IMPULSIVE EJECTION OF GAS IN BIPOLAR PLANETARY NEBULAE

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The assumed flow structure:

- Formation of bipolar PNe during binary interaction at periastron passage.
- Violent mass transfer from AGB to a companion.
- Impulsive jets launched at several 100 km/sec by a companion.
- Jets interact with the AGB extended envelope.
- Acceleration process time $<$ photon-diffusion time. NEW

Optically thin

Radiative cooling time assuming optically thin gas

$$t_{\rm rad} = \frac{5}{2}\frac{nkT}{n_e n_p \Lambda} \simeq 60 \left(\frac{v_j}{1000\ {\rm km\ s^{-1}}}\right)^4 \left(\frac{\dot{M}_f}{10^{-4} M_\odot\ {\rm yr^{-1}}}\right)^{-1} \left(\frac{\delta}{0.2}\right) \left(\frac{r}{1000\ {\rm AU}}\right)^2 {\rm yr}$$

δ is solid angle of the two jets

Flow time:

$$t_{\rm f} \equiv \frac{r}{v_f} \simeq 50 \left(\frac{r}{1000\ {\rm AU}}\right) \left(\frac{v_f}{100\ {\rm km\ s^{-1}}}\right)^{-1} {\rm yr}$$

For adiabatic flow of the fast bipolar outflow:

$$r_{\rm ad} \gtrsim 1000 \left(\frac{\dot{M}_f}{10^{-4} M_\odot\ {\rm yr^{-1}}}\right) \left(\frac{v_j}{1000\ {\rm km\ s^{-1}}}\right)^{-4} \left(\frac{v_f}{100\ {\rm km\ s^{-1}}}\right)^{-1} \left(\frac{\delta}{0.2}\right)^{-1} {\rm AU}$$

The Optically thick phase

(Akashi & Soker 2013, MNRAS)

Photons diffusion time through the dense AGB shell

$$\tau_{\rm diff} = \frac{M\kappa}{4 r_I c} \simeq 0.12 \left(\frac{M_I}{0.1 M_\odot} \right) \left(\frac{r_I}{10 \ {\rm AU}} \right)^{-1} \ {\rm yr}$$

Flow time:

$$t_f = \frac{r}{v_f} = 0.1 \left(\frac{r}{10{\rm AU}} \right) \left(\frac{v_f}{500 \ {\rm km \ s^{-1}}} \right)^{-1} {\rm yr}$$

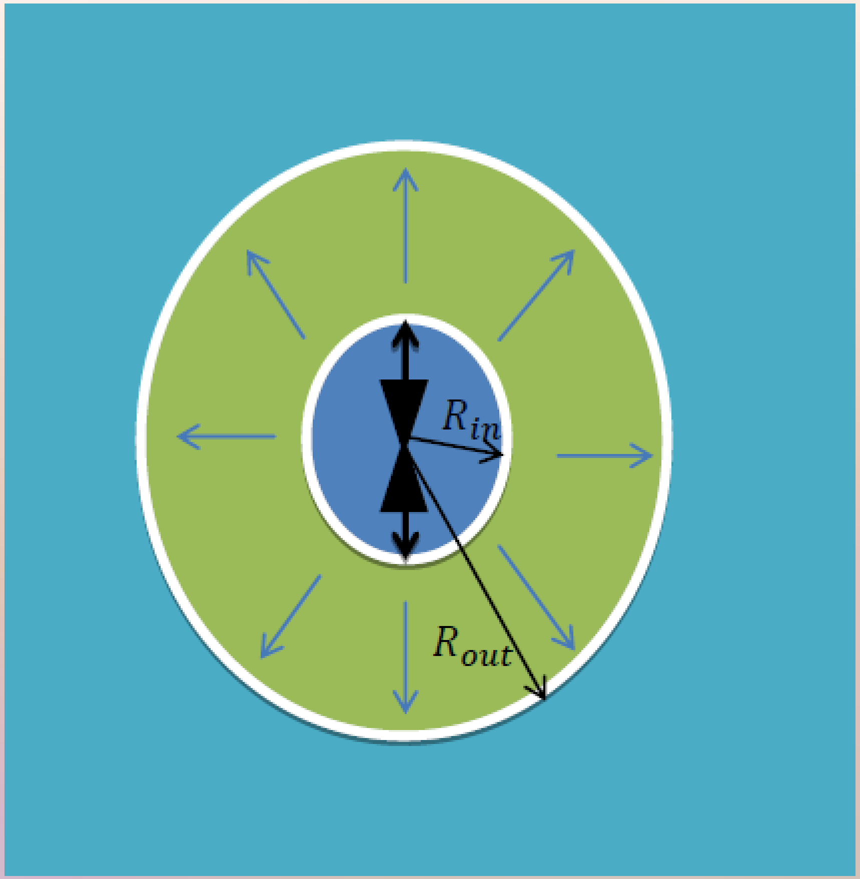
$$\frac{\tau_{\rm diff}}{t_{\rm f}} = \frac{M\kappa}{4 r_I} \frac{v_f}{c} = \pi \tau_r \frac{v_f}{c} \simeq 1.3 \left(\frac{M_I}{0.1 M_\odot} \right) \left(\frac{v_f}{500 \ {\rm km \ s^{-1}}} \right) \left(\frac{r_I}{10 \ {\rm AU}} \right)^{-2}$$

Numerical Setup:

- 3D simulations using Flash code.
- Cartesian grid (x,y,z).
- No gravity.
- Instead of radiative transfer and cooling, we lower the adiabatic index γ to mimic cooling. (Applicable only at the early stages, before adiabatic losses.)
- Several values of γ were tested.

Initial Conditions:

- AGB shell : $M_{shell} = 0.1 M_{\odot}$; $v_{shell} = 10 \frac{km}{\sec}$
- *Jets* : $v_j = 1000 \frac{km}{\sec}$; $\dot{M}_j = 0.13 \frac{M_{\odot}}{yr}$
- *Jets* active for 2 months (total mass in jets $0.02 M_{\odot}$)
- Initial Temperature of shell and jets: 10,000K
- Half opening angle of jets: 50°

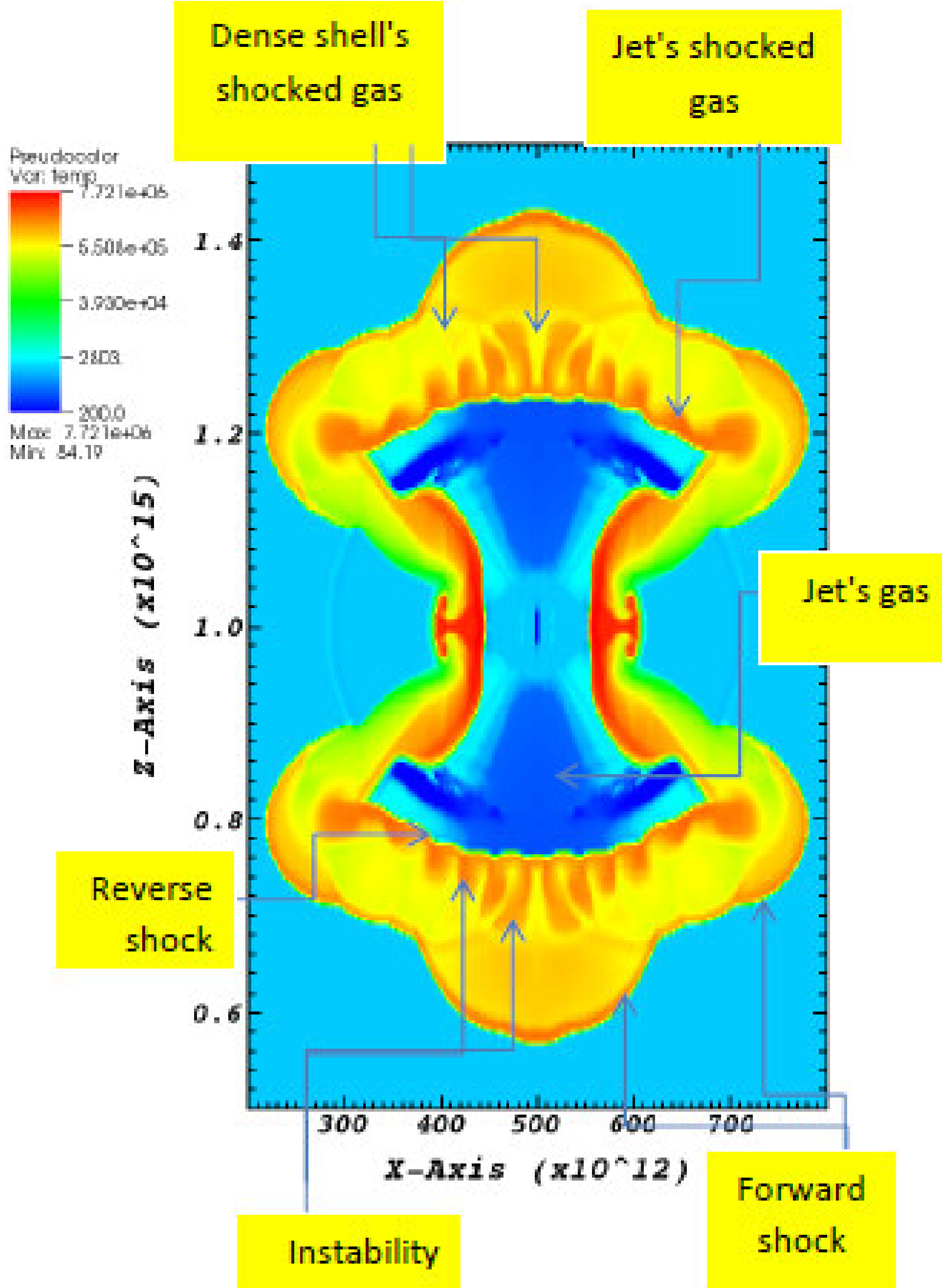


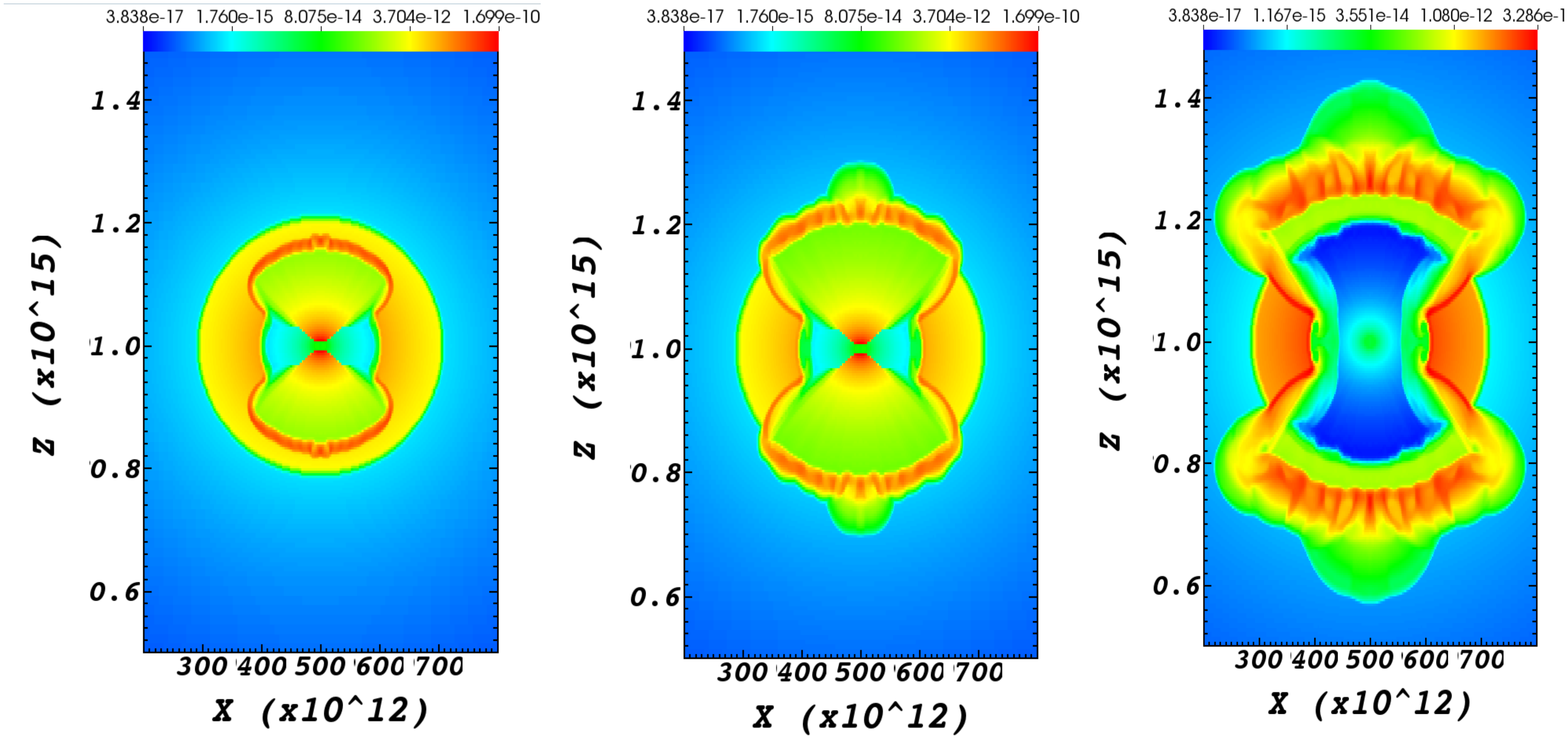
The flow set-up:

- Two opposite jets are launched from near the center starting at t= 0, and are active for two months.
- A spherical dense shell with an outward velocity of 10 km/sec is placed in the region 10^{14} $cm < r < 2*10^{14}$ cm.
- The regions not occupied by the dense shell are filled at t=0 with a low density wind radially expanding with a velocity of 10 km/sec.

The temperature map (log scale) for the run with γ=1.1 at t=76 days.

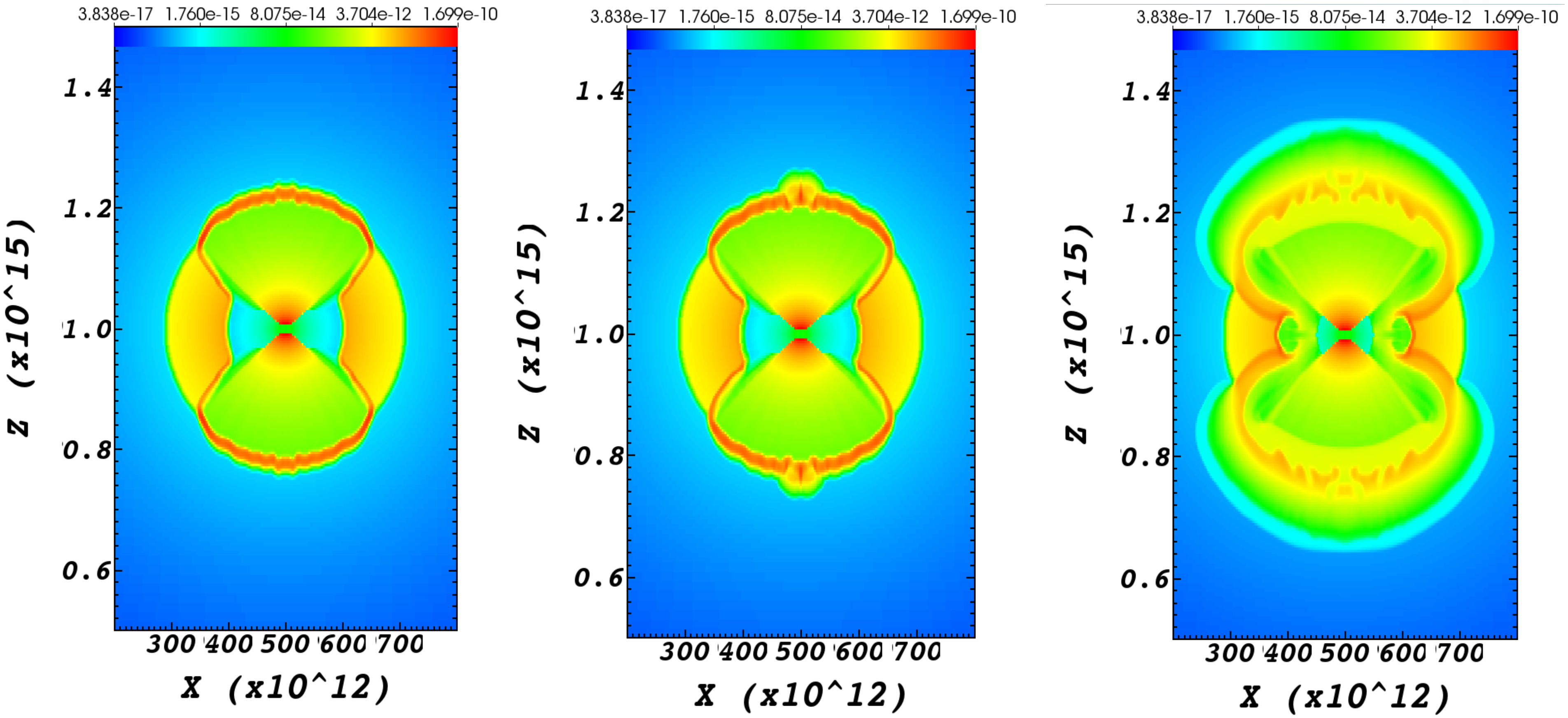
(We simulate the entire space and apply no symmetry-folding.)





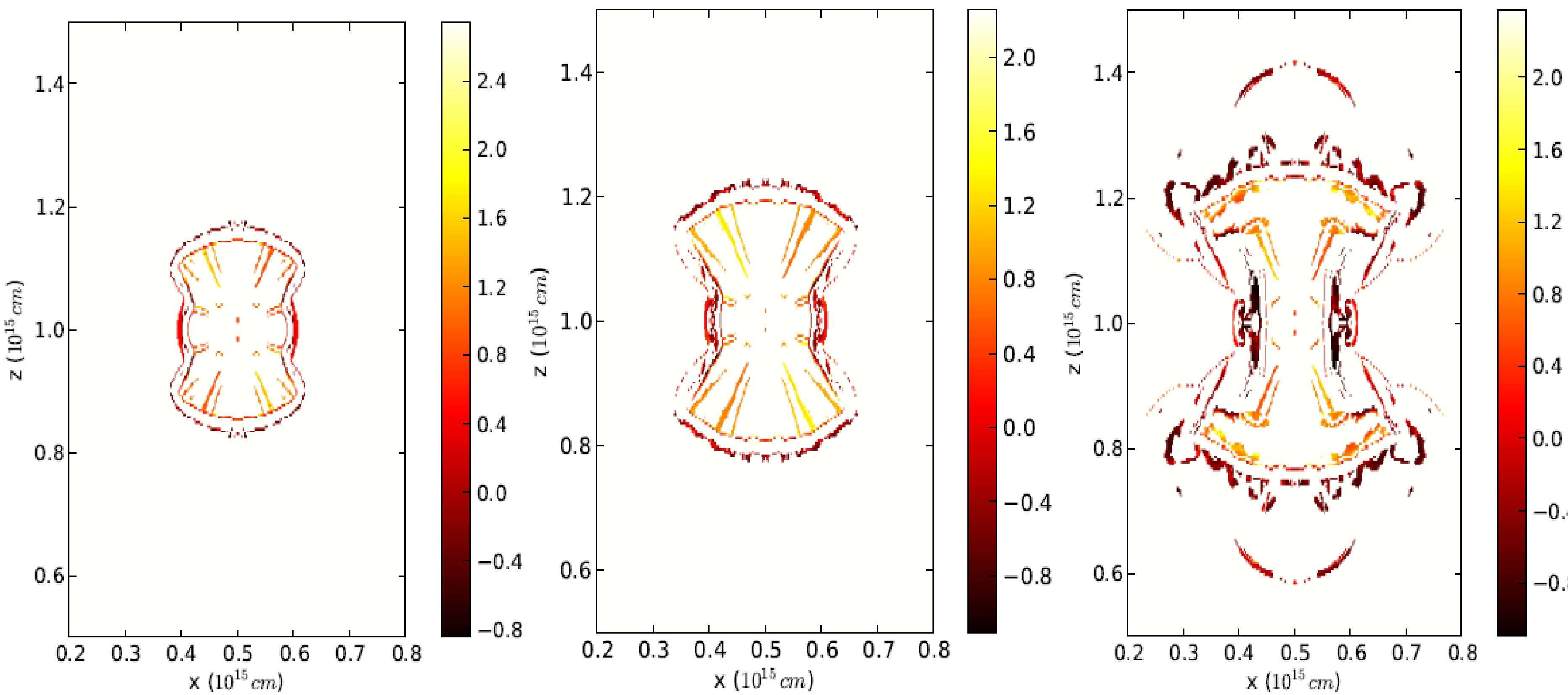
The density maps (log scale) at three times for the $\gamma = 1.1$ run.

Color coding is in $g\ cm^{-3}$.
Times: 34.5, 57.6, 76.1 days.
Units on the axes are in cm.



Three density maps (log scale) at t=57.6 days for γ : 1.02, 1.05, and 1.67.

Units on the axes are in cm.



- The ratio of the Rayleigh-Taylor instability growth time to the time of the simulation (log scale) for $\gamma = 1.1$.
- Red regions are less stable.
- In yellow regions the instability growth time is long.
- White regions are stable.

Summary

We simulated a new regime in jets-AGB wind interaction where the photon diffusion time must be considered.
Our main findings:

- Instabilities developed and dense ‘fingers’ are formed very close to the binary system.
- At much later times a bipolar PN with clumpy lobes and a linear distance-velocity (v=K r) relation will be observed.
- Possible candidates for this scenario: NGC 6302

Meaburn et al 2008, MNRAS
Szyszka et al 2011, MNRAS

Supplements

Numerical Setup:

- 3D simulations are performed Flash code.
- AMR :(7 levels, 2^10 cells in each direction)
- Cartesian grid (x,y,z) with outflow BC at all boundary surfaces.
- Neither gravity nor radiative cooling included as the interaction region is optically thick.
- Instead of calculating radiative cooling and radiative transfer, that are too complicated, we lower the adiabatic index gamma to mimic cooling by photon diffusion.
- We simulate several values of the adiabatic index gamma.