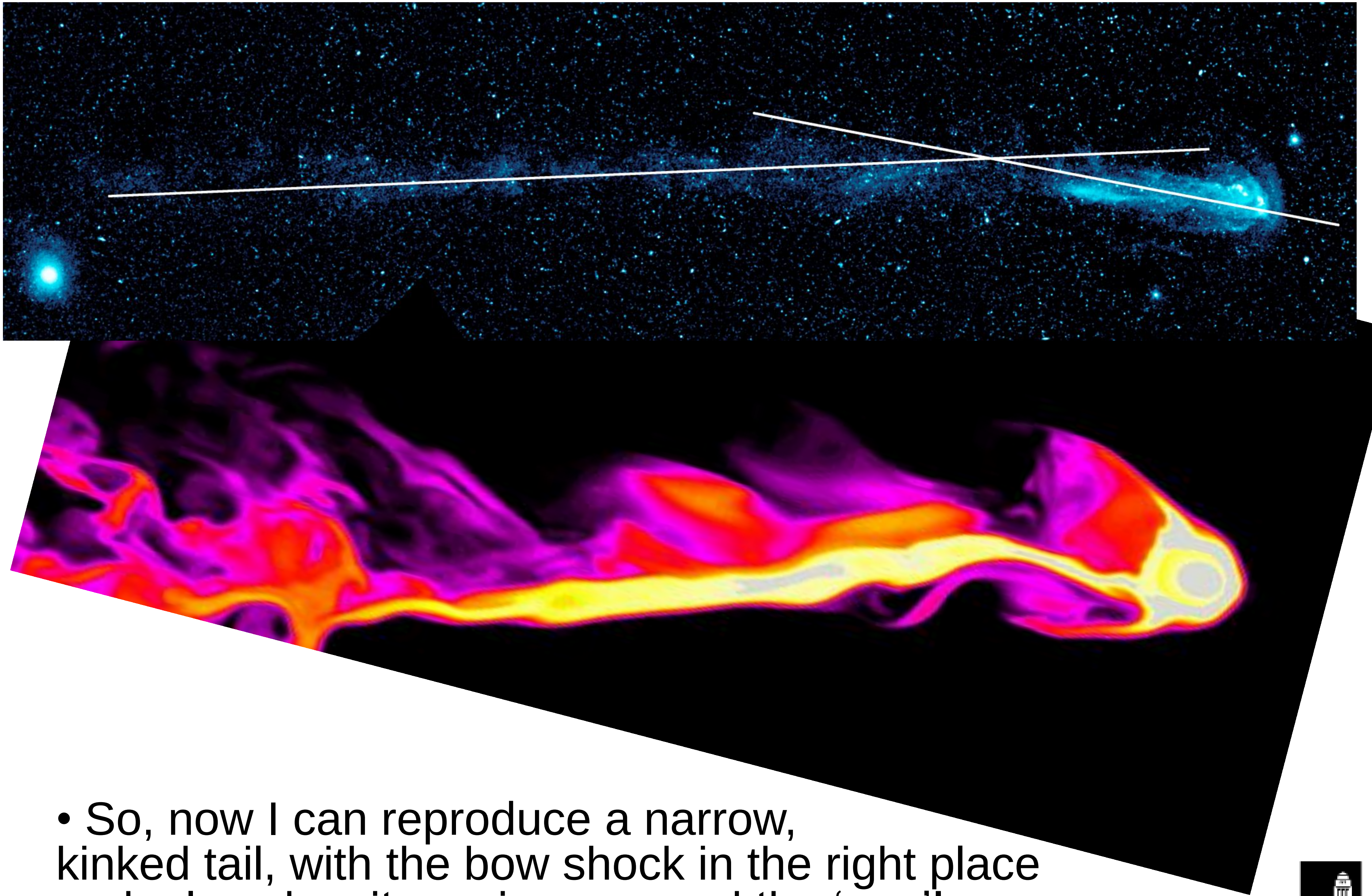

- So, now I can reproduce a narrow, kinked tail, with the bow shock in the right place and a low density regions around the 'gap'!

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Mira… a Rosetta stone of astrophysics

- The tail of Mira represents almost half a million years of mass-loss history – the entire lifetime on the AGB.

- Current understanding of mass-loss during this stage of evolution is sketchy at best:-
  - AGB winds are symmetric, how do asymmetric PNe form?
  - how do helium flashes etc alter the circumstellar structure?

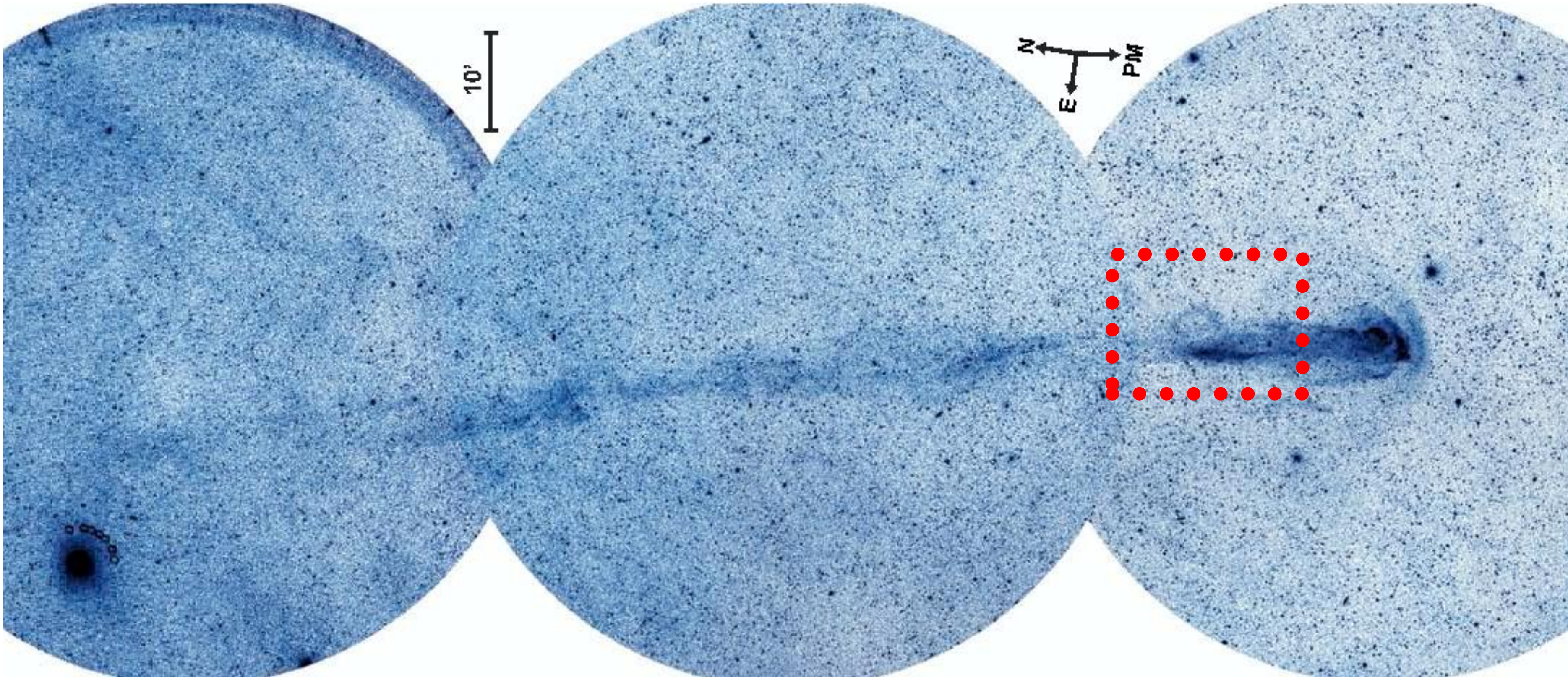
There is no clear picture!

If we can disentangle the effects of ISM interaction…

we can reveal the mass-loss history of a star for the first time…

a Rosetta stone of astrophysics!

Whirlpools in space?



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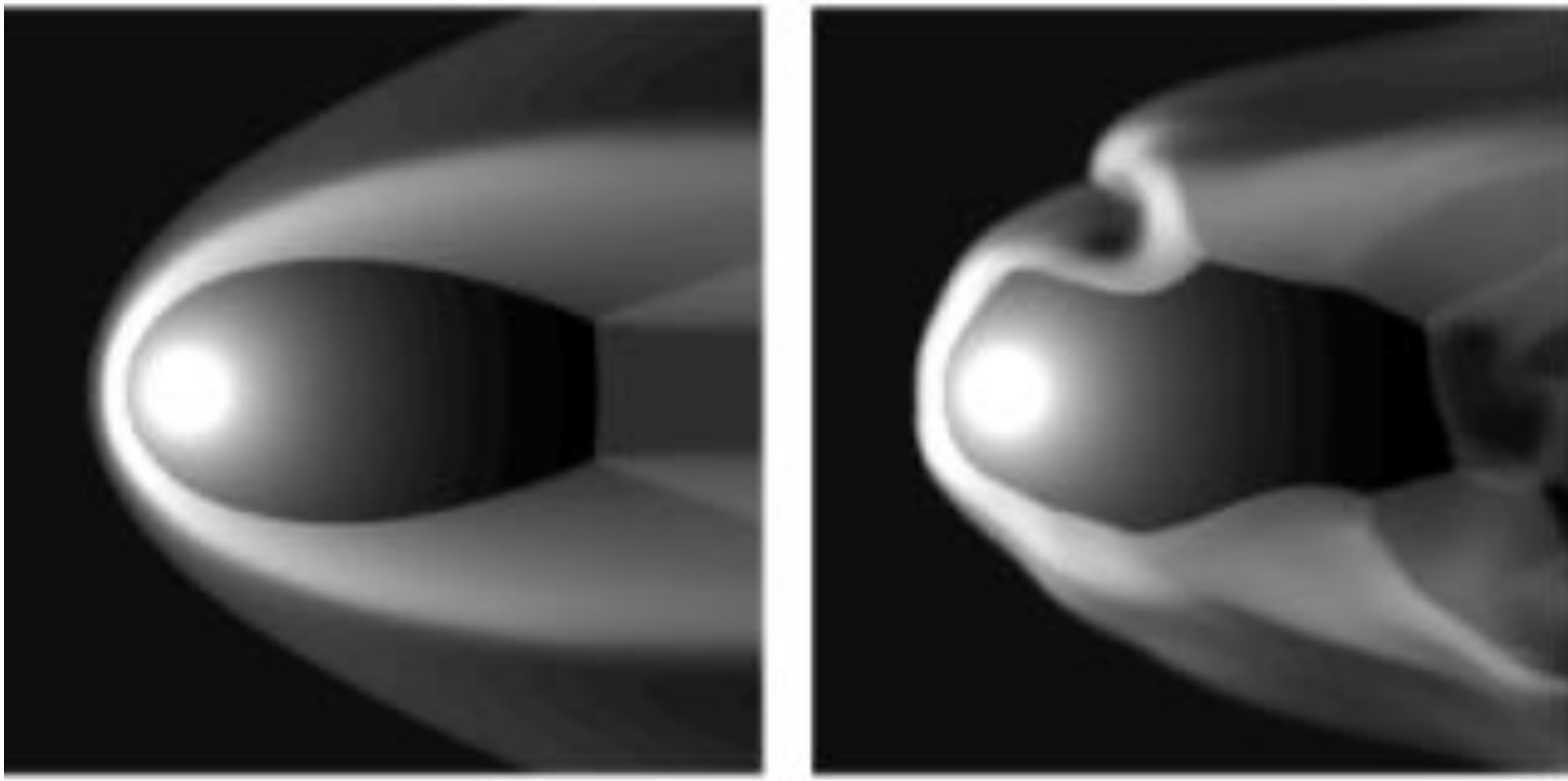
Whirlpools in space?



Turbulent vortices ram-pressure-stripped from the head of the bow shock

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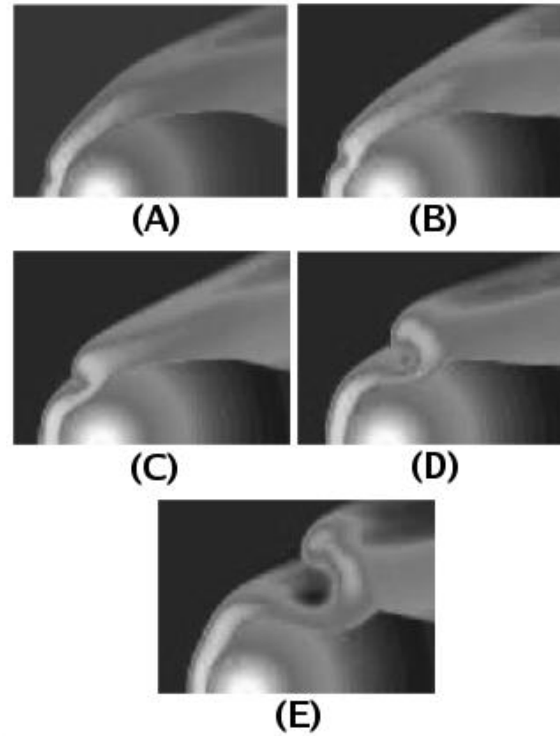
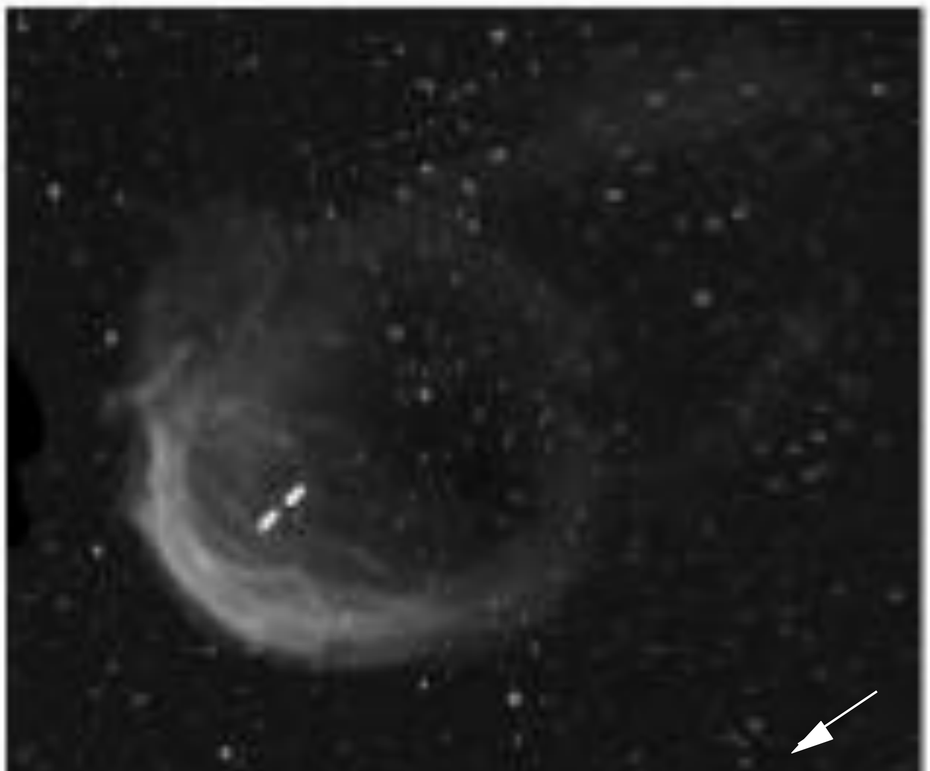
Vortices in space.





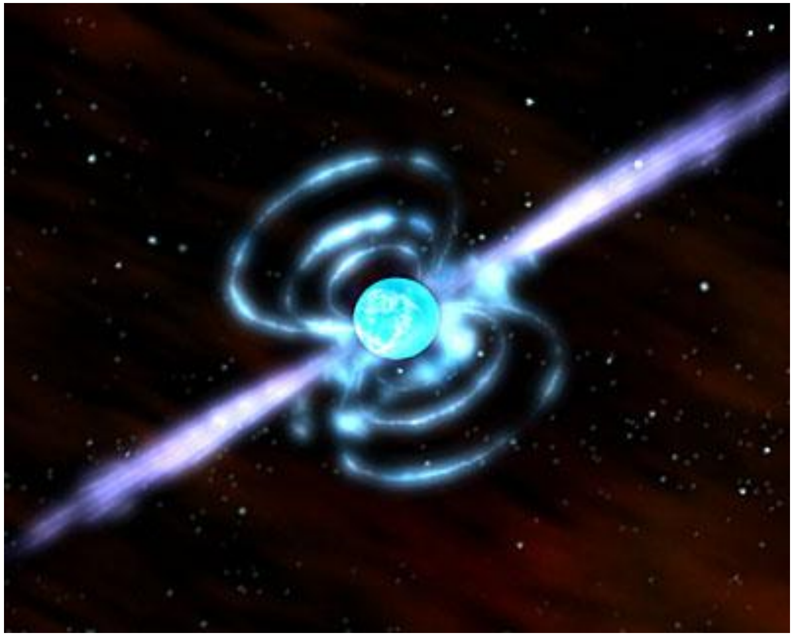
Let’s get back down to Earth…

What might happen to our Earth when the Sun goes through this stage of evolution?

The short answer is complete destruction!

But this won’t happen for another 5 billion years, so no need to worry just yet.

What happens after a supernova - the evolution of pulsars



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Overview

- What *is* a supernova?
- Pulsars
- Magnetic fields
- What happens in the crust of neutron stars?
- Scales of the magnetic field – the need for high performance computing
- MHD Simulations
- Future work

Super-what?

- Massive stars, greater than ~9 times bigger than our sun.
- Eventually run out of hydrogen fuel.
- Run away nuclear reaction in the core burns heavier elements.
- Leads to core collapse and a 'supernova' explosion.
- Most of the elements on Earth were built inside stellar cores like this and similar death throes of stars – we are all made of this star dust!
- Some supernovae (less than ~20 times more massive than our Sun) leave a tiny remnant behind.
- With even more massive progenitor stars, the remnant is unable to withstand its own gravity and collapses into a black hole.

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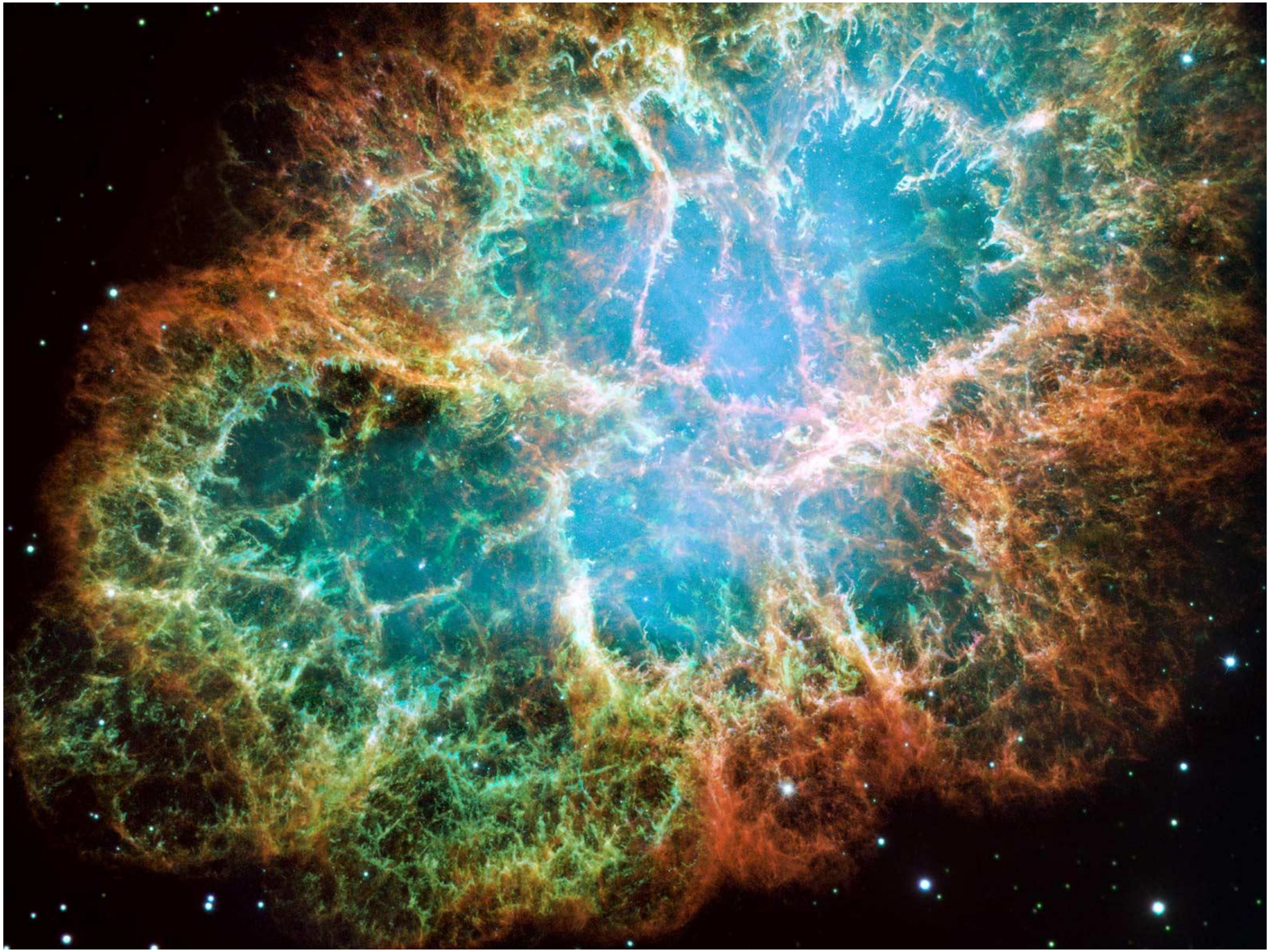
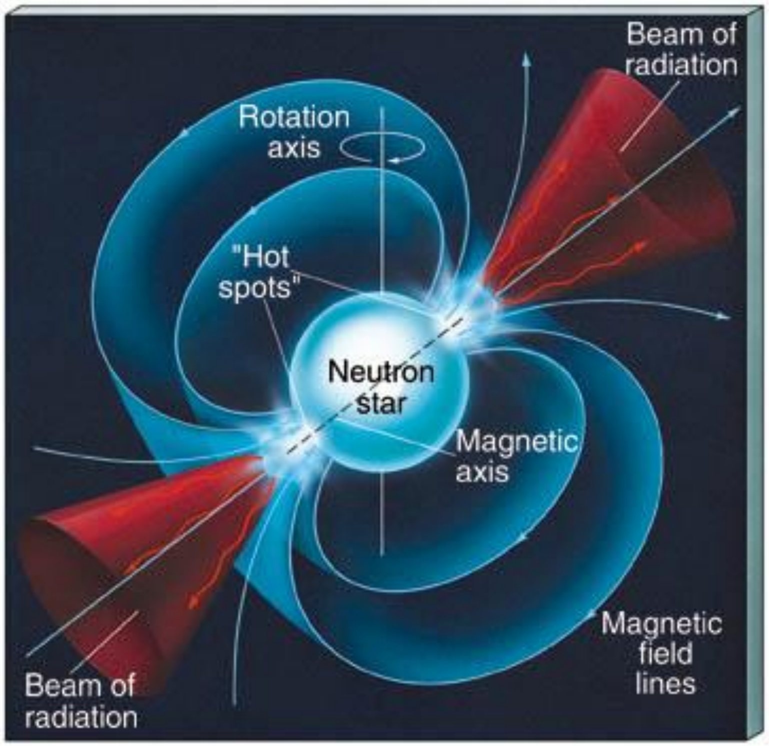
Supernova



Neutron stars



What is a pulsar?

- Spinning lighthouse sending out radio waves.
- Spin rates from a few times a second to 1000s.
- 30km in diameter.
- ~1.4 solar masses.
- Strongest magnetic fields in the universe: 10^8–10^{14} G, c.f. Earth field 0.3-0.6G, NMR/MRI ~4×10^5G.
- Association between spin slow down and decreasing magnetic field strength.

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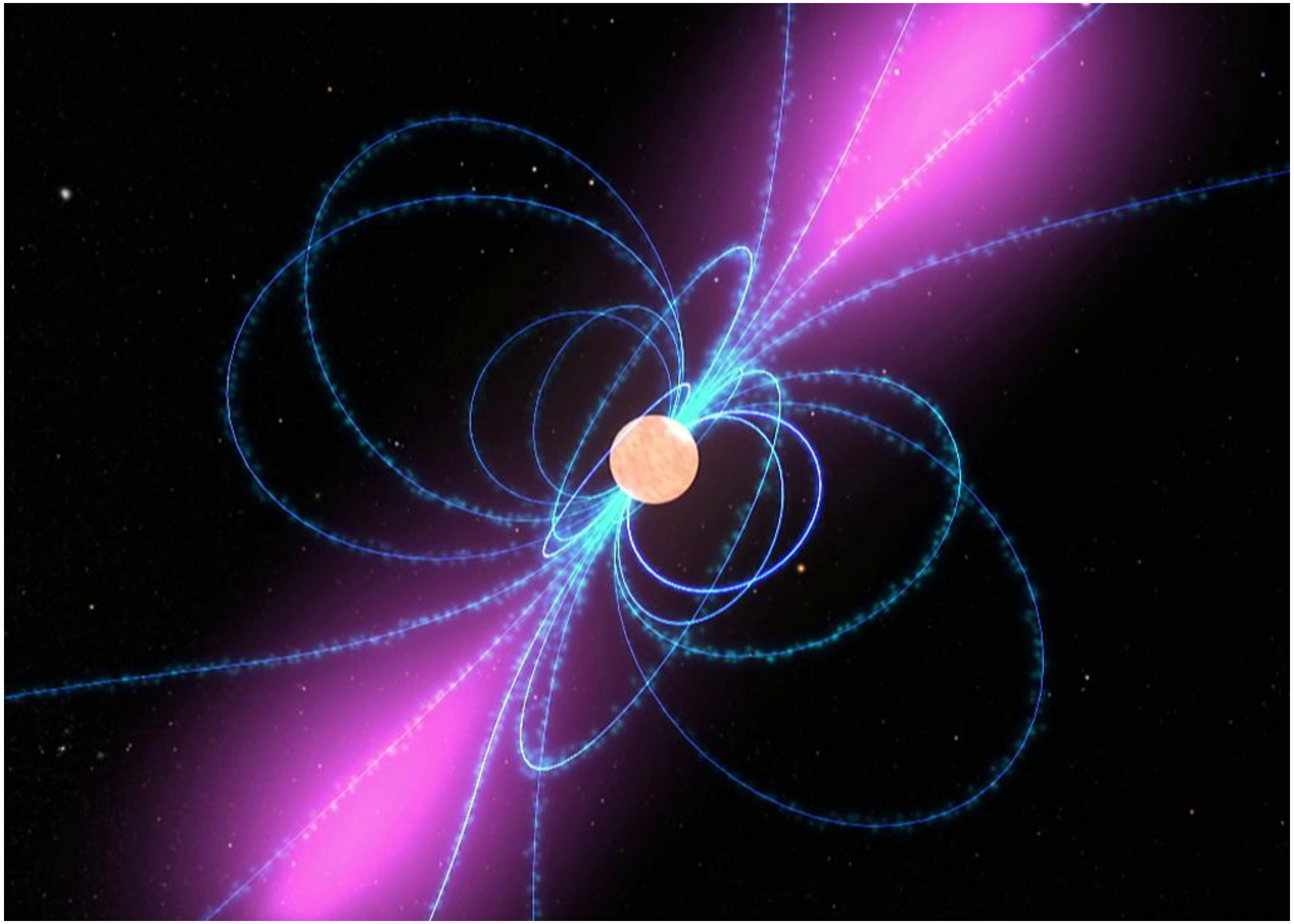
What is a pulsar?

- Crab pulsar, supernova witnessed by Chinese astronomers in 1054AD.
- Rotation rate of 30 times per second.



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Crusts of neutron stars

- In the crusts of isolated neutron stars, the electrons are thought to move through a frozen lattice of atoms.
- Turbulence rearranges the magnetic field energy.
- Resistance (Ohmic decay) acts faster on smaller lengthscales, thereby accelerating magnetic field decay.
- Since the governing equation is scale invariant, a very small box will see the large-scale field as a background field
  => expect the smallest scales in the system to be anisotropic.
- Inverse cascades of turbulent energy may be the way in which a neutron star obtains a large scale ordered field the primarily small scale disordered initial state.

Equation of neutron star turbulence

Governing equation for the magnetic field, derived from the equations of motion of charged particles and Faraday's law:-

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \left(\frac{\boldsymbol{j}}{\sigma_0}\right) + \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

Ambipolar diffusion

Ohmic decay

$$- \left(\frac{m_p/\tau_{pn} - m_e^*/\tau_{en}}{m_p/\tau_{pn} + m_e^*/\tau_{en}}\right) \nabla \times \left(\frac{\boldsymbol{j} \times \boldsymbol{B}}{n_c e}\right)$$

Hall drift

where $\boldsymbol{j} = \dfrac{c\nabla \times \boldsymbol{B}}{4\pi}$

In the crusts of neutron stars protons are immobilized, electrons carry all the current and ambipolar diffusion is eliminated:-

$$\frac{\partial B}{\partial t} = -\frac{c}{4\pi n_c e} \nabla \times [(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}] + \frac{c^2}{4\pi\sigma_0} \nabla^2 \boldsymbol{B}$$

Simulations

- Solve by expanding field components in Fourier series in three dimensions.
- Standard pseudo-spectral techniques to evaluate the nonlinear terms.
- MPI FFTW library (v2.1.5) to achieve massive parallelisation.
  - New MPI library (3.3 beta) released yesterday
- Time integration using a second order Runge-Kutta method.

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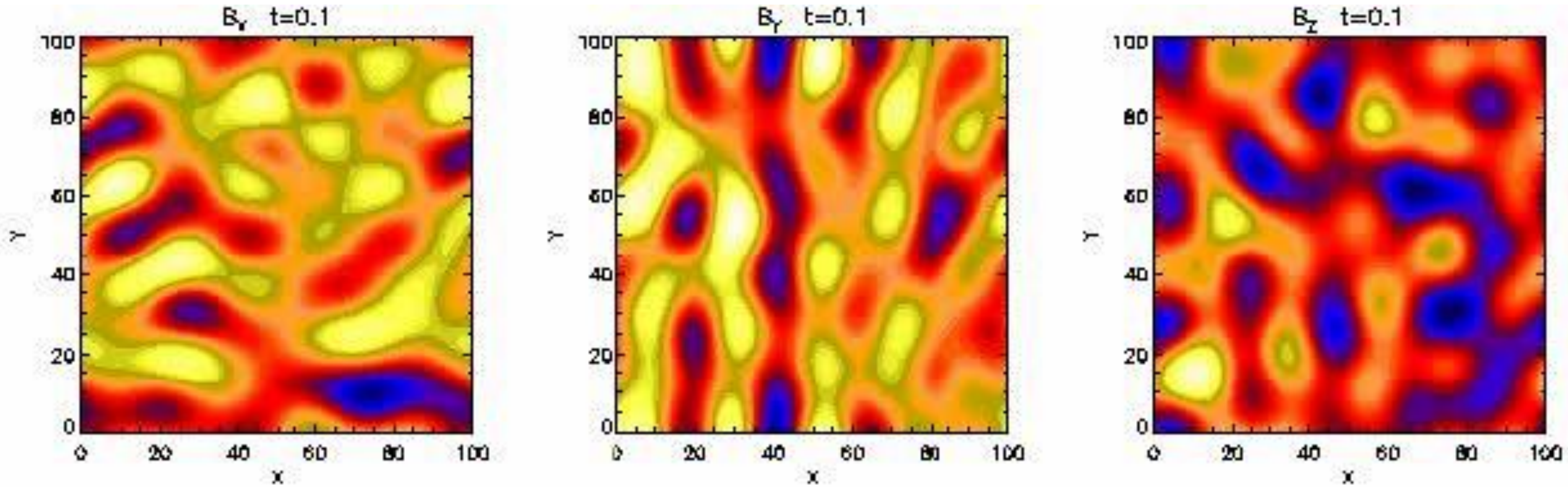
Turbulence



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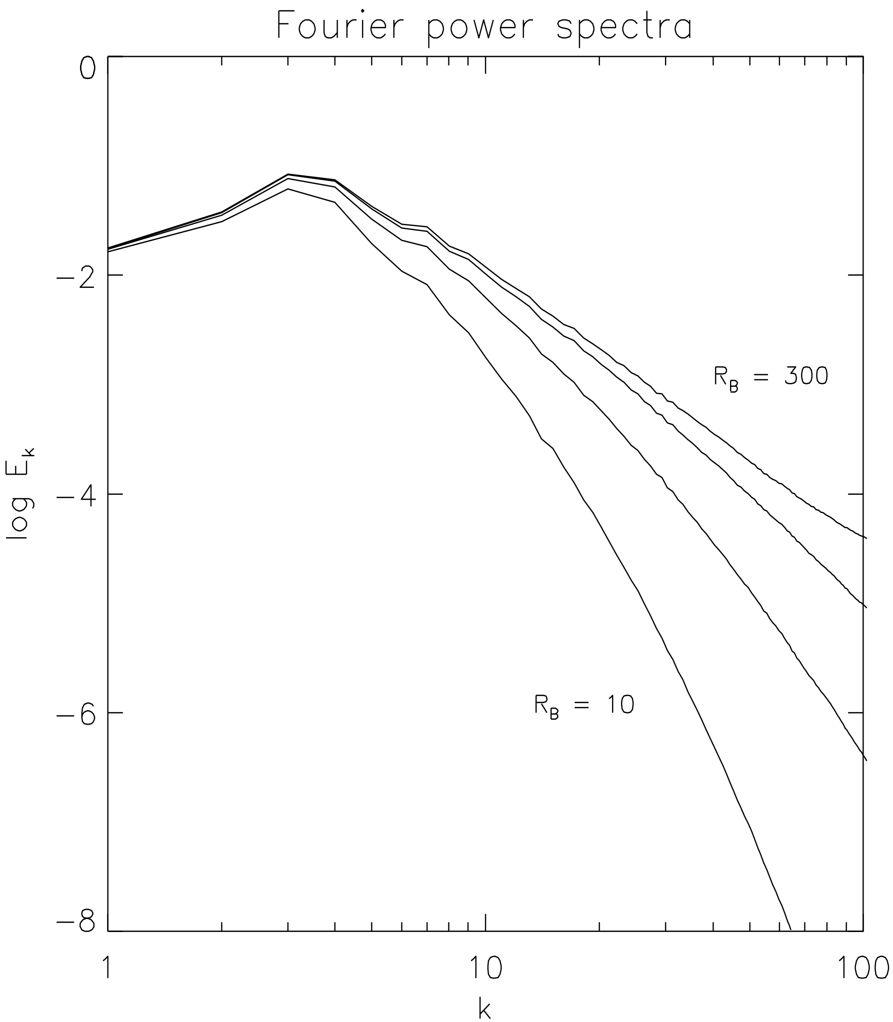
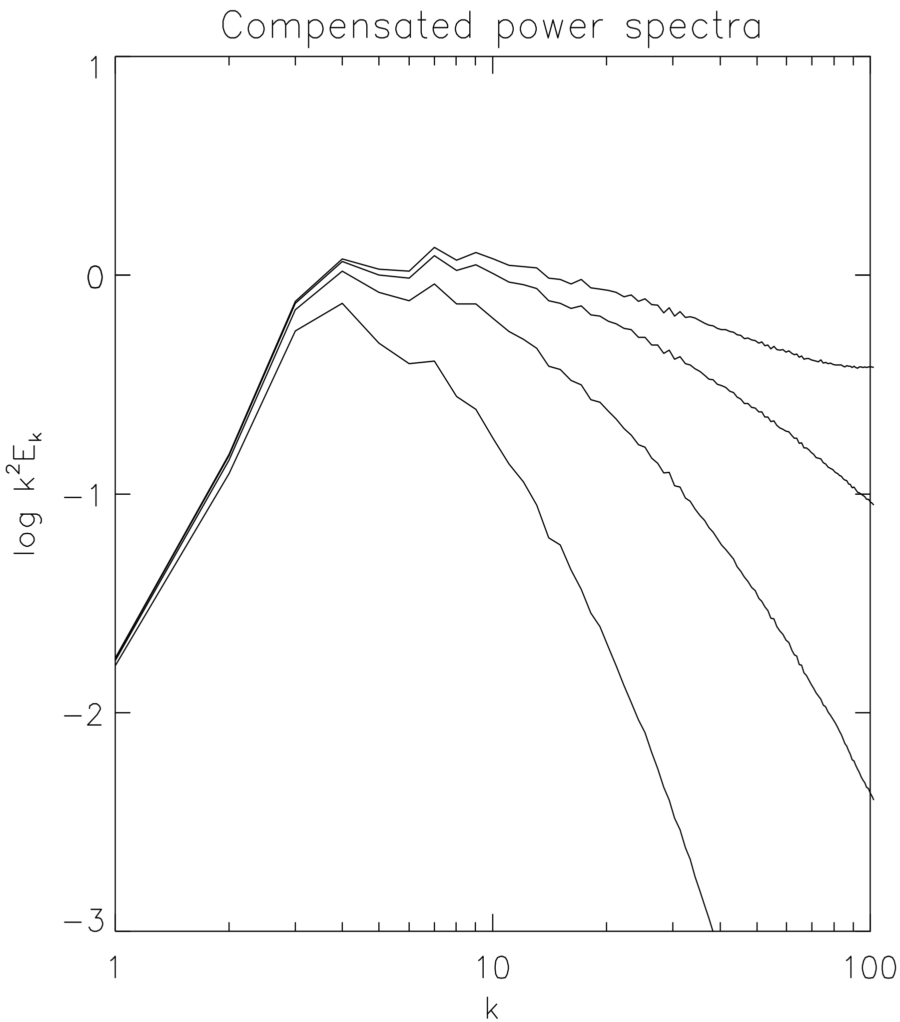
Turbulence power spectra





- turbulent spectrum: k^{-2}

t=0.2

Future work...

BUT, in a neutron star densities, temperatures and hence conductivities vary hugely over the crust.

=> New 3D code with varying conductivity.

Thank you for listening.

Any questions?

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