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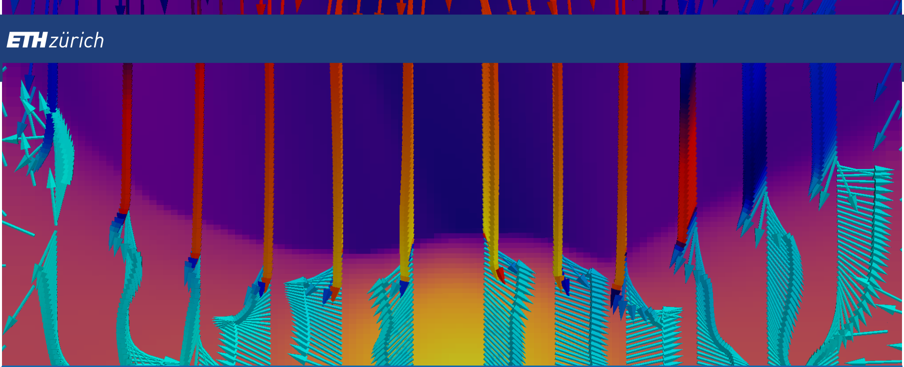

Visualising JUPITER Hydrodynamic Simulations using Paraview and VTK

Evert Nasedkin

Supervised By:

Dr. Judit Szulágyi and Prof. Hans Martin Schmid

Introduction

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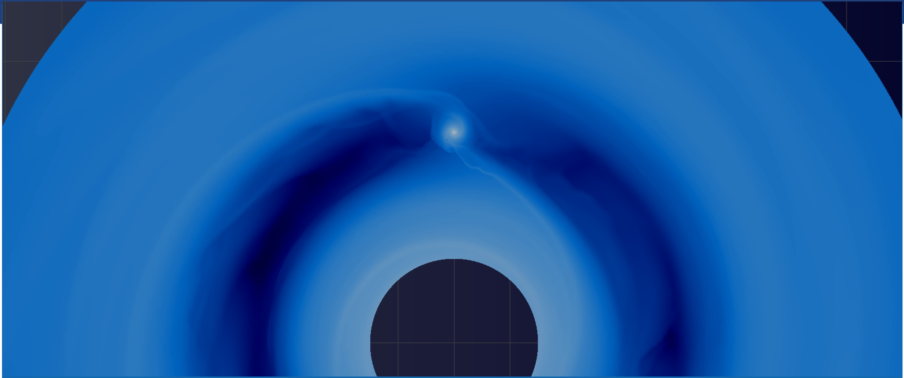
- Modern 3D hydrodynamic simulations help us explore the environment of circumstellar and circumplanetary disks, providing insight into the formation process.
- The goal of this project was to process data from the `JUPITER` simulations and create effective visualisations for studying the outputs.

Outline

1. JUPITER
2. Data Processing
3. Visualisation
4. Science Results
5. Concluding Remarks



Density field of a protoplanetary disk.

JUPITER

JUPITER Hydrodynamic Simulations

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- It is based of a Godunov [3] finite volume method for solving conservation equations on cell surfaces by solving the Riemann problem across the cell boundaries.

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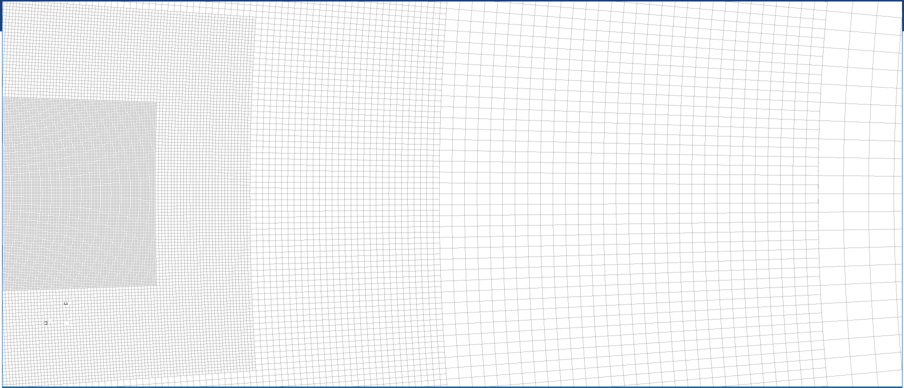
- The solutions are interpolated between mesh levels to improve computation time
- However, using multiple mesh levels adds a much higher level of complexity, as multiple boundary conditions must be defined, and overlapping regions dealt with. Each program will have different requirements for how to write and render multiple mesh levels.



Adaptive mesh grid used in JUPITER simulations

Data Processing

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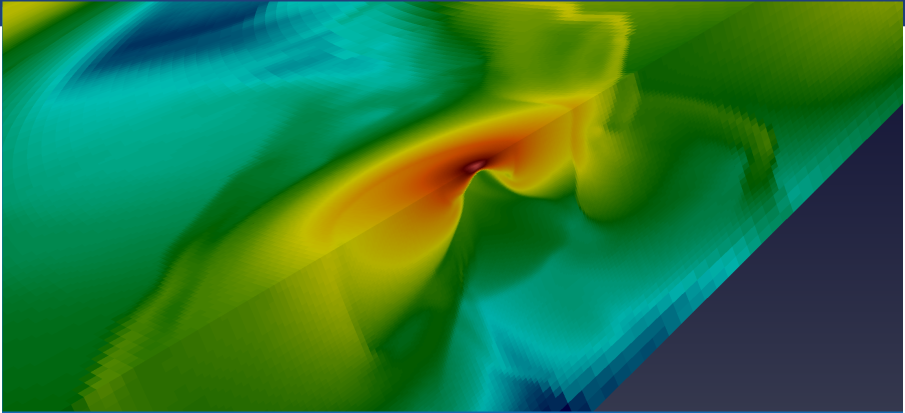
- Each vertex of each cell was indexed to the grid points read in from the output file. Any cell from an outer layer that overlapped with a finer mesh level was rejected, and the data point associated with that cell filtered out.
- Hydrodynamic fields were converted to CGS units, and velocity vector fields were transformed from spherical to Cartesian coordinates



3D Visualisation using Paraview

Visualisation

Paraview

- Paraview is an open-source visualisation program designed for dealing with large datasets [6].

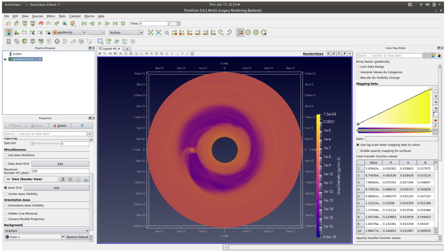


Figure: 2 Paraview user interface.

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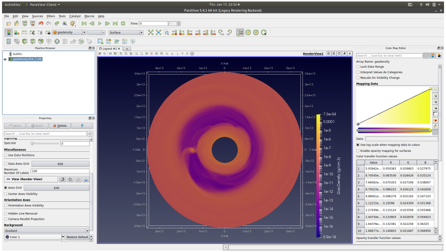
- In general, data is read in as a VTK file, processed with various filters and outputs a rendered image.



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Paraview

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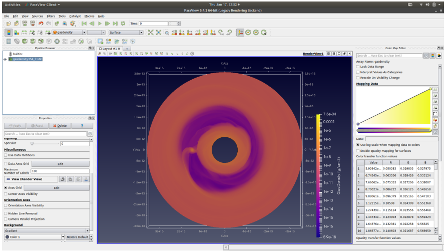

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Paraview

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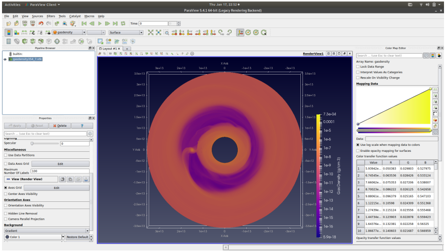
- The user guide is 250 pages long, so unfortunately I don't have time to go into much depth.



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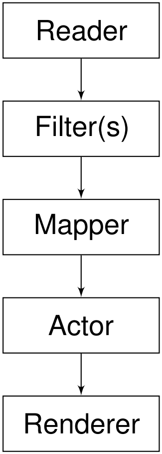
VTK Pipeline



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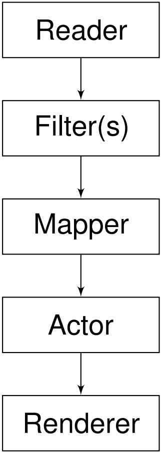
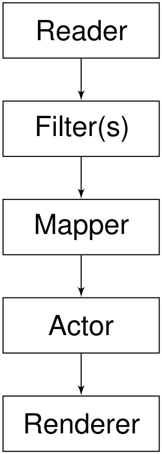


Python VTK

- Paraview is a wrapper for the VTK C++ library, which also has a Python interface [7]
- This can be used to automate renders, with similar outputs to Paraview.
- In addition, the Python VTK libraries can be used to convert VTK files to numpy arrays, which can be used to generate publication quality plots using matplotlib.

VTK Pipeline



Numpy and Matplotlib

- VTK files can be converted to numpy arrays using the vtk_to_numpy module.

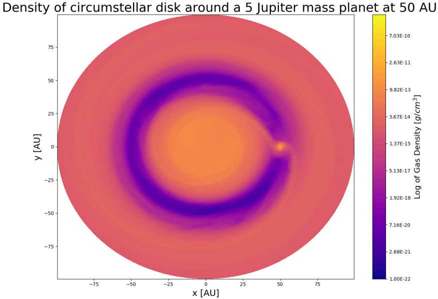


Figure: 3 Mid-plane density of a circumplanetary disk plotted using matplotlib.

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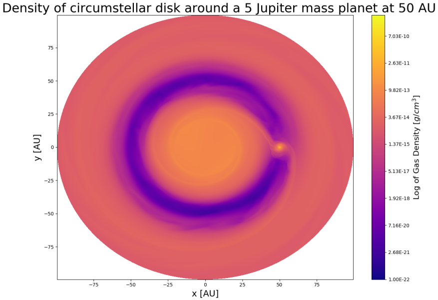
- 2D plots can be made using the pyplot.tricontrouf() function.



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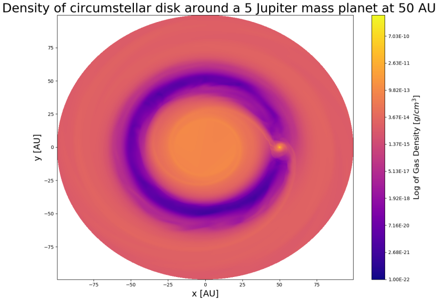
Numpy and Matplotlib

- VTK files can be converted to numpy arrays using the vtk_to_numpy module.
- 2D plots can be made using the pyplot.tricontrouf() function.
- However, this method is of limited use, as many matplotlib functions require regridding of data, which results in large (many GB) memory usage.



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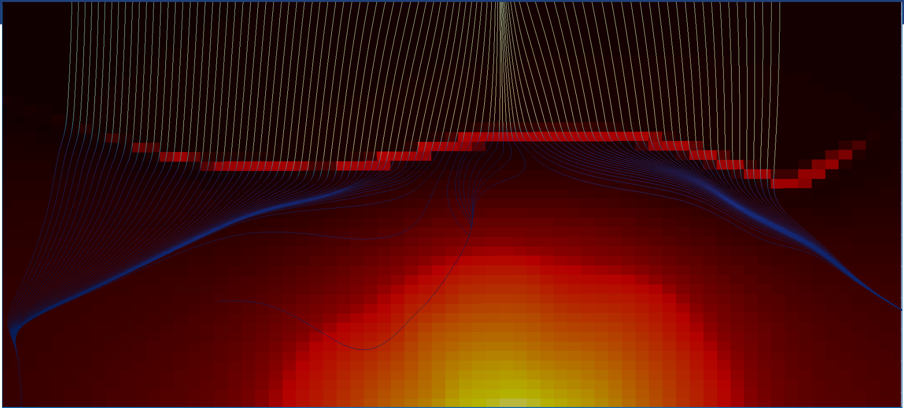

High temperature shock front near an accreting planet

Science Results

Circumplanetary disks are de-accretion disks

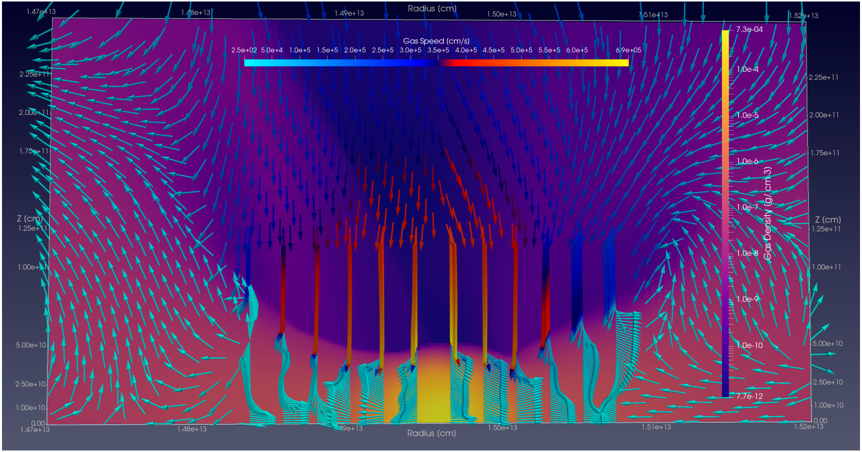

Figure: 4 Vertical of infall of gas onto the CPD. Velocities are projected onto the xz plane.

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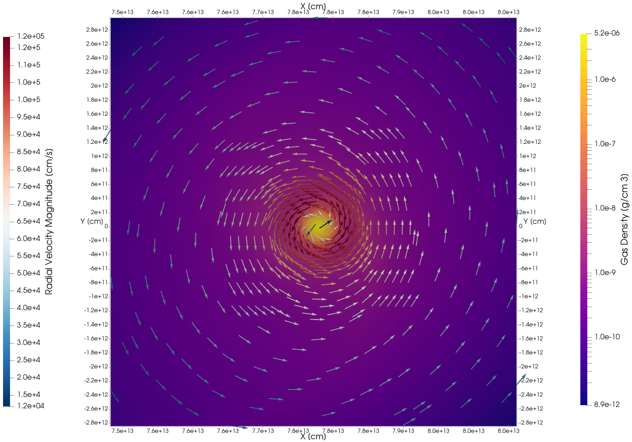

Figure: 5 Spiral outflow of the circumplanetary disk. Velocities are projected onto the xy plane.

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- Inflow of gas towards the circumplanetary disk is from the vertical direction.
- Gas spirals outwards in the CPD before being recirculated into the CSD.
- At 20 planet radii, where inflowing and outflowing gas meet, a dust trap is formed, providing a location for planet formation [8].

Inflowing gas shocks as it approaches the planet

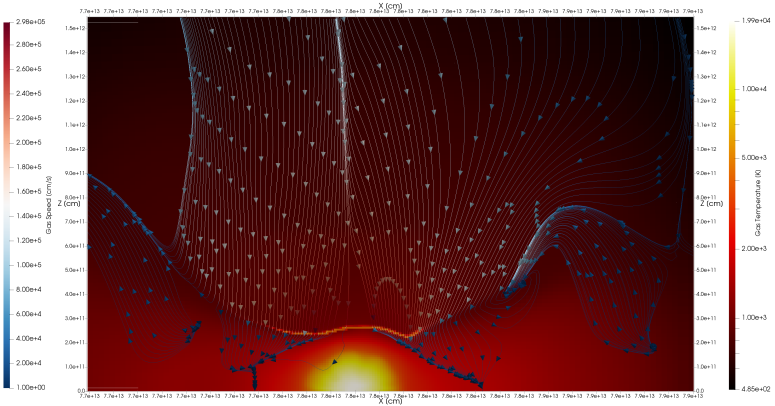

Figure: Infalling gas shocking on the upper boundary of the CPD.

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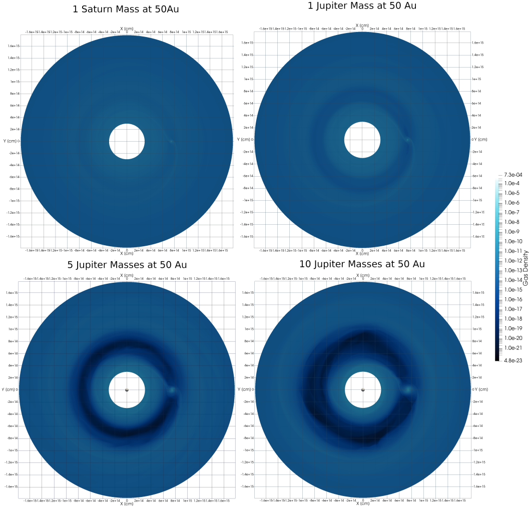
- Gas surrounding the planet is heated through the accretion process, undergoing adiabatic compression, increasing the pressure.
- Inflowing gas is accelerated towards the planet, before shocking onthe CPD surface, and losing some of its energy to heat.
- This high temperature shock may induce ionization of the inflowing gas, though this is dependant on the planet mass (and therefore the speed of the incoming gas).

Gap width and depth is influenced by planet mass



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Gap width and depth is influenced by planet mass

- From $1M_J$ to $10M_J$ at 50 AU, we see the gap width increase by a factor of 2, and the minimum density drop by 4 orders of magnitude.
- Small scale structure, such as spiral arms and asymmetries are more visible in disks with higher mass planets.
- Observable disk features can help derive the properties of embedded planets, therefore it is worth studying them further.

Conclusions

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- Various visualisation techniques have been explored, which is key to understanding and interpreting the results.
- The outputs of the tested simulations support the new picture of accretion, with accreting gas being drawn in vertically, and spiralling outward into the CPD.

Acknowledgements

I'd sincerely like to thank **Dr. Judit Szulágyi** for taking me on for such an interesting semester project. She's been an excellent mentor, and I couldn't have asked for a better supervisor.

I'd also like to thank **Prof. Hans Martin Schmid** for leading the Star and Planet Formation group, and allowing me to be a part of it.

Finally, thanks the rest of the group for putting up with me... and continuing to do so going forward!

References

J. Szulágyi, A. Morbidelli, A. Crida, and F. Masset, "Accretion of jupiter-mass planets in the limit of vanishing viscosity," *Astrophysical Journal*, vol. 782, no. 2, 2014.

J. Szulágyi, F. Masset, E. Lega, A. Crida, A. Morbidelli, and T. Guillot, "Circumplanetary disk or circumplanetary envelope ?," vol. 10, no. May, pp. 1–10, 2016.

S. K. Godunov, "A difference method for numerical calculation of discontinuous solutions of the equations of hydrodynamics," vol. 47 (89), pp. 271–306, 1959.

R. Hockney and J. Eastwood, *Computer Simulation Using Particles*.
CRC Press, 1988.

Visual Toolkit Organization, "VTK File Formats," pp. 1–19, 2009.

J. Ahrens, B. Geveci, and C. Law, *ParaView: An End-User Tool for Large Data Visualization*.
Elsevier, 2005.

L. Avila and I. Kitware, *The VTK User's Guide*.
Kitware, 2010.

M. Cilibrasi, J. Szulágyi, L. Mayer, J. Drazkowska, Y. Miguel, and P. Inderbitzi, "Satellites form fast & late: a population synthesis for the galilean moons," *Monthly Notices of the Royal Astronomical Society*, vol. 480, no. 4, pp. 4355–4368, 2018.

Code

`https://github.com/nenasedk/JUPITER_VTKFileConversion`