3D Radiative Transfer models of Planetary Nebulae with CRONOS and CLOUDY

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Abstract:
We present our ideas about a new setup for a full 3D radiative transfer hydrodynamic (RT-HD) computation for planetary nebulae (PNe). The setup is based on the 3D MHD code CRONOS, using low dissipative conservation numerical schemes for hydrodynamics and MHD (Kissmann et al. 2008, MNRAS, 391, 1577), and on CLOUDY (Ferland et al. 2013, RevMexAA, 49, 137).
New to our ideas is the implementation of CLOUDY for the radiative terms. While in previous works internal cooling was calculated using analytical cooling curves from Dalgarno & McCray (1972, ARA&A, 10, 375) for the lower temperatures and from Gerritsen & Icke (1997, A&A, 325, 972) for the high temperature regime, we intend to use the sophisticated physics of CLOUDY in a similar way as for CLOUDY 3D (Morisset 2011, ASCL, 03015). The hydrodynamic calculations provide the density and velocity structure. Repeatedly, a CLOUDY model is calculated to derive cooling, absorption and radiative pressure acceleration terms for the hydro code.
We show the feasibility of this setup for symmetric and asymmetric geometries of PNe. Euclidean grids are used to avoid imprinting. We present first tests for this setup and results on the numerical stability. These simulations were run using different geometries, like e.g. disks. Another group is working on 3D hydrodynamic models of particle acceleration in radiatively driven colliding winds of massive star binary systems (Reitberger et al. 2013, submitted to APJ). Although this is a completely different energy regime, binary systems are of great interest for asymmetric PNe as well. The setup allows us simulations using any arbitrary geometry.

Our setup:
The heart of our setup is CRONOS, allowing arbitrary hydrodynamics and MHD simulations. The CRONOS code (Kissmann et al. 2008, MNRAS, 391, 1577; Kleimann et al. 2009, AnGeo, 27, 989) is a finite-volume MHD code optimized for the simulation of compressible astrophysical plasmas. The code is second-order accurate in space and allows for Cartesian, cylindrical, and spherical grid layouts. CRONOS uses approximate Riemann solvers for the time integration of the HD and MHD equations.
Currently we consider hydrodynamics as sufficient. CRONOS allows us to implement modules on top of its hydrodynamic simulation code. As next step we are extending our model by an interface to CLOUDY, to establish a full 3D radiative transfer calculation additional to the hydrodynamics. CLOUDY will only be invoked from time to time to calculate the required values for the radiative transfer in our model.
We do not focus on the origin of the CSPN wind. So the inner part of the nebula, the region where the CSPN is located, is implemented as a pre-determined source term of the model. Here we rather focus on the evolution of the outer regions of the nebula.

Tests of our setup:
The initial steps were to test our model environment and the numerical stability of CRONOS. For this we built a set of different test cases. The first case was to check if the mass-loss-rate stays constant within the region of interest. Therefore we considered an isothermal stellar wind. For this test we filled the whole area with an initial, but unphysical density function (we picked a $1/r$ -function). With this density function we have let the model evolve. For an isothermal stellar wind the mass-loss-rate for each shell must be the same. In figure 1 the resulting constant mass-loss-rate is shown.
In a subsequent test, we added a torodial disk with a density contrast of 1:10 around the CSPN-region. The still isothermal wind collides with the inner edge of this disk. After some time we can see a bipolar, jet-like outflow and the initial disk diffuses (see figure 2).

Outlook:
Currently we use the full energy equation instead of the (unphysical) isothermal model. Additionally we implement gravity as a source term and add a full treatment of the self-gravity field. As final steps we will implement the radiative transfer using CLOUDY. By this we will get a very sophisticated model of the evolution of the outer PN regions.

Results:
The tests of a constant mass-loss-rate $\dot{M} = 4\pi r^2 \cdot \rho(r) \cdot v(r)$ resulting from a given unphysical initial condition works very well (see figure 1) and the simulation of an evolving disk around the CSPN is promising (see figure 2).
In the second test we can see evolving jet-like structures from the high-density disk. These jet-like outflows may be a hint, why we can't see disks around the rather weak bipolar nebulae, although they could have evolved during the AGB-phase. This topic needs further investigations.
The goal of this project is to establish a general simulation environment. We intend to extend our model from spherically symmetric to general asymmetric initial conditions. The whole evolution of the outer regions of PNe will be investigated including both hydrodynamics and radiative transfer.

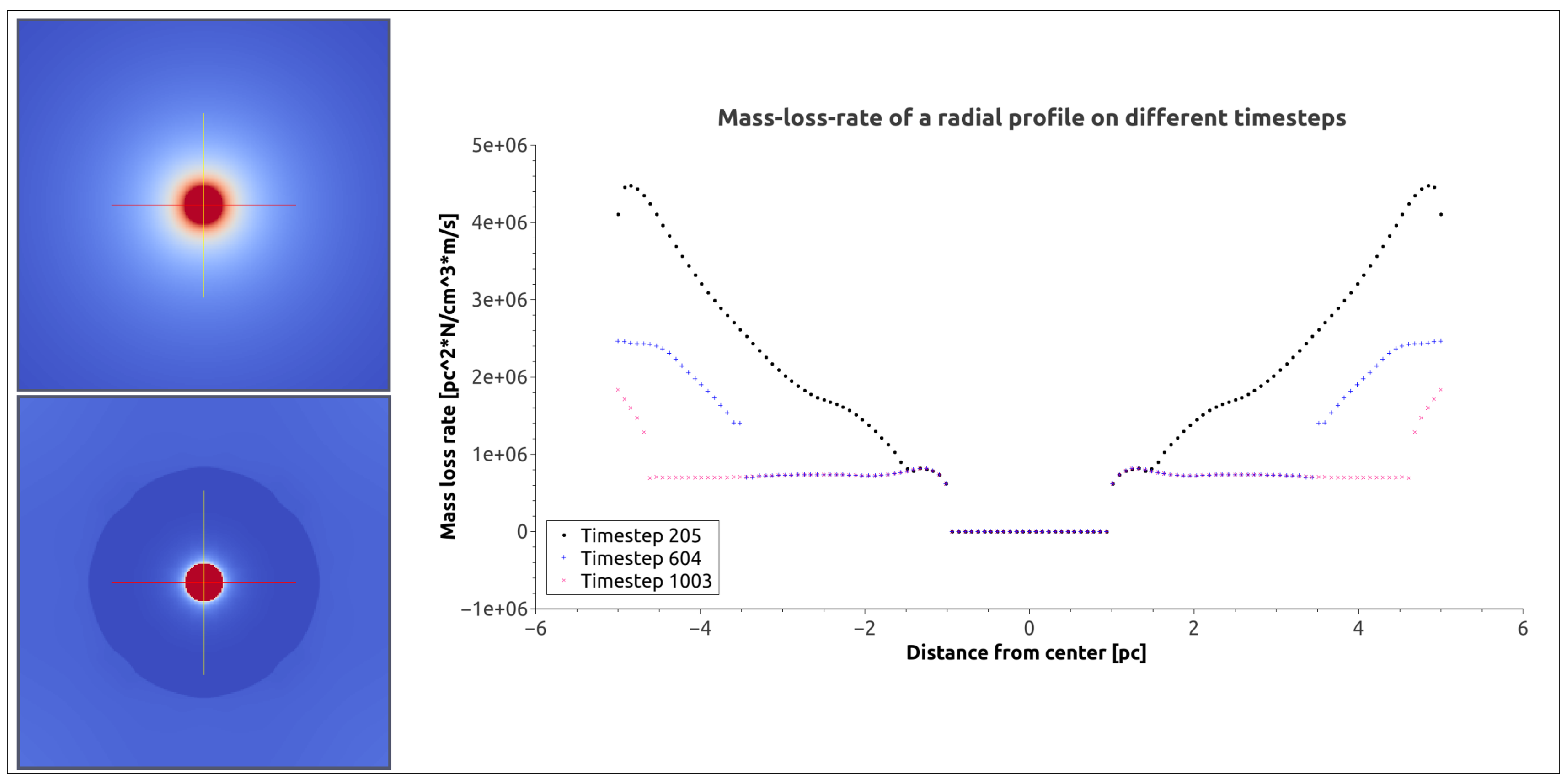

Figure 1:
On the left we show two density profiles at time-steps t = 0 (top) and t = 604 (bottom). On the right the test of the evolution of the mass-loss-rate for different time-steps is shown. The development from the rather unphysical initial condition to an (almost) constant mass loss rate is illustrated.

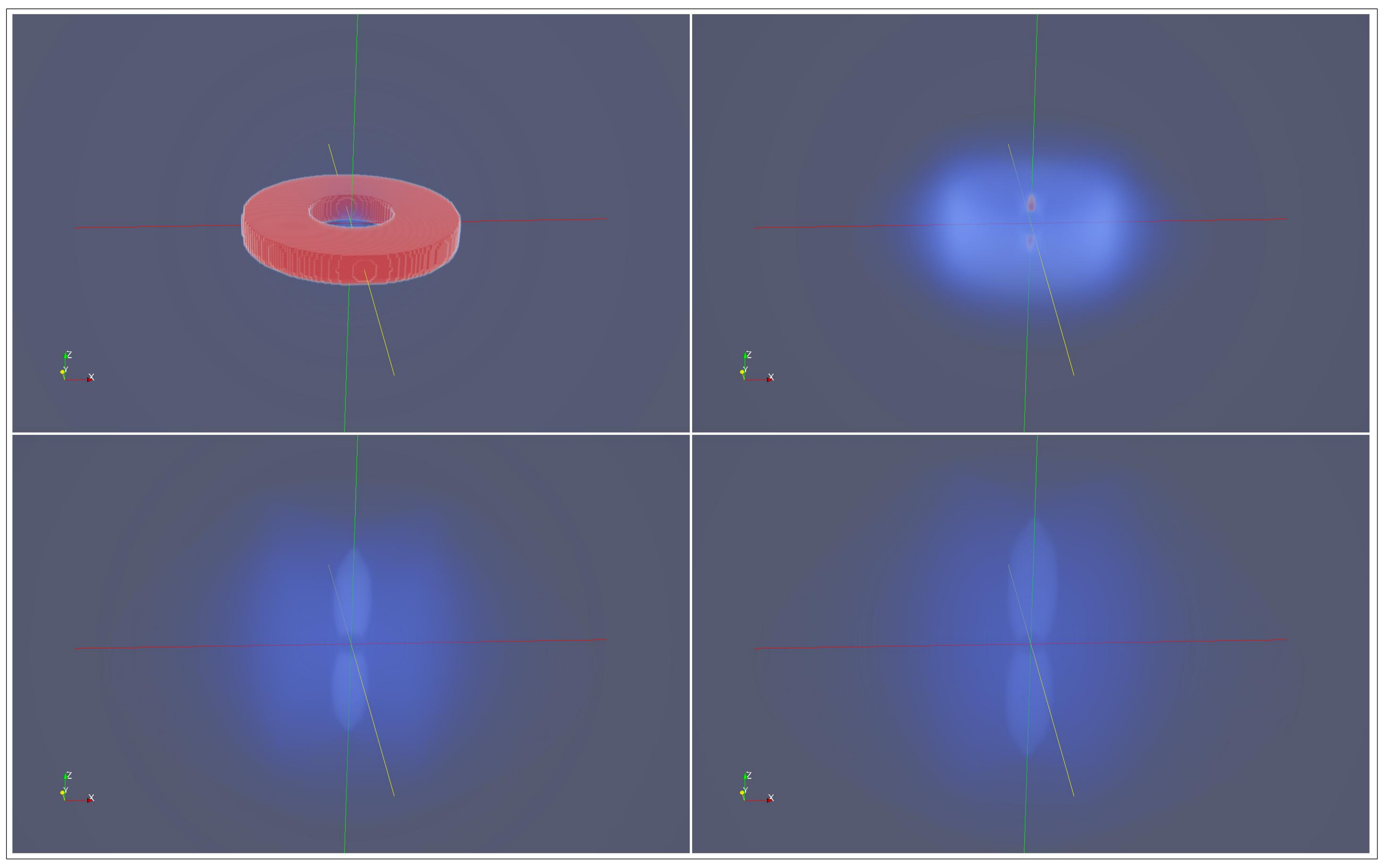

Figure 2:
Evolution of an initial high-density disk interacting with an isothermal stellar wind. The upper left panel shows a rendering of the initial conditions after a few time-steps (therefore a bit smeary), the disk is clearly visible. The following panels show the evolving jet-like structures at different times. While these jet-like features become more observable, the disk diffuses more and more. The model is still an isothermal hydrodynamic simulation without gravity. Up next we intend to add the full treatment of the energy equation in our hydrodynamic models.

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