High-resolution simulations and visualization of protoplanetary disks

Paweł Ciecieląg, Tomasz Plewa, Michał Różyczka
Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716
Warsaw, Poland

Abstract.
A problem of mass flow in the immediate vicinity of a planet embedded in a protoplanetary disk is studied numerically in two dimensions. Large differences in temporal and spatial scales involved suggest that a specialized discretization method for solution of hydrodynamical equations may offer great savings in computational resources, and can make extensive parameter studies feasible. Preliminary results obtained with help of Adaptive Mesh Refinement technique and high-order explicit Eulerian solver are presented. This combination of numerical techniques appears to be an excellent tool which allows for direct simulations of mass flow in vicinity of the accretor at moderate computational cost. In particular, it is possible to resolve the surface of the planet and to model the process of planet growth with minimal set of assumptions. Some issues related to visualization of the results and future prospects are discussed briefly.

1. The Method
Extremely small temporal and spatial scales involved in the problem of accretion onto a protoplanet necessitate the use of nonuniform discretization in the vicinity of the accretor. In our study we used adaptive mesh refinement (AMR) method combined with a high-resolution Godunov-type advection scheme (AMRA, Plewa & Müller 2000). The AMR discretization scheme follows the approach of Berger and Colella (1989). The computational domain is covered by a set of completely nested patches occupying levels. The levels create a refinement hierarchy. As one moves toward higher levels, the numerical resolution increases by a prescribed integer factor (separate for every direction). The net flow of material between patches at different levels is carefully accounted for in order to preserve conservation properties of hydrodynamical equations. Boundary data for child patches are either obtained by parabolic two-dimensional conservative interpolation of parental data or set according to prescribed boundary conditions.

Hydrodynamical equations are solved with the help of the Direct Eulerian Piecewise-Parabolic Method (PPMDE) of Colella & Woodward (1984), as implemented in HERAKLES solver (Plewa & Müller 2000). Simulations have been done in spherical polar coordinates in a frame of reference corotating with the protoplanet. HERAKLES guarantees exact conservation of angular momentum...
which is particularly important in numerical modeling of disk accretion problems. The use of its multifluid option with tracer materials distributed within disk (not presented here) allows to identify the origin of the material accreted onto protoplanet. The AMRA code is written purely in FORTRAN 77 and has been successfully used on both vector supercomputers and superscalar cache-oriented workstations. Its parallelization on shared memory machines exploits microtasking (through the use of vendor-specific directives) or the OpenMP standard.

2. Simulation setup

The computational domain extends from 0.25 to 2.5 radii of the planet’s orbit. We employ 7 levels with refinement ratios ranging from (2,4) to (4,4). The base level contains the protoplanetary (circumstellar) disk while the 7th level contains the planet and its immediate vicinity. The base grid consist of 128 \times 128 cells uniformly distributed in \( r \) and \( \theta \). The effective resolution at the 7th level is 131072 \times 524288 in \( r \) and \( \theta \), respectively. The topmost five levels are schematically shown in Figure 1. White lines are boundaries of the patches. There are 1, 1, 1, 12, 4 and 49 patches at levels 1-7, respectively. The structure of the grid at level 7 is shown in Figure 2f with individual cell boundaries drawn.
Figure 2. Surface density distribution in the final model (frames (a)-(e)) and the distribution of grid cells at level 7 in the vicinity of the planet (frame (f)). There are \( \sim 8 \) grid cells in the radius of the planet.
with white lines (the dark blue circle shows size of the planet).

3. Physical model

The simulation is initialized with a Keplerian disk. Originally the disk has a mass of 0.01 $M_\odot$, constant $h/r$ ratio of 0.05 and surface density proportional to $r^{-1/2}$. The temperature is a fixed function of $r$ throughout the simulation. There is no explicit viscosity in the disk. At the outer and inner boundary of the base grid the gas is allowed to flow freely from the computational domain. No inflow is allowed for. The accretion onto the planet is accounted for in a very simplified way. At every time step the mean value of the density within two planetary radii is calculated, and whenever it is higher then a preset value, the excess gas is removed. At $t = 0$ a planet of one Jupiter mass in inserted into the disk on a circular orbit. The radius of the orbit and the mass of the planet remain constant throughout the simulation. The disk is allowed to evolve for 100 planetary orbits. A gap is cleared in it, and a secondary, circumplanetary disk is formed.

The sequence of surface plots in Figure 2 shows the final structure of both disks (the surface density distribution is displayed). The red peak in Figure 2a is the unresolved image of the very dense circumplanetary disk. We have been able for the first time to see the details of the latter (Figures 2(c)-d). The streams of gas flowing across the gap from left and right edge of the frame (light blue) collide with the outer part of the circumplanetary disk. The collision regions (green wedges) bear strong resemblance to hot spots in cataclysmic binaries. In every region two strong shock waves are excited, one of them propagating into the stream, and the other into the disk. The shocked gas flows from the collision region along a loosely wound spiral towards the planet ((Figure 2e). This picture is significantly more detailed than the one recently published by Lubow, Seibert, & Artymowicz (2000). Streamlines of the flow around the planet are shown in Figure 3 and they are in good accordance with those of Lubow et al.

Our simulation is of preliminary nature, and its sole purpose is to demonstrate the capabilities of AMRA. Currently, we are improving the physics of the model. One of the problems we are going to attack is the calculation of the accurate value of the gravitational torque from the disk onto the planet in the phase preceding gap formation.

4. Visualization

To visualize the complicated AMRA output, we have chosen the AVS/Express environment for visual programming. It allows the user to quickly build simple applications employing standard library modules. Advanced users can develop their own, highly specialized modules and applications. Our AMRA-visualization application (VISA) is partly based on modules written by Favre, Walder, & Follini (1999), which have been substantially modified, and partly on our own modules. A screenshot of VISA is shown in Figure 4. The panel and the viewer are contained in the two topmost windows, while the bottom window contains the AVS/Express programming platform. Currently we are able to read the AMR
Figure 3. Streamlines of the flow near the circumplanetary disk.

Figure 4. A screenshot of the visa application.
data, extract components, perform mathematical operations on data sets and coordinates, extract any subset of levels or patches, and apply to them various visualization techniques (e.g., 2-D plot, surface plot, isolines, slice). Streamlines can also be calculated. The application is still under development, and new options are being added.

**Acknowledgments.** This research is supported by the Polish Committee for Scientific Research through the grant 2.P03D.004.13.

**References**

Berger, M. J., & Colella, P. 1989, J. Comput. Phys., 82, 64
Colella, P., & Woodward, P.R. 1984, J. Comput. Phys., 59, 264
Plewa, T., & Müller, E. 2000, Comp. Phys. Commun. (in preparation)
Lubow, S.H, Seibert, M., & Artymowicz, P. 2000, ApJ (astro-ph/9910404)
Favre, J. M., Walder, R., & Follini, D. 1998, in Proceedings, 40th Cray User Group Conference, Stuttgart, Germany (June 1998)