Title: Relativistic Magnetohydrodynamic Bondi--Hoyle Accretion

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Abstract: I present a relativistic study of axisymmetric magnetohydrodynamic Bondi--Hoyle accretion onto a moving Kerr black hole. The equations of general relativistic magnetohydrodynamics are solved using high resolution shock capturing methods, involving the use of linearised Riemann solvers. In this study I use the ideal MHD limit, which assumes no viscosity and infinite conductivity. The fluid flow is completely specified by the adiabatic constant $Gamma$, the asymptotic speed of sound c_s^infty, and the plasma beta parameter $beta_P$. In particular I restrict the investigation to asymptotically supersonic flows where $v_infty ge c_rms^infty$. To determine the stability of the flow I measure the accretion rates of the energy, and mass. The models presented in this study exhibit a matter density depletion in the downstream region of the black hole which tends to vacuum in convergence tests. This is a feature due to the presence of the magnetic field, more specifically the magnetic pressure, which is not seen in purely hydrodynamic studies. The models investigated present a tendency towards a steady state, which is in agreement with previous studies performed by Font and Iban'ez (1998) using a purely hydrodynamic model.

Relativistic Bondi–Hoyle Accretion

Black hole accretor

GRMHD -
Bondi–Hoyle
Accretion

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- Michel – Stationary black hole accretor (1972)
- Petrich – axisymmetric accretion, perfect fluid models (1988,1989)
- Font – Axisymmetric and Nonaxisymmetric accretion, perfect fluid models (1998, 1999)
- Blakely – Non-symmetric perfect fluid (2009)
- Farris – BH accretion in binary black hole mergers (2009)
- Dönmez – BH accretion to explain QPO's (2010)
- Very few relativistic treatments, none involve magnetic fields.

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Black Hole Spacetime Backgrounds

We make restrictive assumptions

- Mass and angular momentum accretion rates are insufficient to modify the spacetime considerably

Leaves us with a fixed spacetime background satisfying Einstein's field equations

- Two special cases with closed form solutions
  - Axisymmetric Black Hole, Kerr solution, with parameters M, a
  - Spherically Symmetric Black Hole, Schwarzschild solution, with parameters $M, a \rightarrow 0$

The Matter Model

- We assume the fluid background is an ideal fluid with no shear stress, heat flow, or viscosity.
- $P = (\Gamma - 1)\epsilon\rho_0$
- Perfect conductor limit (infinite conductivity)
  $\rightarrow F^{\mu\nu} u_{\nu} = 0$
- Ideal Magnetohydrodynamics

Equations of Motion

- $\nabla_\mu J^\mu = 0$ – Conservation of baryon density
- $\nabla_\mu T^{\mu\nu} = 0$ – Conservation of total stress-energy
- $\nabla_\mu \left({}^*F^{\mu\nu} \right) = 0$ – Maxwell equations

Use ADM variables to reduce these to a set of coupled partial differential equations

Numerical Route

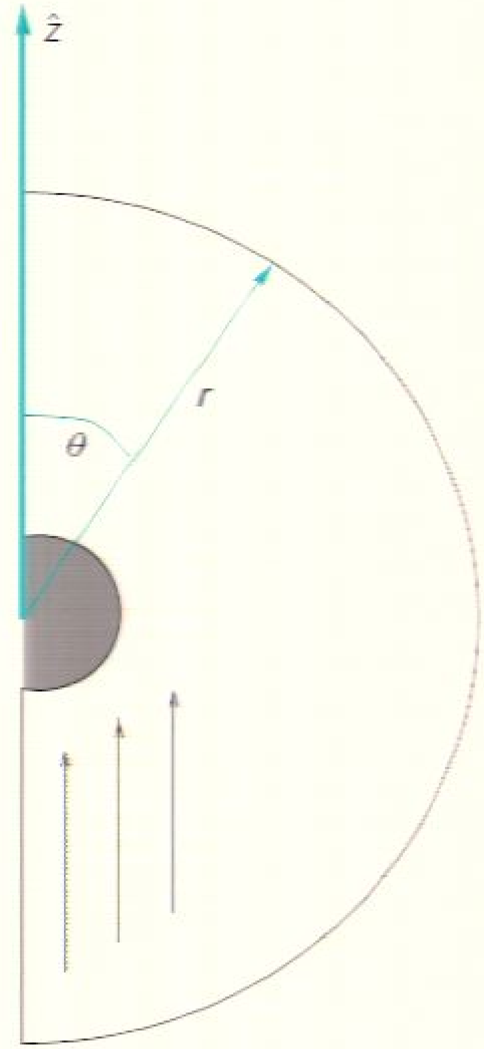
Valencia Formulation

$$\partial_t \mathbf{Q} + \partial_i \mathbf{F}^i(\mathbf{Q}) = \mathbf{S}(\mathbf{Q})$$

- Finite volume high-resolution shock-capturing techniques to discretize
- Captures shocks, integrates equations of motion ove discontinuous data sets
- HLL flux approximation
- Second order Runge–Kutta time integration

Hyperbolic divergence cleaning $\Rightarrow \nabla \cdot \mathbf{B} = 0$

Geometric Setup - Axisymmetry



Flow is fully specified by fou asymptotic parameters:

- Speed of sound c_S^∞
- Adiabatic Constant Γ
- Black hole velocity v_∞
- Plasma beta β_P^∞

Magnetohydrodynamic Axisymmetric Accretion, Soft Fluid, Zero Spin

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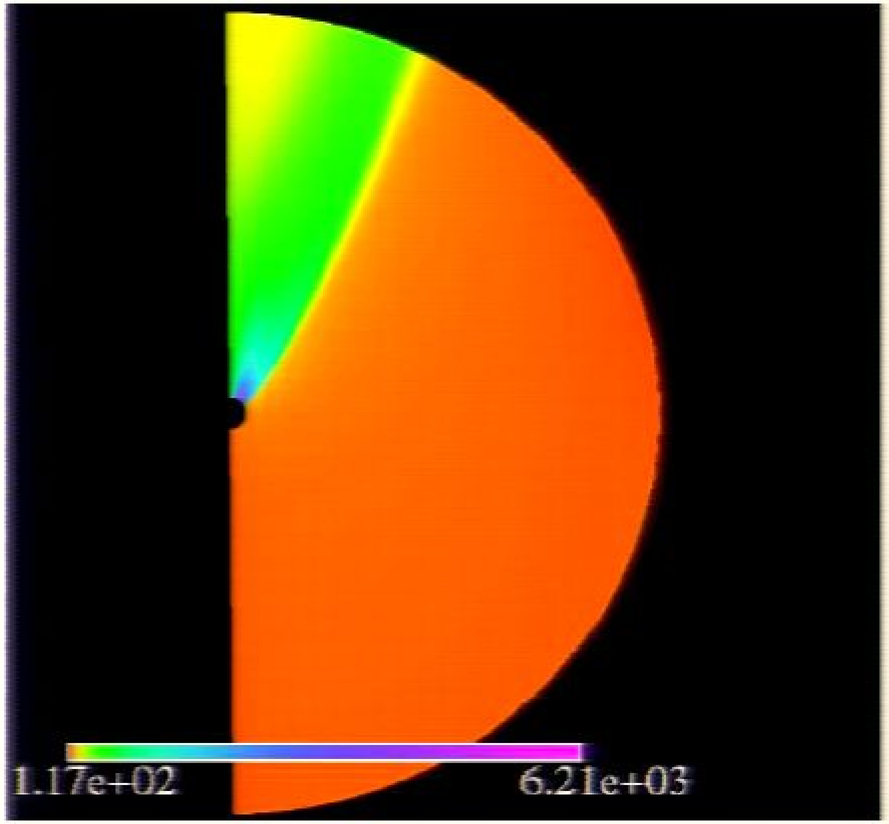
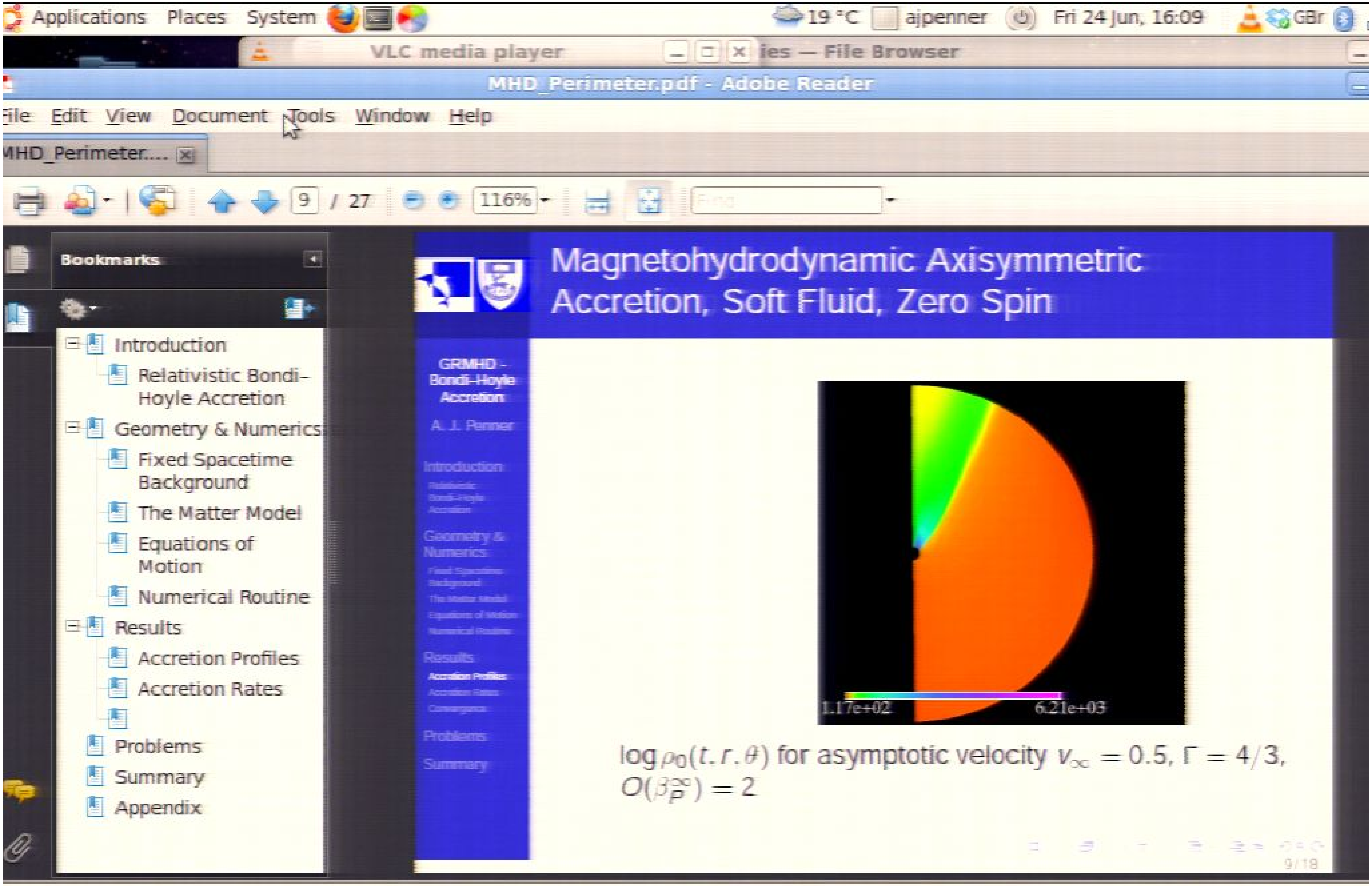


log $\rho_0(t, r, \theta)$ for asymptotic velocity $v_\infty = 0.5$, $\Gamma = 4/3$, $O(\beta_P^\infty) = 2$



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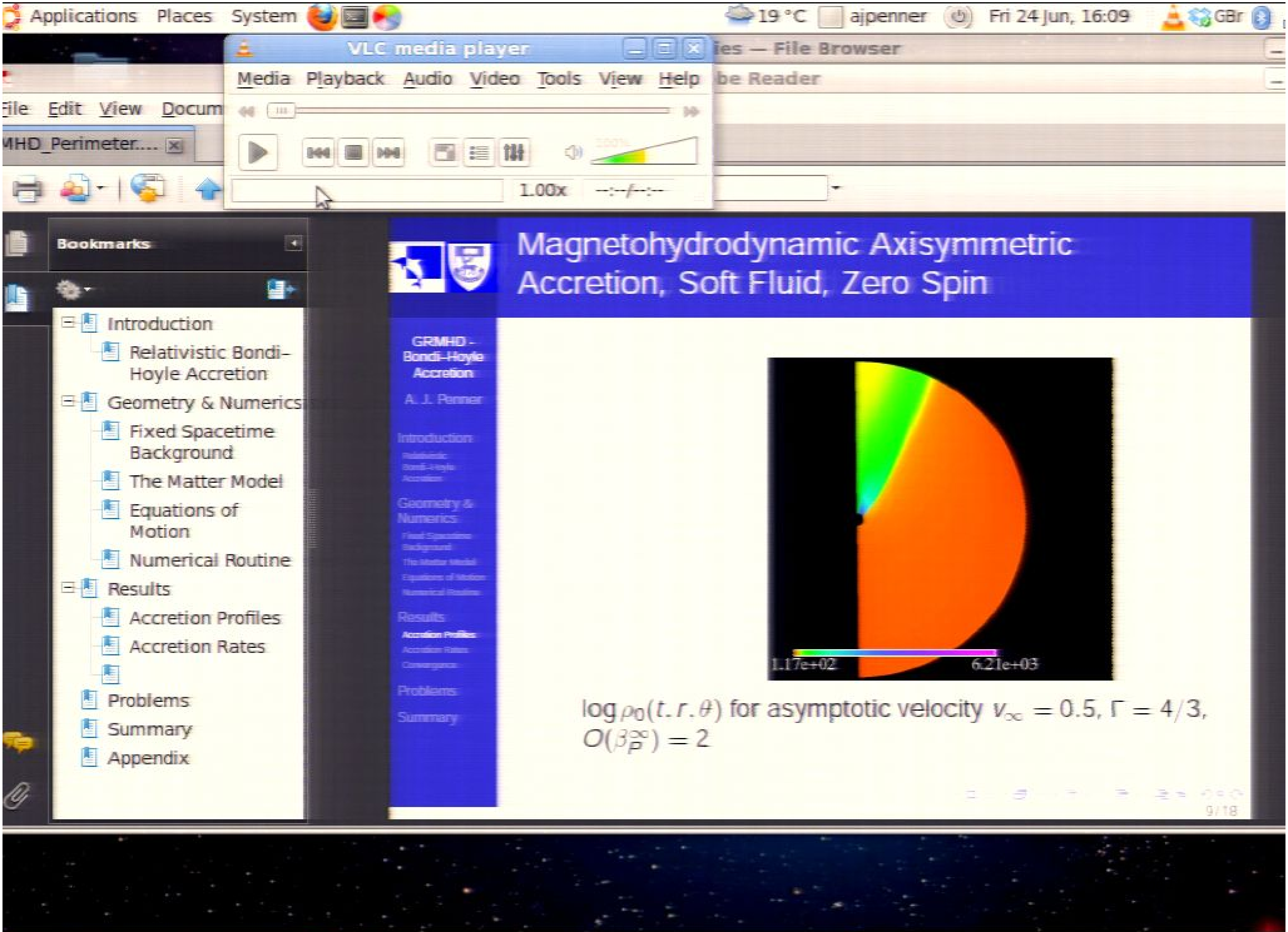

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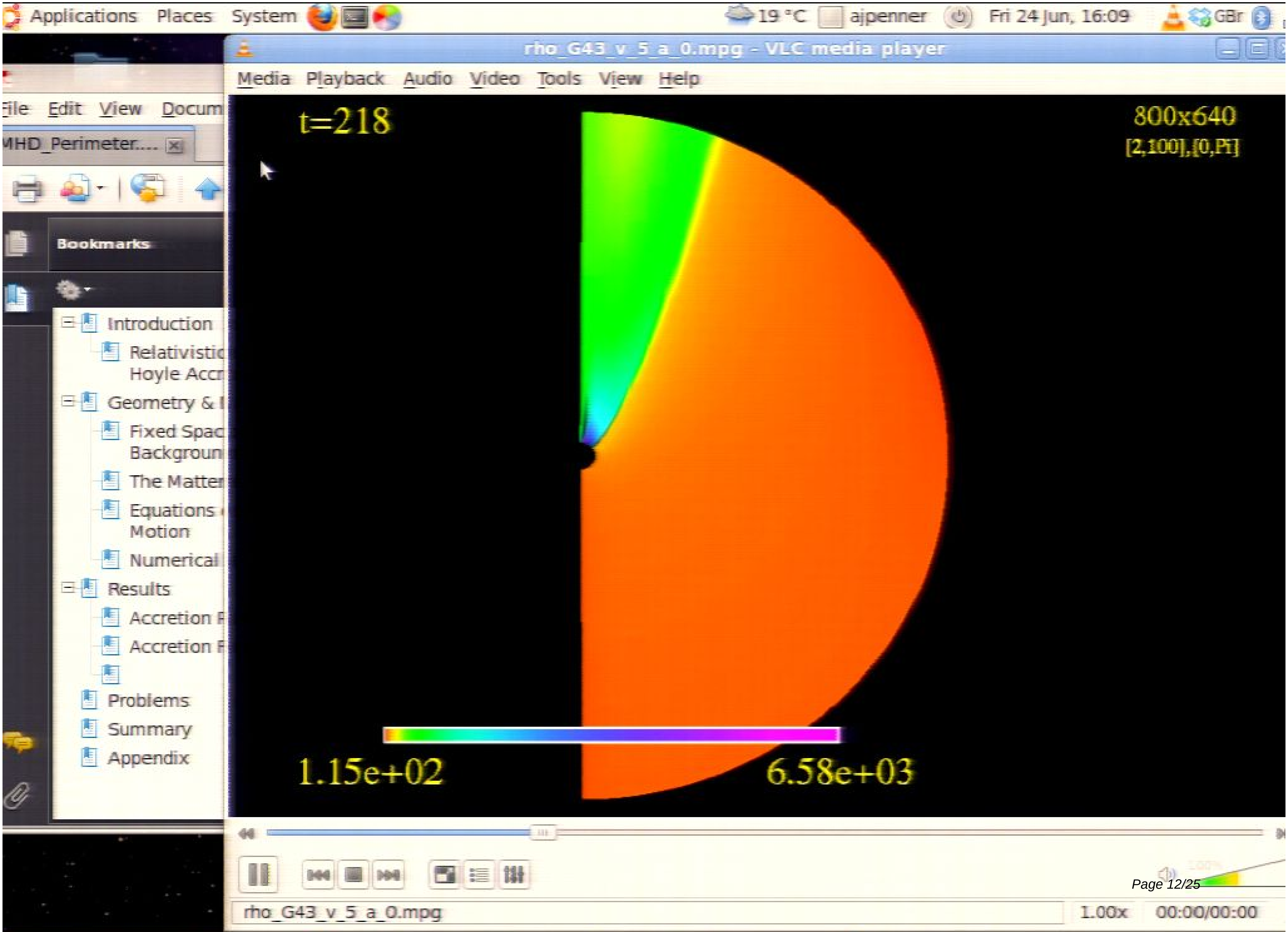
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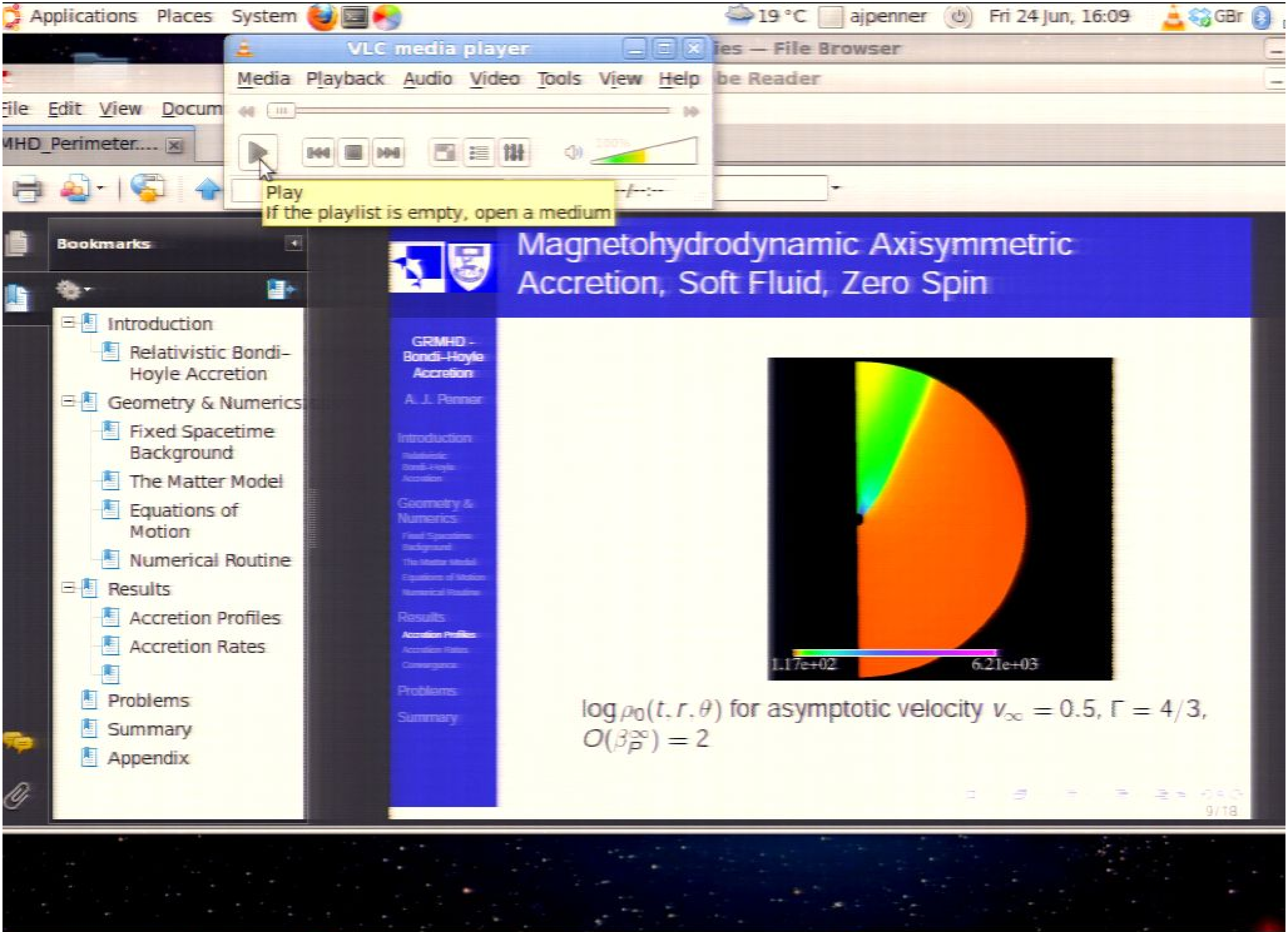

Magnetohydrodynamic Axisymmetric Accretion, Soft Fluid, Zero Spin

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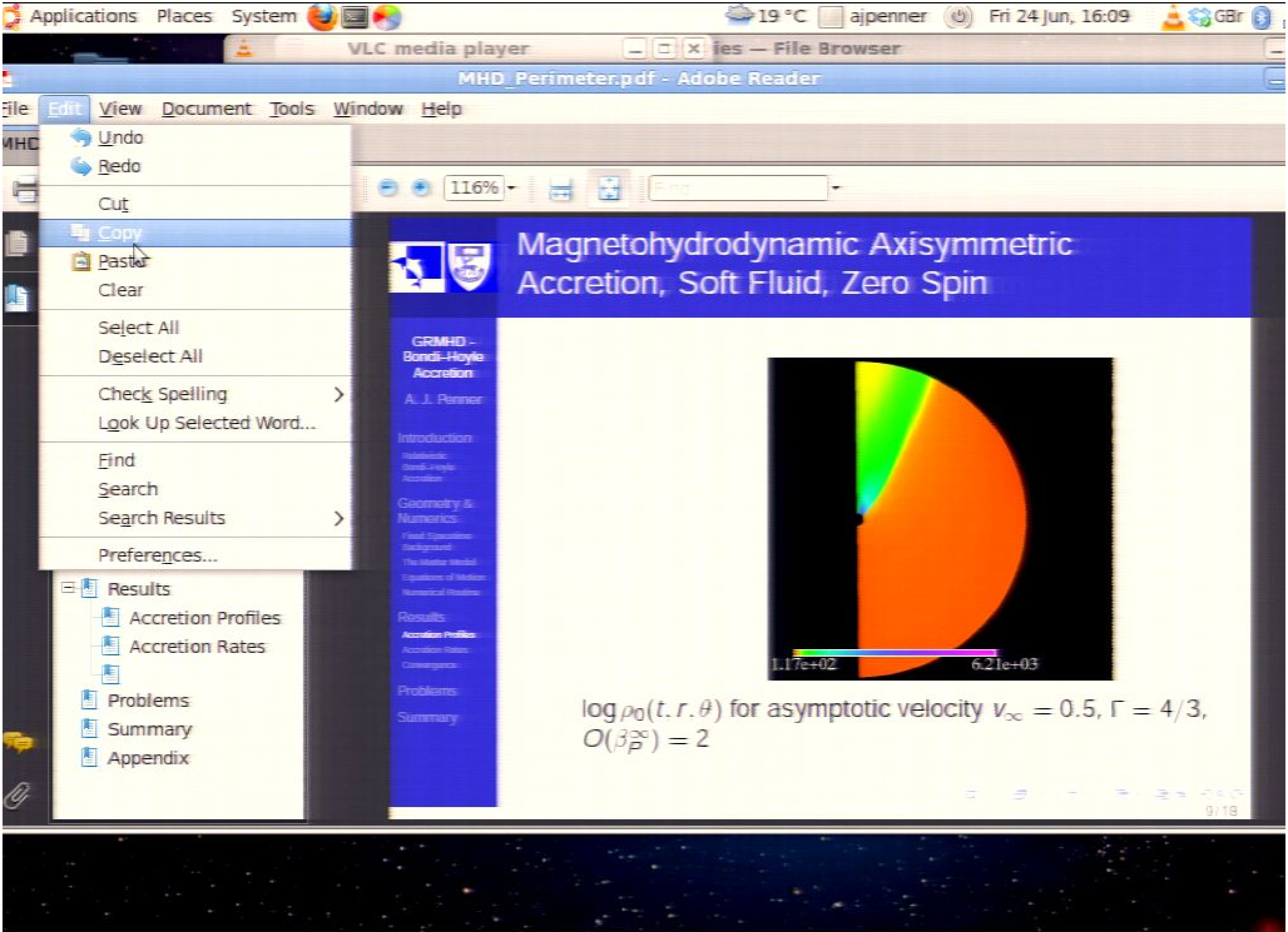

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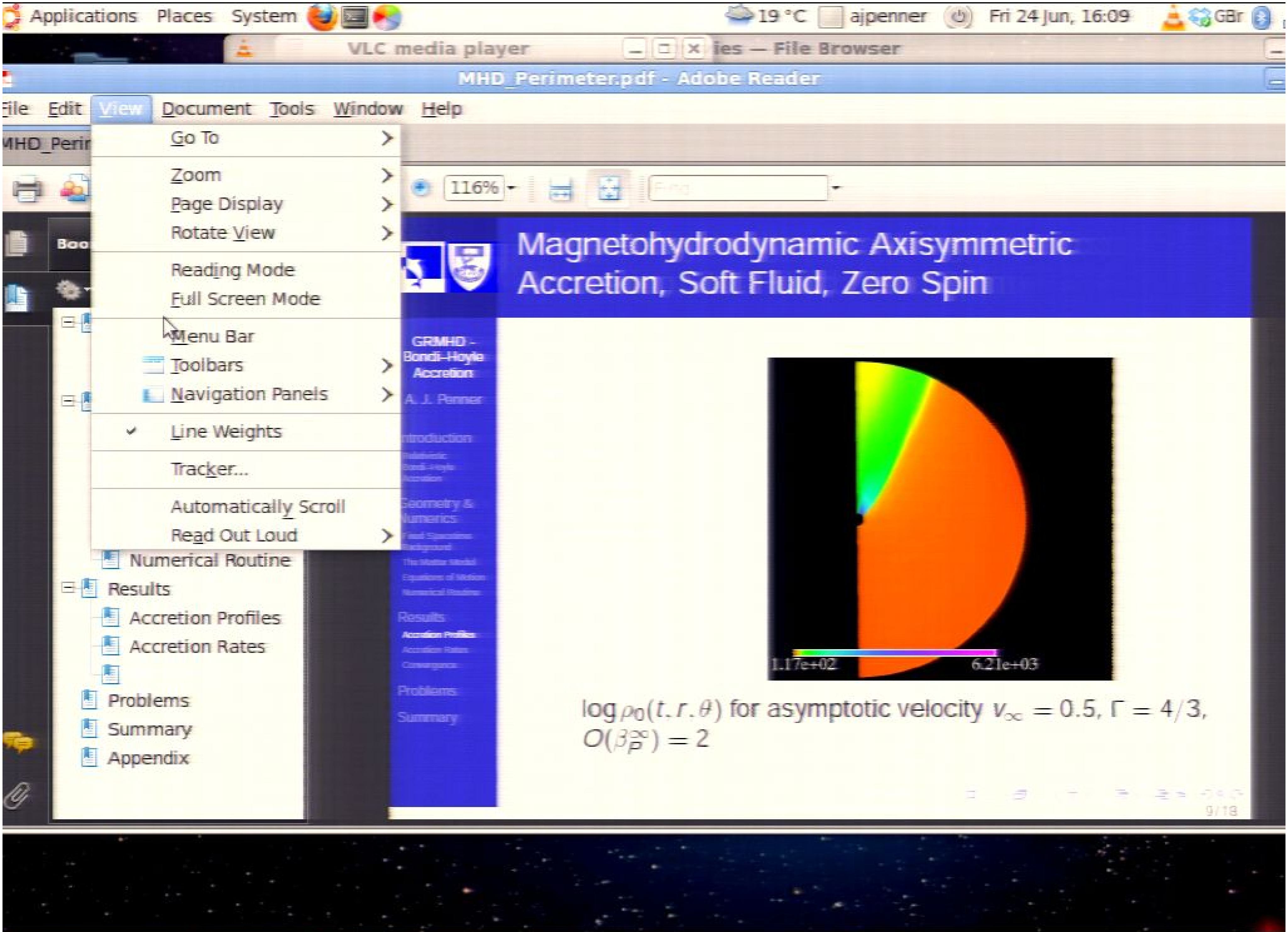

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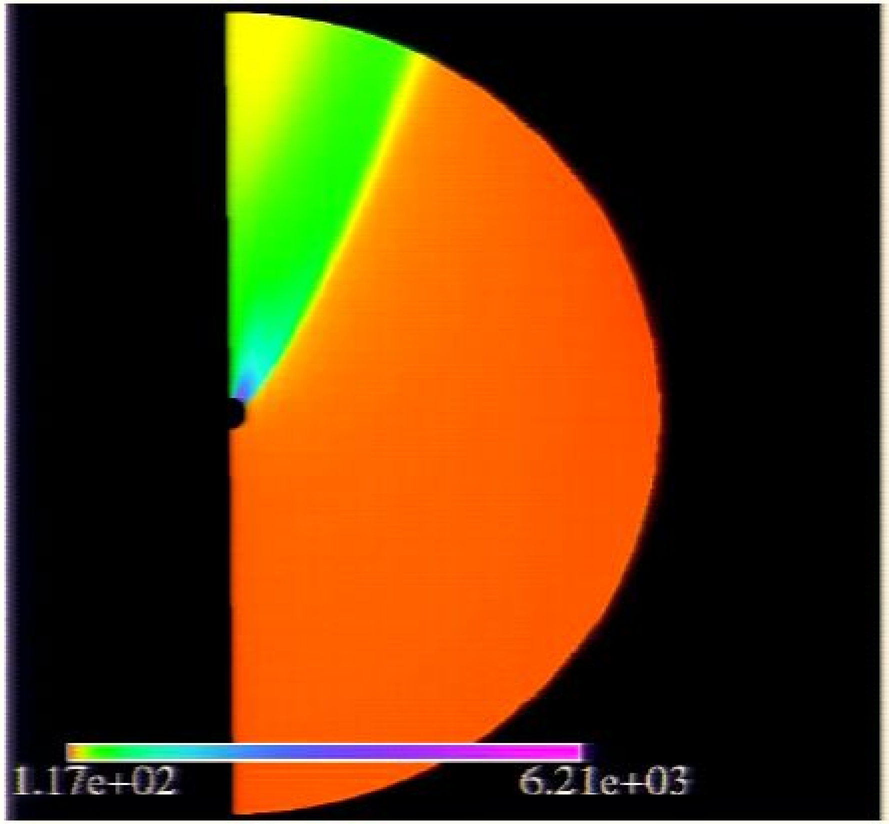

$\log \rho_0(t, r, \theta)$ for asymptotic velocity $v_\infty = 0.5$, $\Gamma = 4/3$, $O(\beta_P^\infty) = 2$

Results – Angular Sections

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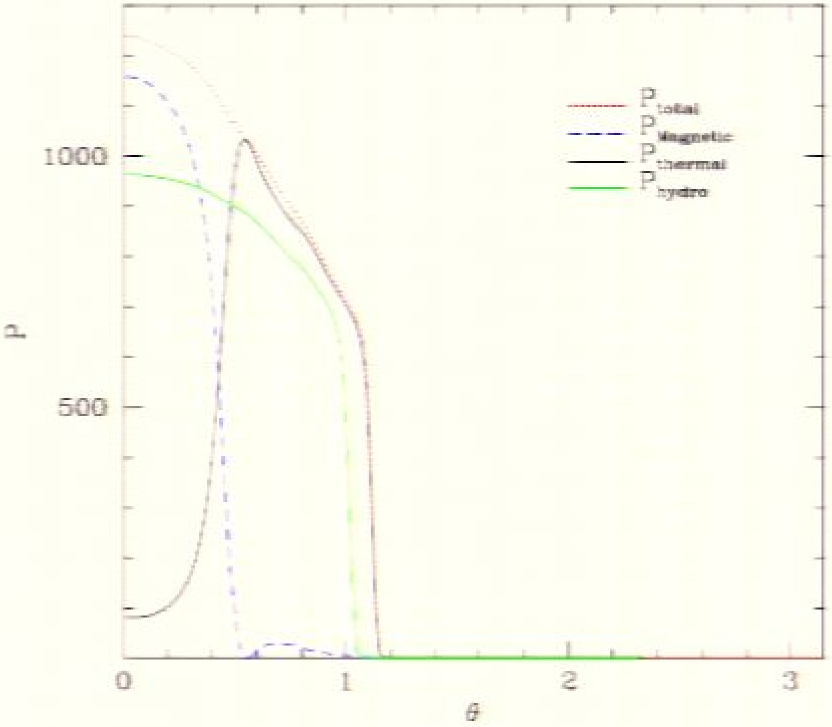
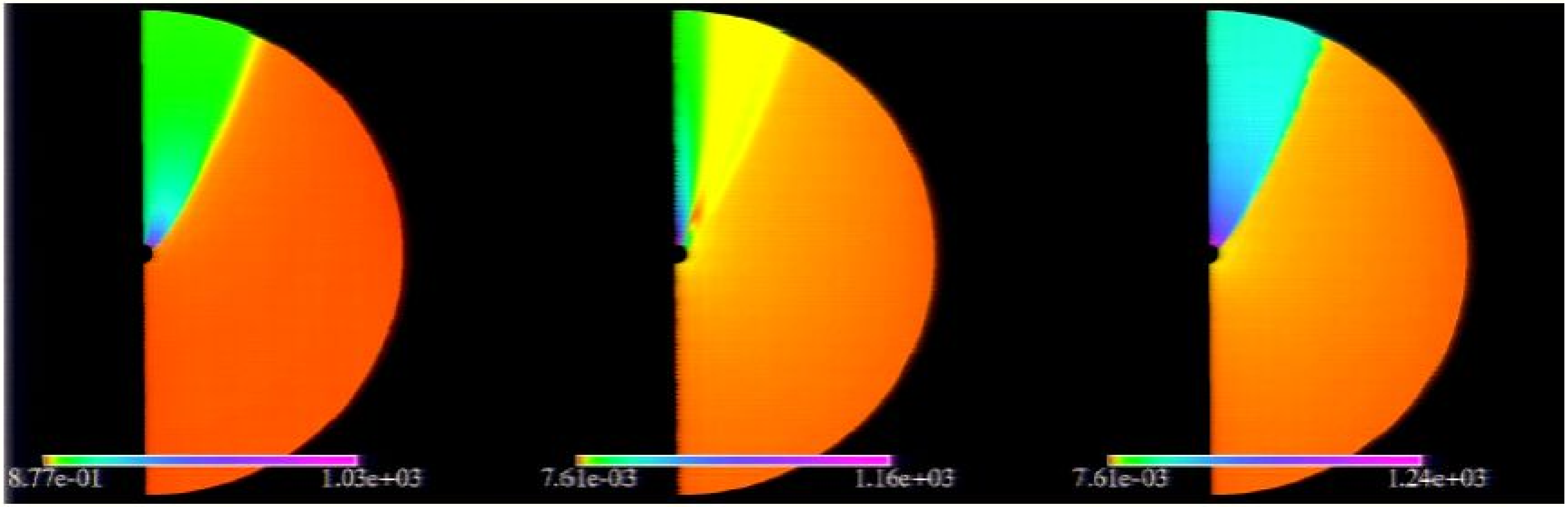


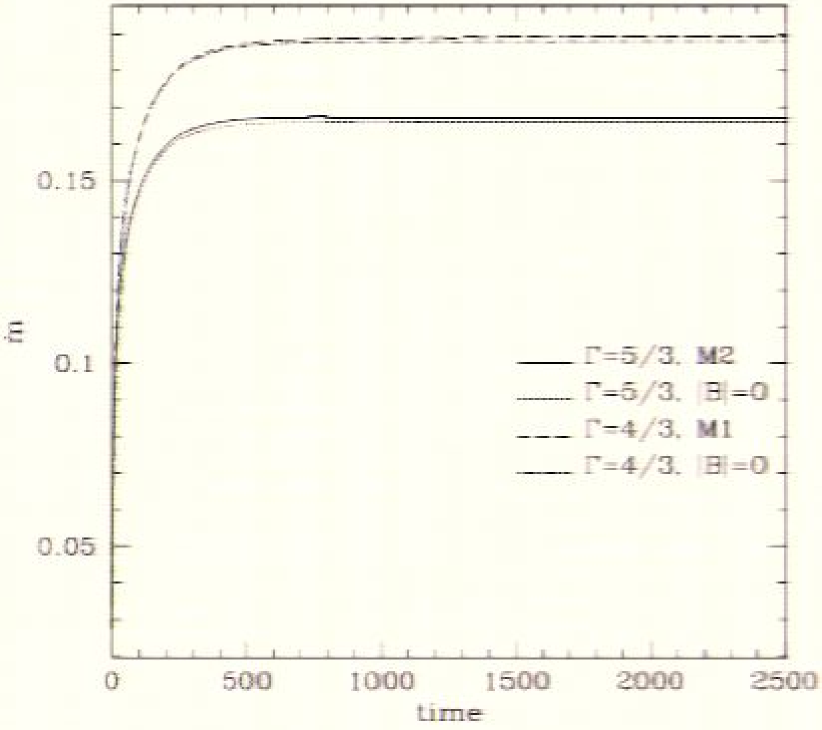
Pressure Profiles $a = 0$

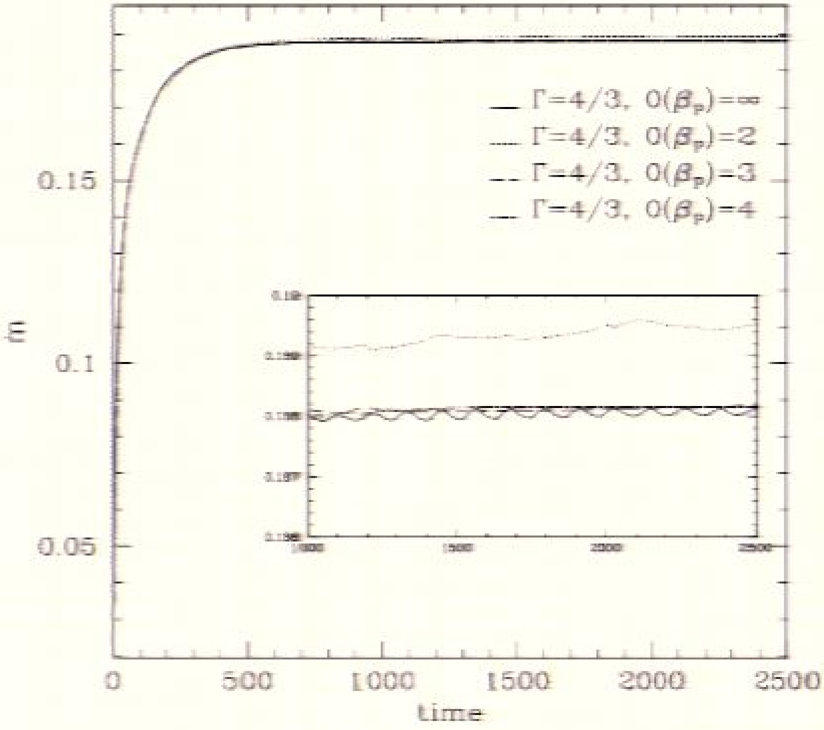
The total pressure looks like one would expect in a hydrodynamic flow, $t = 2500M$



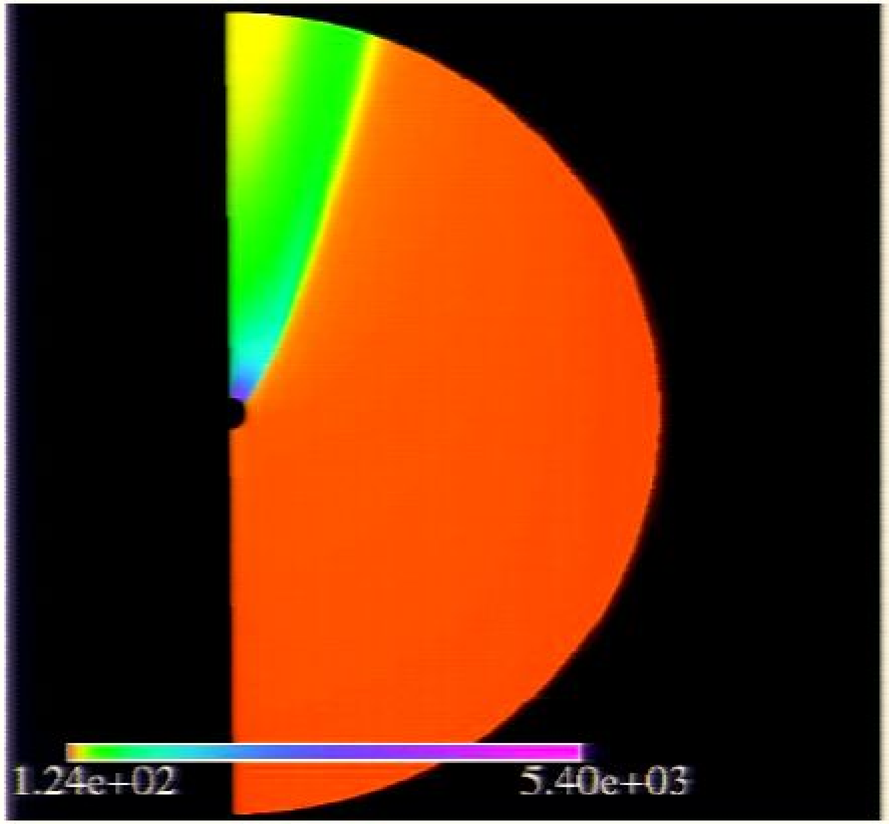
$P_{\text{thermal}}(r, \theta)$ $P_{\text{magnetic}}(r, \theta)$ $P_{\text{total}}(r, \theta)$

Mass Accretion Rates $a = 0$



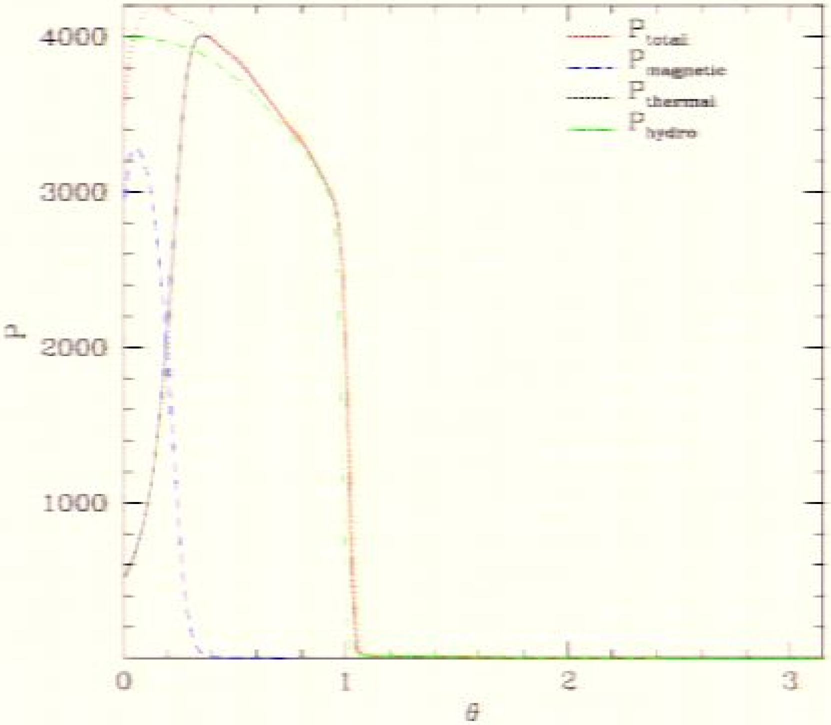


Magnetohydrodynamic Axisymmetric Accretion, Soft Fluid, Non-zero Spin



log $\rho_0(t, r, \theta)$ for asymptotic velocity $v_\infty = 0.5$, $\Gamma = 4/3$, $a = 0.5$, $O(\beta_P^\infty) = 2$

Results – Angular Sections



Mass Accretion Rates $a \neq 0$

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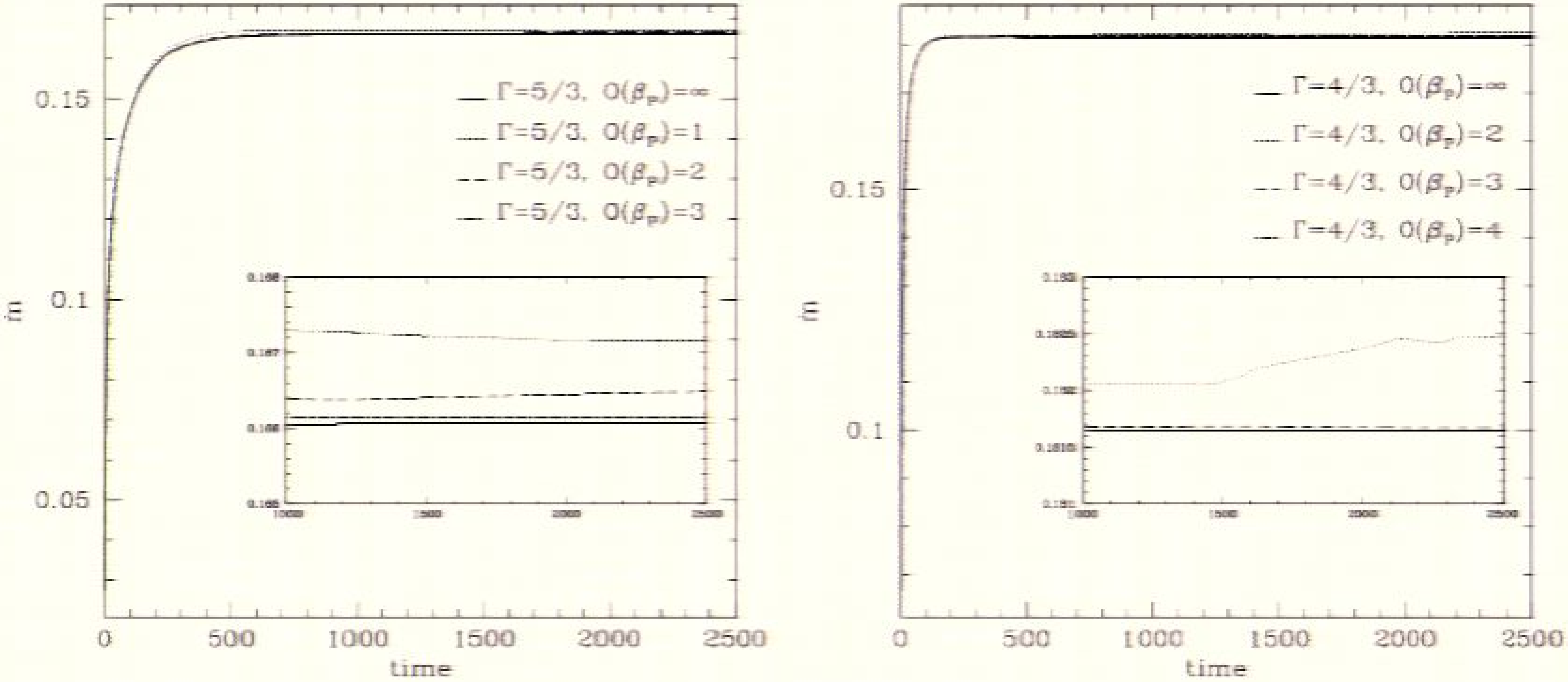
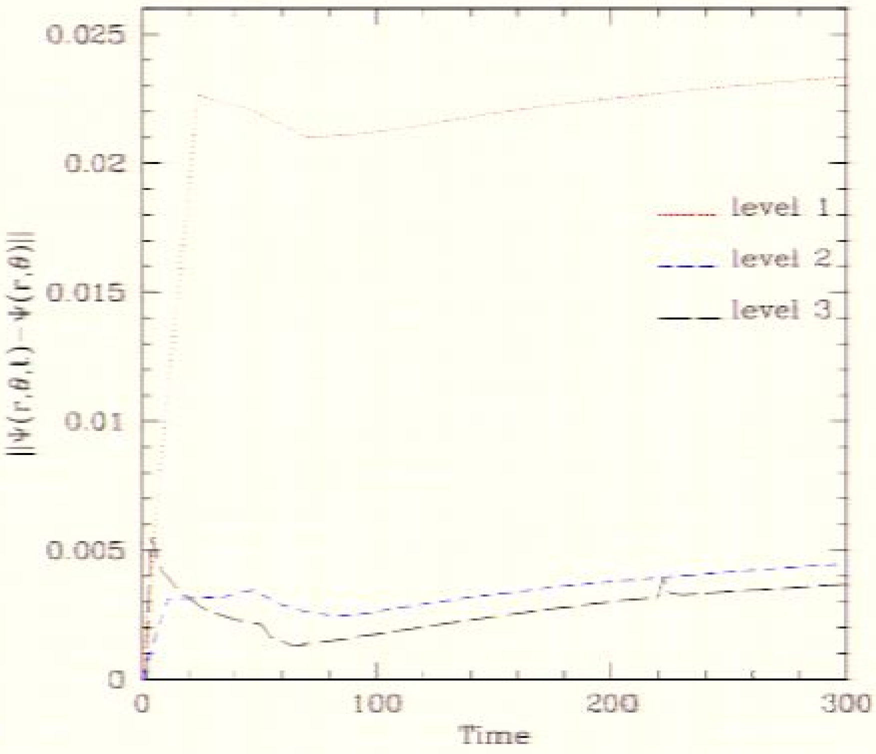


Convergence of Ψ



Convergence tests using the auxiliary function Ψ

Outstanding Issues

- The debate over the best method to enforce $\nabla \cdot \mathbf{B} =$ constraint continues.
- Hyperbolic divergence cleaning introduces additional parameters.
- Real flows are not likely to be uniform, nor ideal fluids
- Electromagnetic accretion

Summary

- The introduction of a magnetic field does not upset steady-state solution.

- The rotating axisymmetric black hole has an impact on the flow morphology.

- Presence of a depletion region near the black hole or the axis of symmetry.

- Another test case for code development.