Molecular cooling in Large Scale Simulations of Protostellar Jets

Jamie O'Sullivan
Landessternwarte(ZAH)

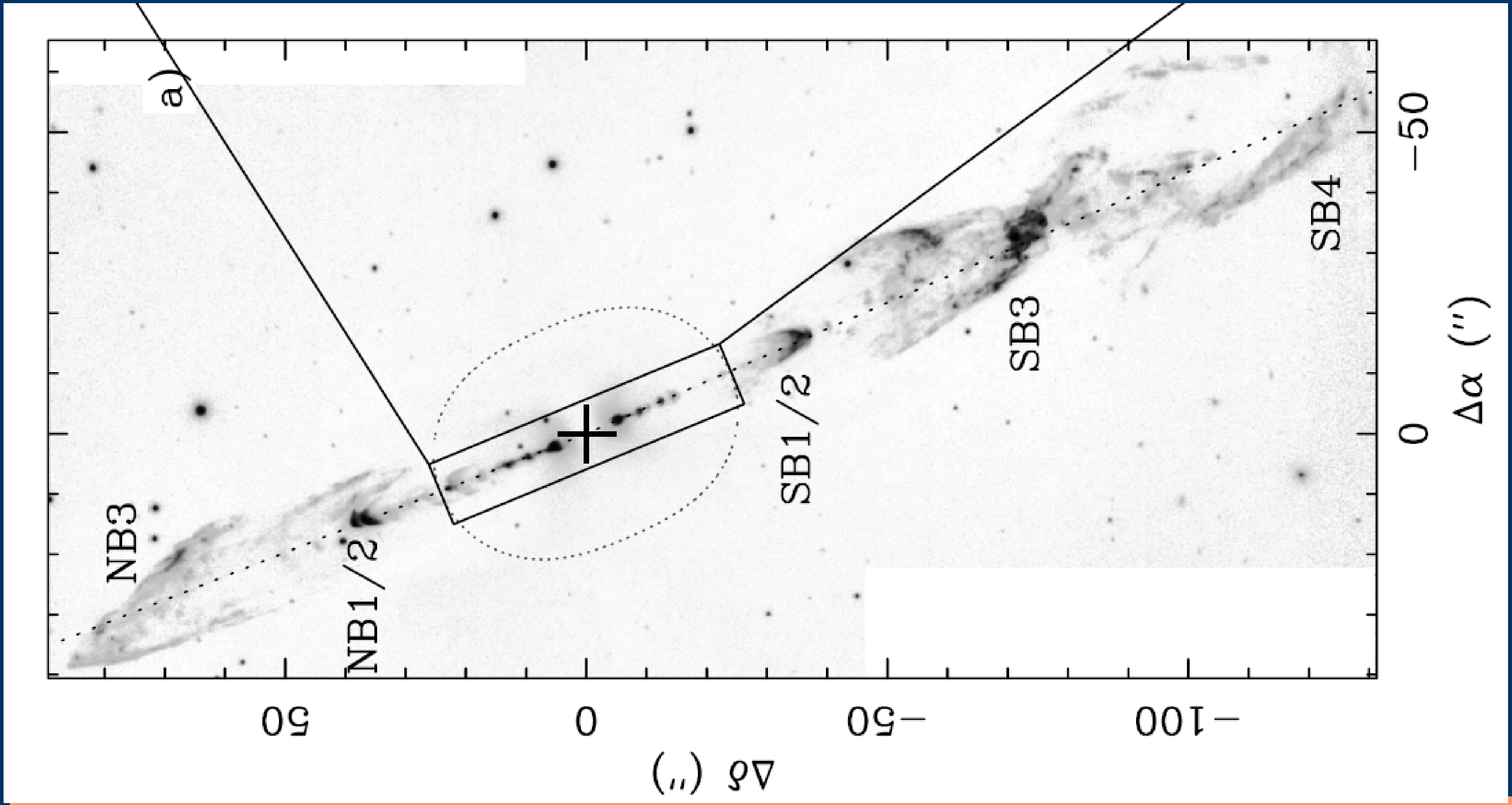
International Max Planck Research School
for Astronomy and Cosmic Physics at the University of Heidelberg

Overview

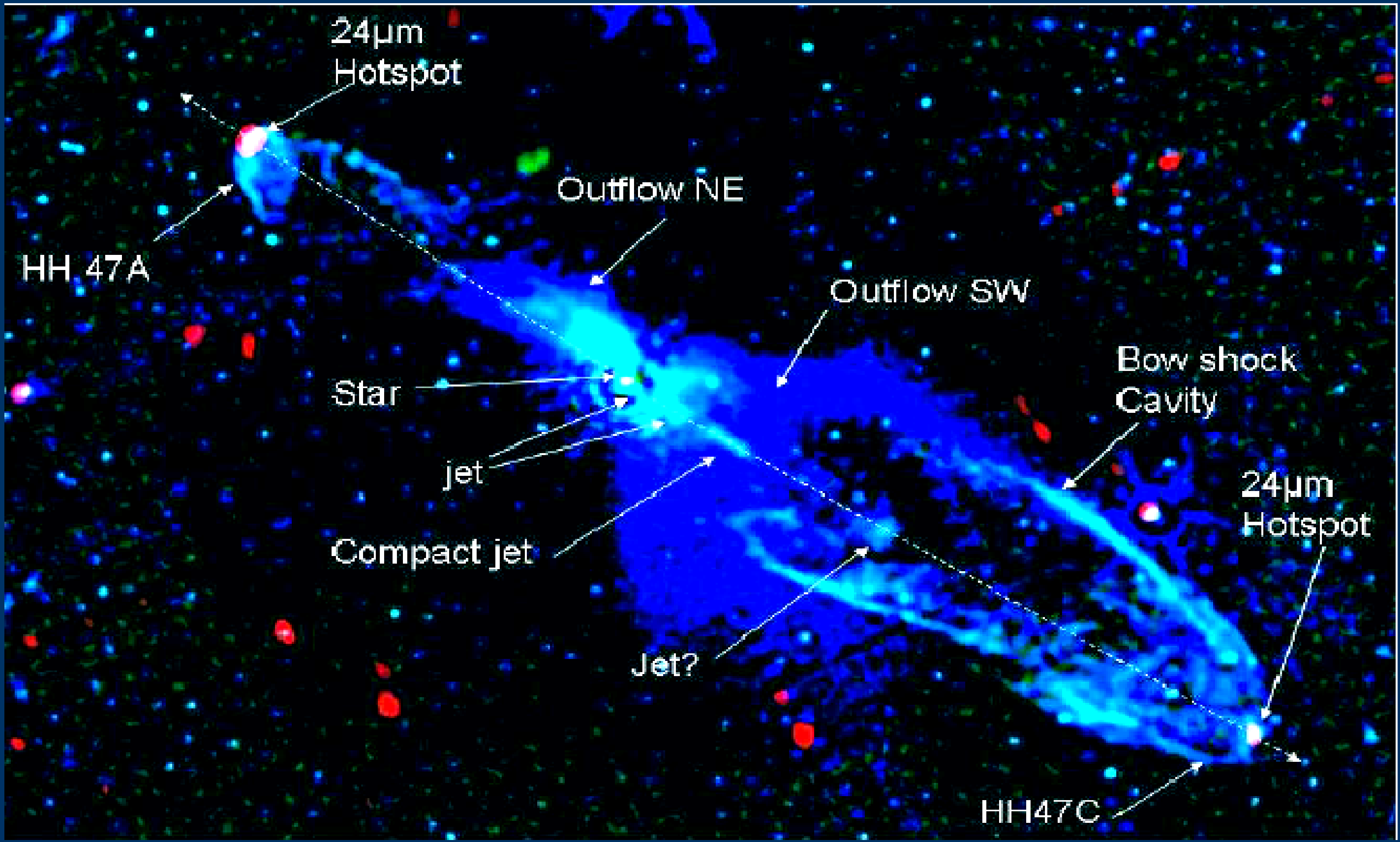
- **Introduction**
  - Summary of the astrophysical scenario addressed
  - Description of the model
- **Earlier Jet simulations**
  - Setup
  - Results
  - Limitations
- **Current Work**
  - 2D simulations
  - 1D Stationary shock
- **Visualisation – Approach & Status**
- **Conclusion**

Section 1: Observations of molecular emission in jets

- HH212 – Lee et al. 2007



Section 1: Observations of molecular emission in jets



HH 47 Velusamy et al. 2007

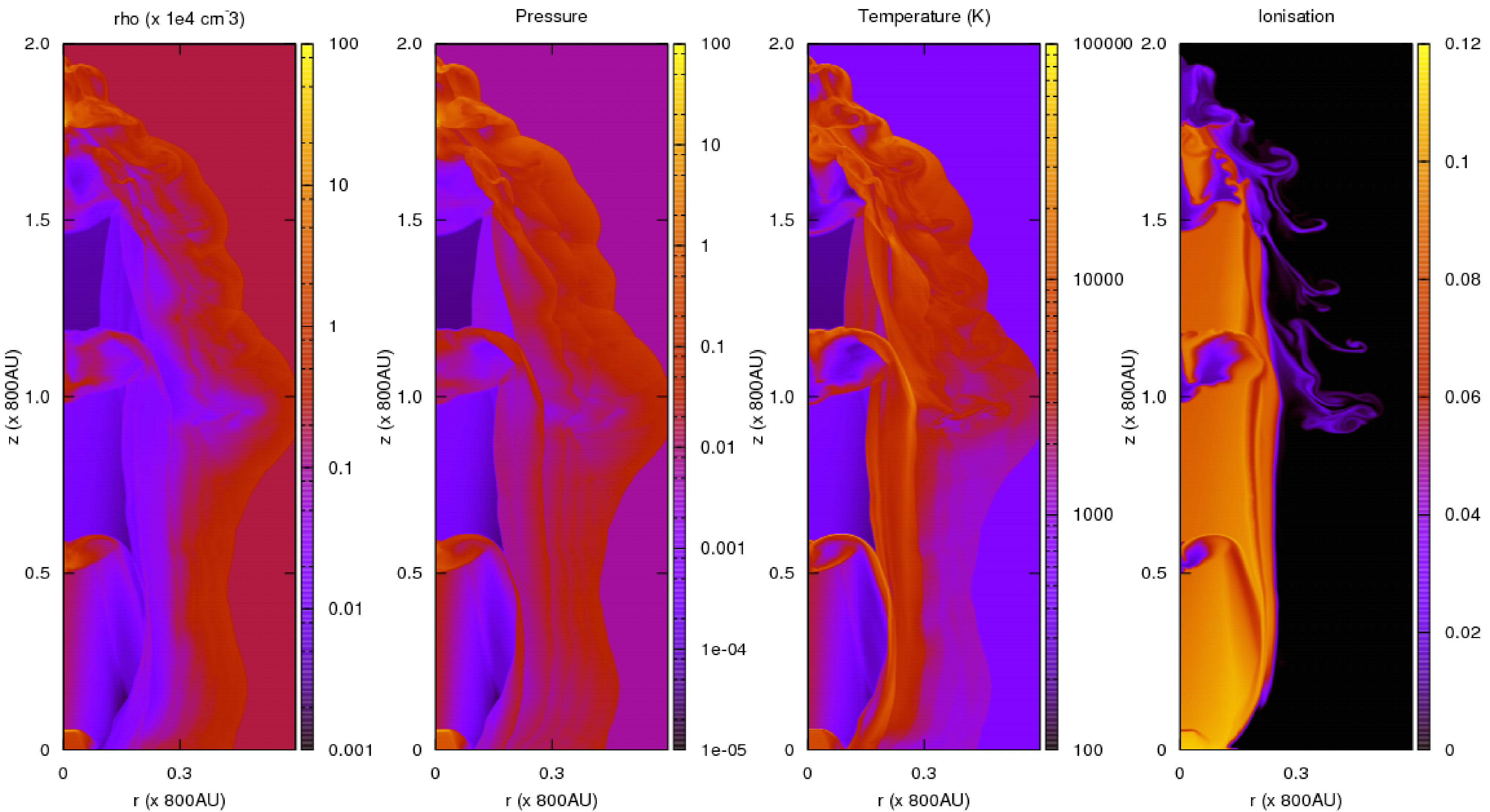
Section 1: Overview of the astrophysical scenario modelled

- Jet-driven outflow model
- Modelling protostellar jets which radiate in the H_2 rovibrational lines, such as HH46/47
- Objective is to carry out simulations to the large scales (~40,000 AU) and to reproduce observed emissions
- Hydrodynamic, with PLUTO finite volume code
- Chemical network of 6 species (HI, HII, e^-, H^-, H2, H2II) to model the H_2 cooling, solved with BDF
- 15 reactions including the two main gas phase H_2 formation pathways
- Cooling functions for atomic hydrogen, and molecular cooling from H_2 (Galli & Palla 1998)

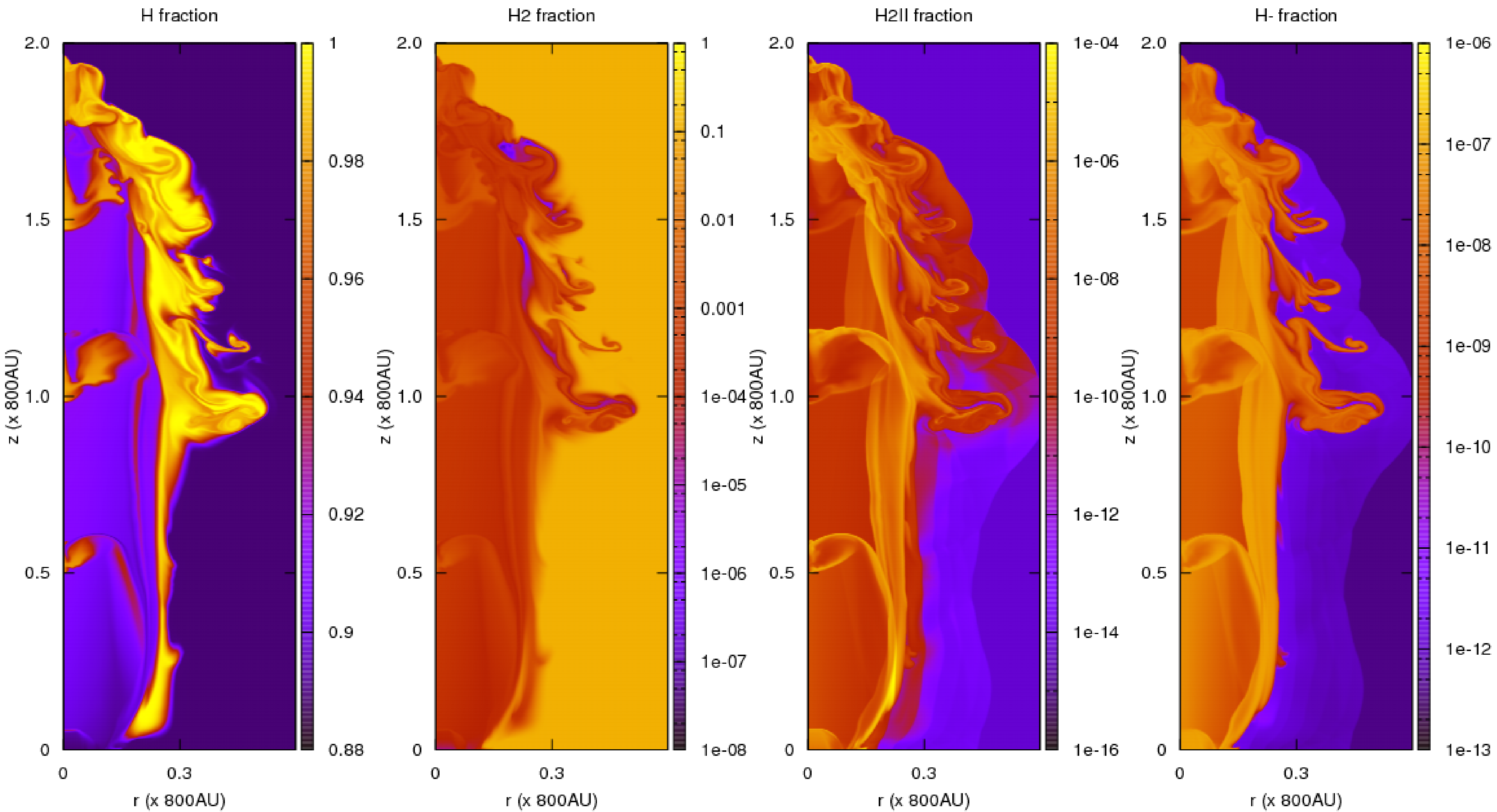
Earlier Jet Simulations: Setup

- Hydrodynamic, 2D cylindrical axisymmetry, 400x2000 on uniform grid
- Parameters:
  - Jet density $\eta = 5$ (overdense jet, 1e4 cm^{-3})
  - Beam sound speed 11km s^{-1}, injected at Mach 12
  - Beam ionisation 10% (value when injected)
  - T_{beam} 1e4 K, $T_{ambient}$ 1e3 K
- Various configurations
  - Steady or Pulsed, with T ~ 80 years, velocity sinusoidally varying between M6 and M12
  - Overdense beam or equal density
  - H_2 abundance in the medium 20% - 40%

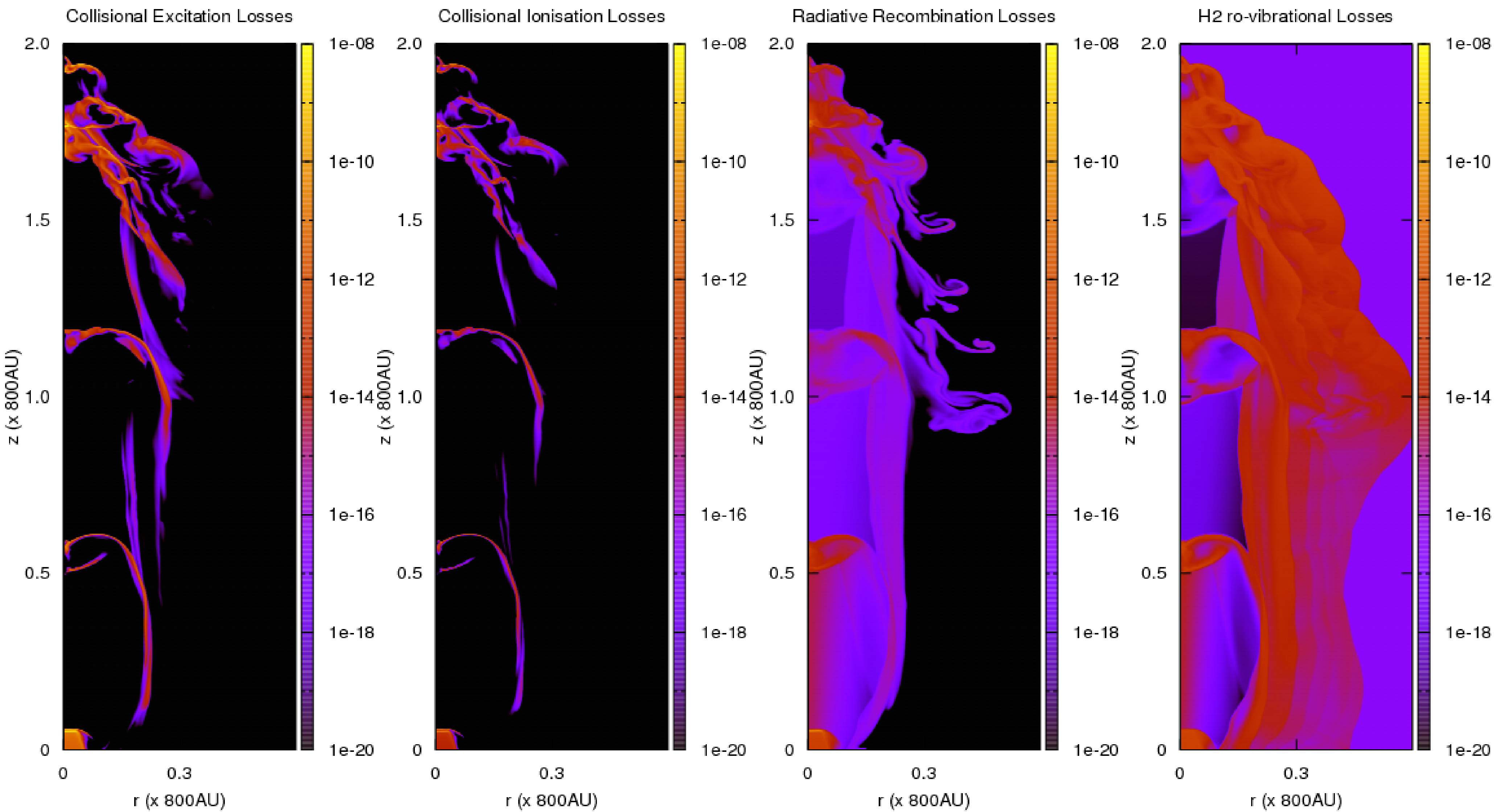
Previous Results: State variables & ionisation



Previous Results: Species Fractions



Previous Results: Cooling Losses

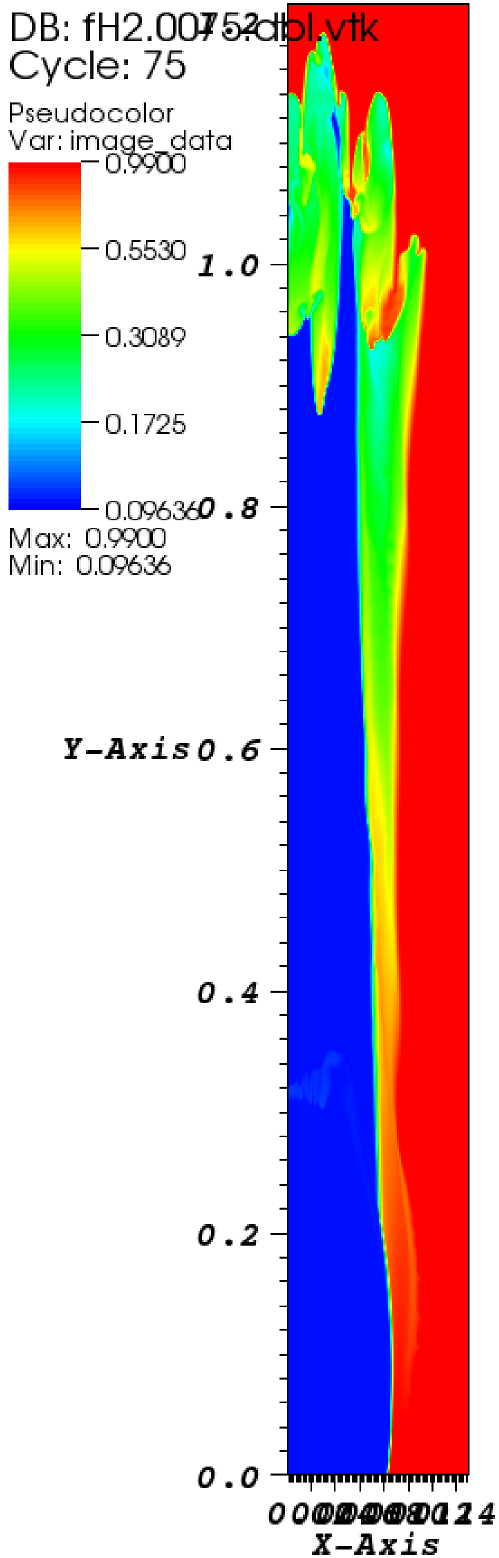


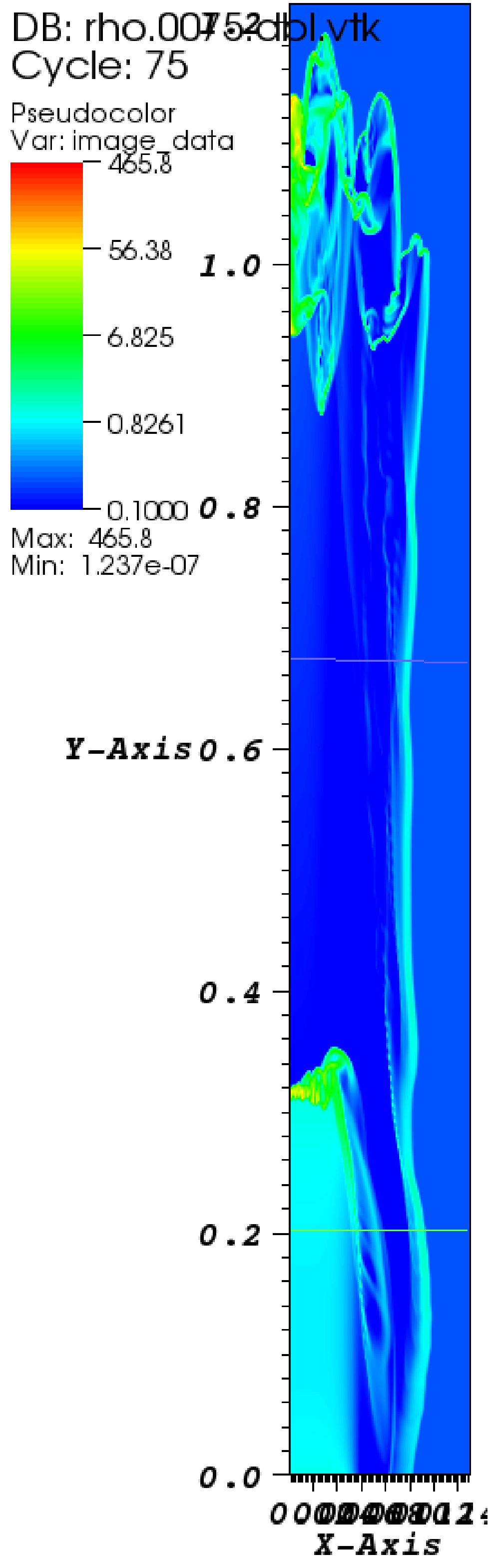
Observations

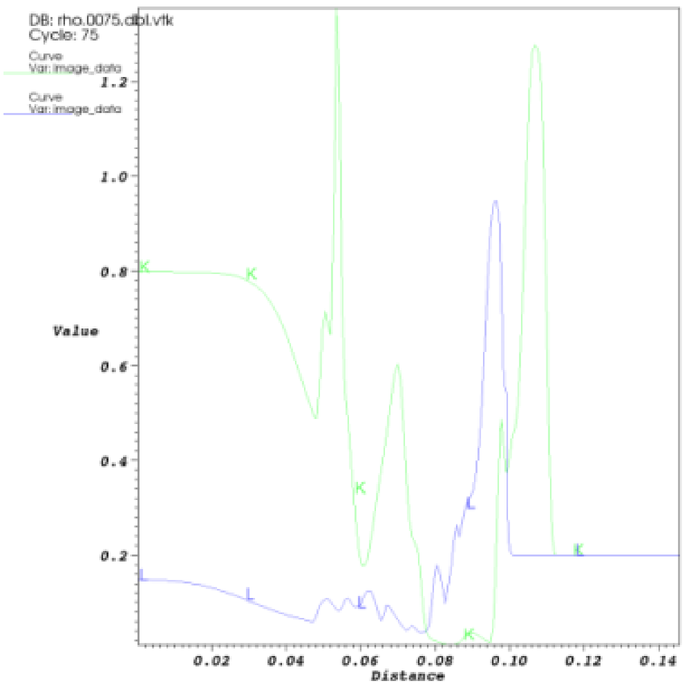
- Results gave a lot of information, but some limitations were apparent
  - Parameters not entirely appropriate for the scenario of a cold molecular cloud
  - Chemistry and cooling terms not entirely appropriate for the appropriate parameters
  - MHD effects not yet included
- These three areas are now being addressed
  - Firstly, keep the same model but alter the parameters, pressure & H_2 fraction of medium, beam pressure & ionisation
  - Also, compare results of chemical and cooling model with a more detailed model in the physical parameter space of interest

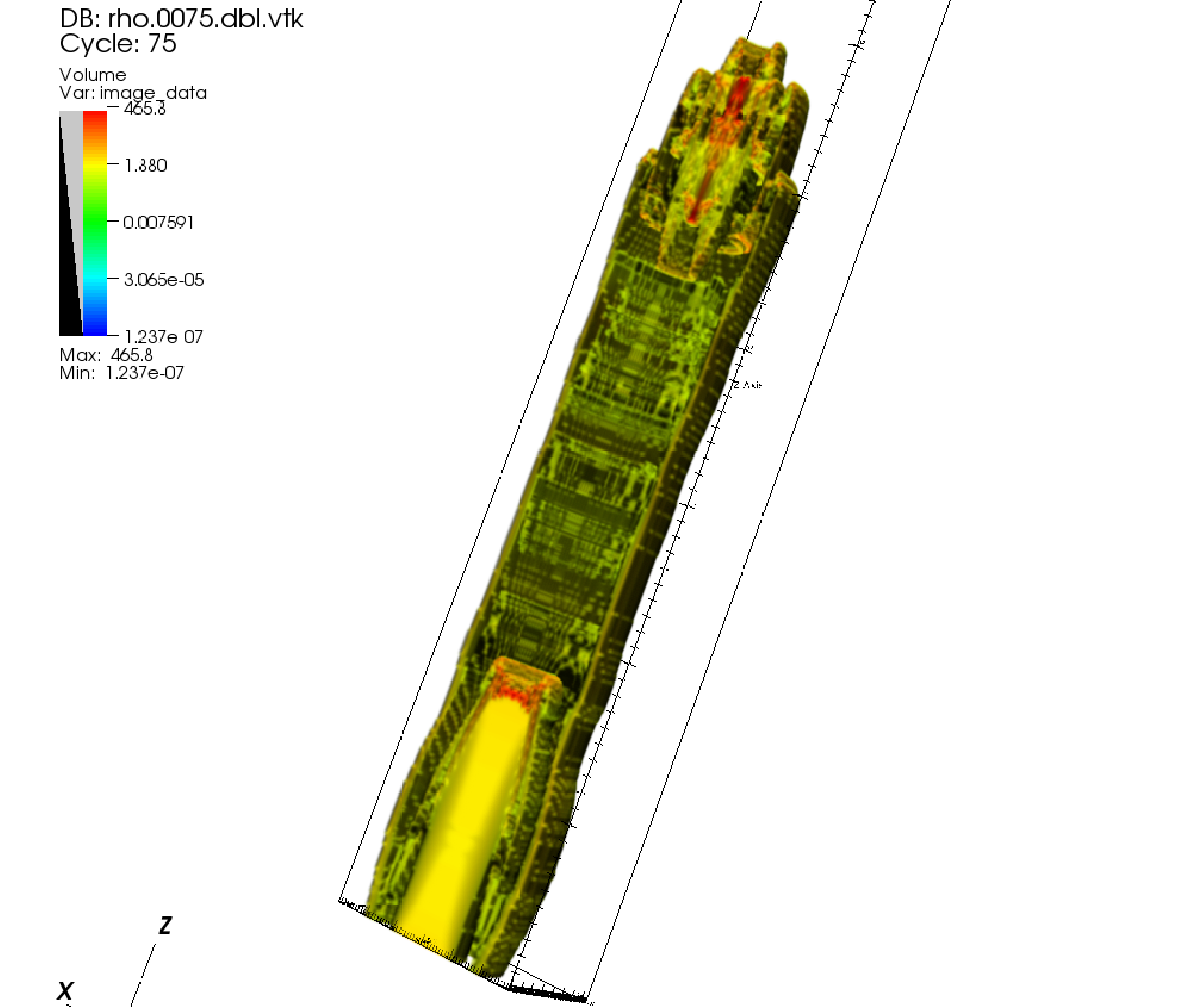
Current and future simulations

- Carrying out simulations with same code now, using more realistic parameters in order to better represent the cold environment
- Parameters:
  - Jet density, again $\eta = 5$ (overdense jet, 1e4 cm^{-3})
  - Beam sound speed 8km s^{-1}, injected at Mach 12
  - Fully molecular ambient medium
  - 10% H2 in the beam
  - T_{beam} 1000 K, $T_{ambient}$ 150 K
- Some numerical difficulties at low temperatures
- Also working on getting AMR simulations running in order to reach larger scales with sufficient resolution


DB: fH2.0075.dbl.vtk
Cycle: 75
Pseudocolor
Var: image_data
0.9900
0.5530
0.3089
0.1725
0.09636
Max: 0.9900
Min: 0.09636
Y-Axis
1.0
0.8
0.6
0.4
0.2
0.0
X-Axis

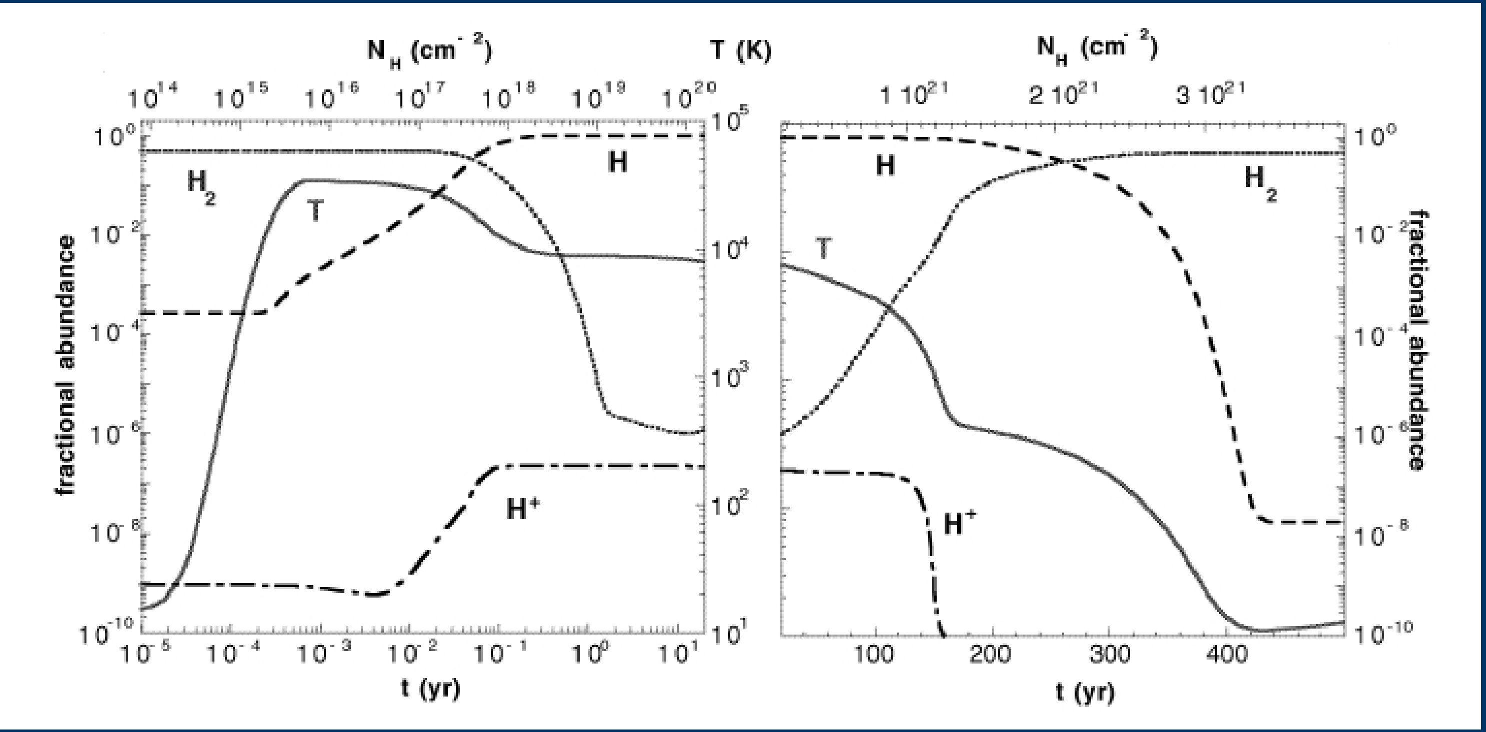

DB: rho.0075.dbl.vtk
Cycle: 75
Pseudocolor
Var: image_data
465.8
56.38
6.825
0.8261
0.1000
Max: 465.8
Min: 1.237e-07
Y-Axis
1.0
0.8
0.6
0.4
0.2
0.0
X-Axis


DB: rho.0075.dbl.vtk
Cycle: 75
Curve
Var: image_data
Curve
Var: image_data
Value
1.2
1.0
0.8
0.6
0.4
0.2
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Distance


DB: rho.0075.dbl.vtk
Cycle: 75
Volume
Var: image_data
465.8
1.880
0.007591
3.065e-05
1.237e-07
Max: 465.8
Min: 1.237e-07
Z Axis
Z
X

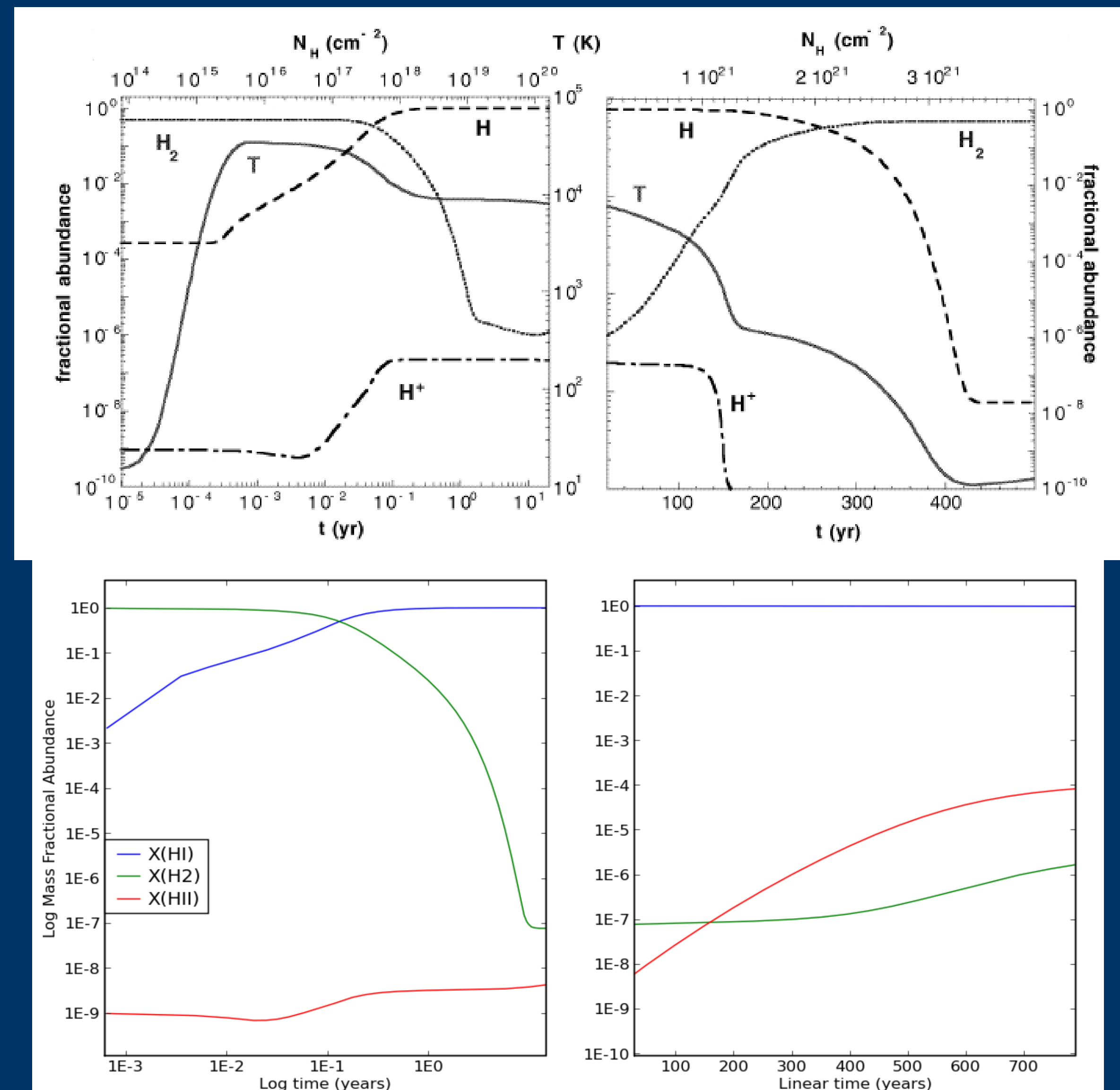
1D stationary J-Shock

- Flower et al. 2003 provides a useful model problem for comparison, also similar approach by Massaglia et al. 2005 for atomic network
- 1D stationary J shock into fully molecular medium at 25km s^{-1}
- “Testbed” post-shock solution code written using GSL
- Can also investigate effect of transverse B field



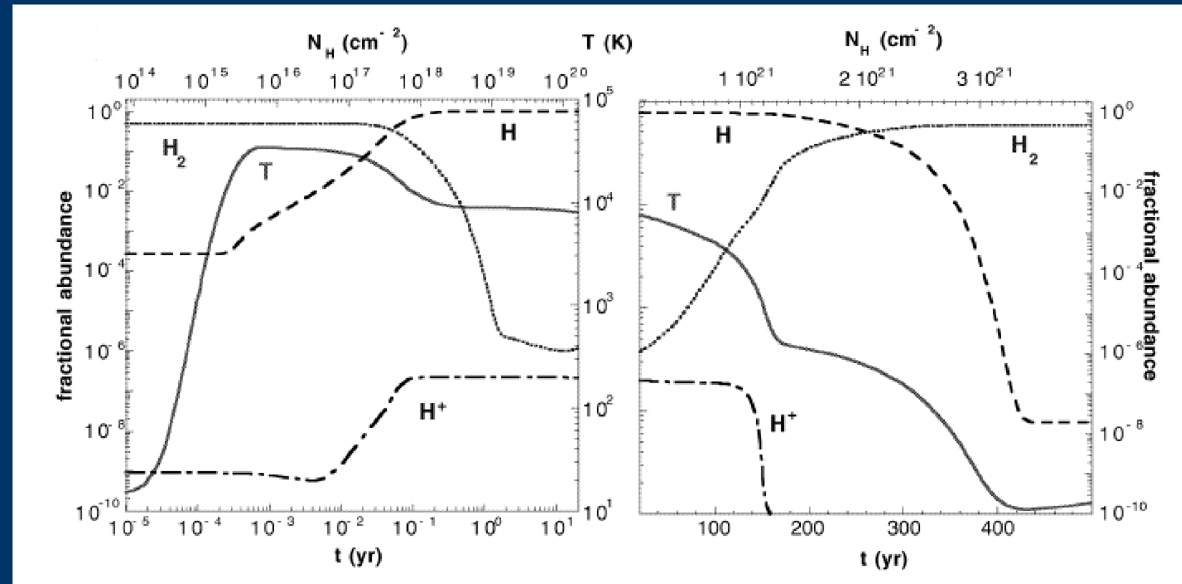
Stationary J-Shock Comparison

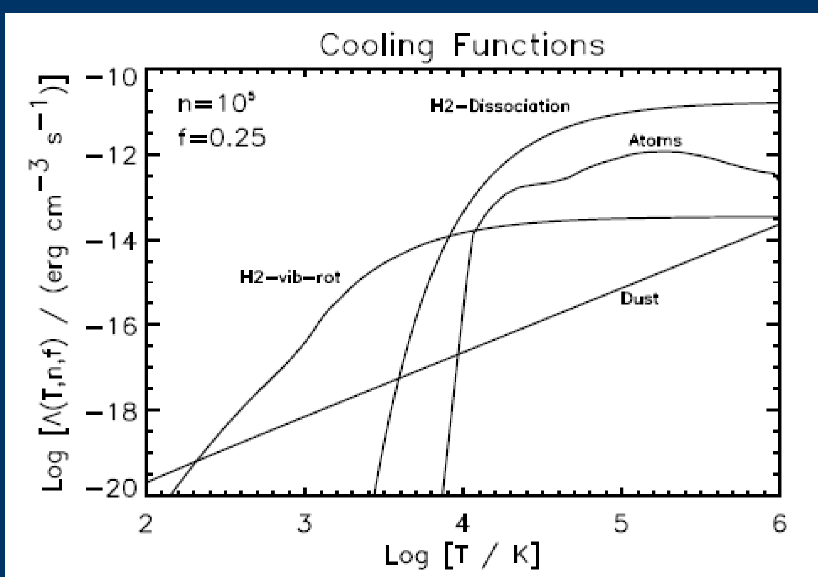
- Initial evolution “fine”, but subsequent evolution is showing two main un-desired features:
  - Time-scale for H2 reformation far too slow
  - Ionisation reaches unrealistic levels
- Both probably have the same explanation:- temperature stays too high for too long -> cooling needs to be reviewed

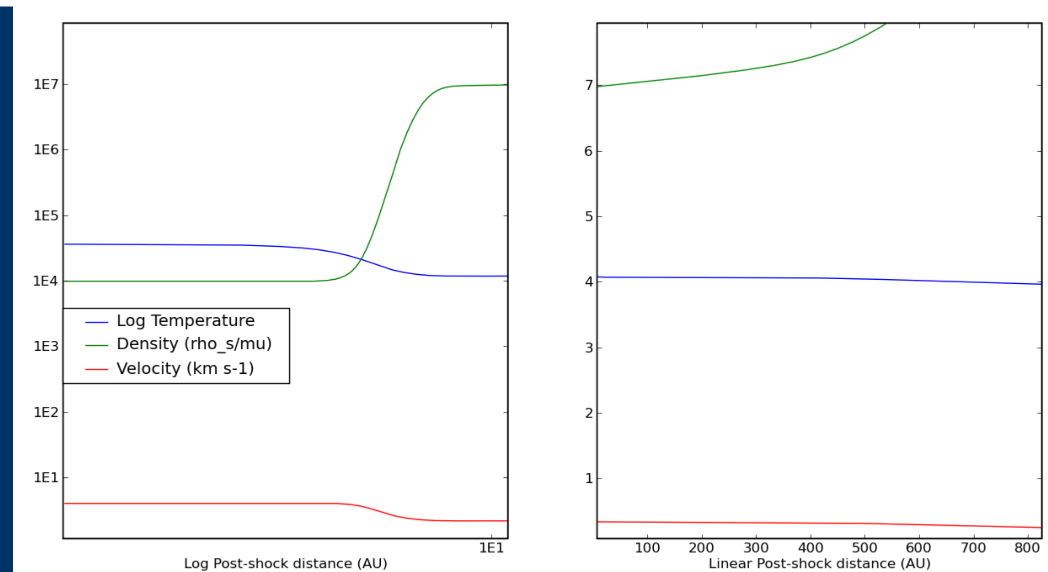


Stationary J-Shock Comparison

- Cooling is too slow despite addition of OI fine structure cooling.
- Currently including H_2 dissociation cooling and H_2-H_2 excitation cooling

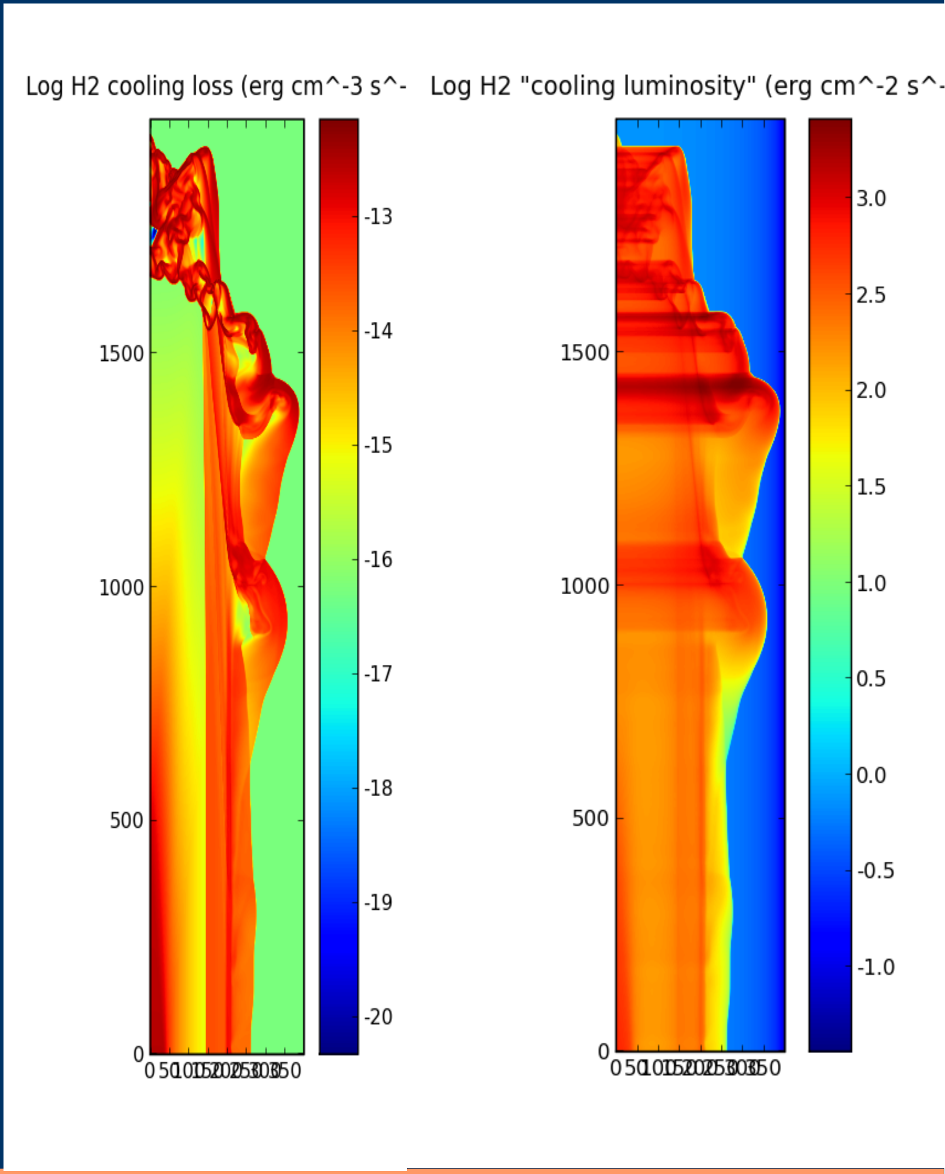






H_2 Emission lines

- Interested in 2.12μm line J1-0 S(1) & 1-0S(3) lines (typically quite strong in observations)
- Given H_2 concentration and temperature output from the model, assume statistical equilibrium (but not LTE) for a 3-vibrational-level H_2 system
- Post-process calculation of level populations as in Suttner et al 1997
- Will be incorporated in the WP5 visualisation pipeline



Conclusion

- Preliminary simulations being carried out with more realistic parameters
- Progress made on refining the model by means of the stationary shock scenario, introducing dust,
- Aiming for a more judicious choice of physical setup for simulations, as well as better estimate of numerical requirements (resolution of cooling/chemistry)
- Large scale simulations with PLUTO AMR on the way...
- Visualisation