Simulations of Super-Eddington Dynamical Mass Transfer in Double White Dwarfs

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Interacting DWD's

- DWD's are driven closer by gravitational radiation and if orbital separation < 5 solar radii, they will undergo mass transfer within a Hubble time (*Bethe & Brown (1998)*)
- Mass transfer can lead the DWD to form other objects
  - Unstable mass transfer leads to merger or tidal disruption
    - M < 1.4 leads to hydrogen poor objects such as extreme Helium, R Coronae Borealis, sub-dwarf B, and sub-dwarf O stars (*Clayton et. al. (2007)*)
    - M > 1.4
      - Runaway nuclear detonation and a Supernova Ia? (*Webbink (1984)*) or
      - Collapses to form compact object (*Mochkovitch & Livio (1990)*)
  - Stable mass transfer leads to AM CVn systems (*Nelemans et. al. (2001)*)

Stability

Whether or not a system is stable to mass transfer depends on (among other things):

(1) Ratio of donor mass to accretor

(2) Equation of state

(3) How efficiently lost orbital angular momentum is restored

- For direct impact w/ polytropic EOS w/ n=2/3
  - Extremely efficient - $q_{crit} = 2/3$
  - Extremely inefficient – $q_{crit}=0.22$ (*Marsh et. al. (2004)*)

(4) Radiation driven mass loss – (discounting angular momentum carried) increases q_{crit} (*Han & Webbink (1999)*)

(5) Dissipation by common envelope – reduces q_{crit}

Super-Eddington Accretion

Spherical Case

- Accretion energy is converted to radiation
- Eddington luminosity based on spherical accretion

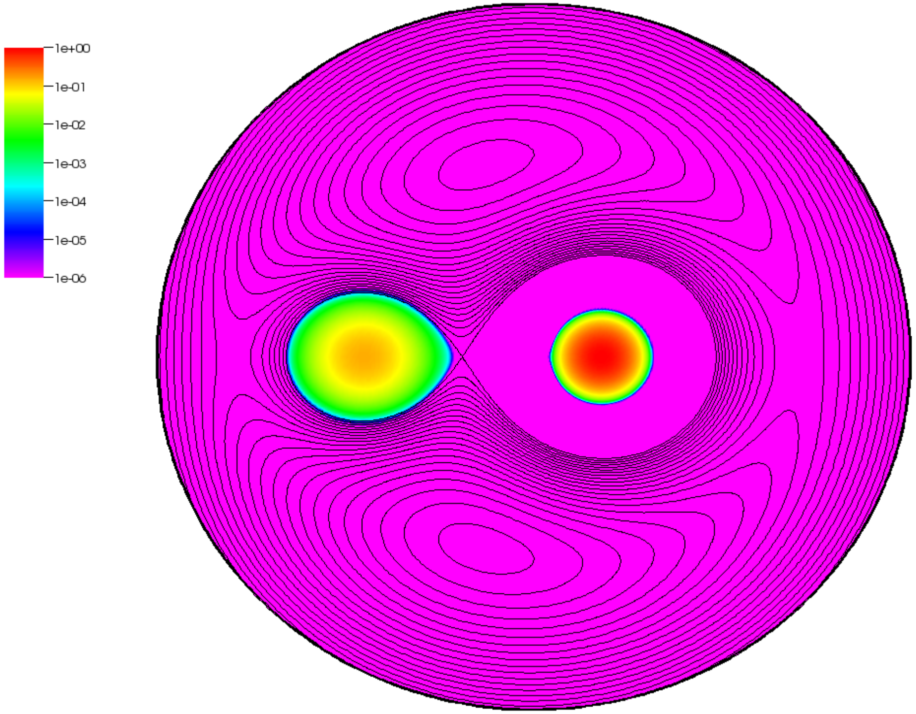
$$L_{\mathrm{Edd}} = \frac{4\pi c G M_1}{\sigma_T} \qquad \dot{M}_{\mathrm{crit}} = \frac{4\pi c G M_1}{\sigma_T \left(\Phi_{\mathrm{L1}} - \Phi_*\right)}$$

- Force of radiation balances the force of gravity and accretion is cut off
- The radiation must interact with the entire length of the accretion column to escape
- If extra mass is dumped onto the accretor in excess of this limit, the extra mass is driven to infinity and an Eddington luminosity escapes as radiation.

Super-Eddington Accretion

DWD case

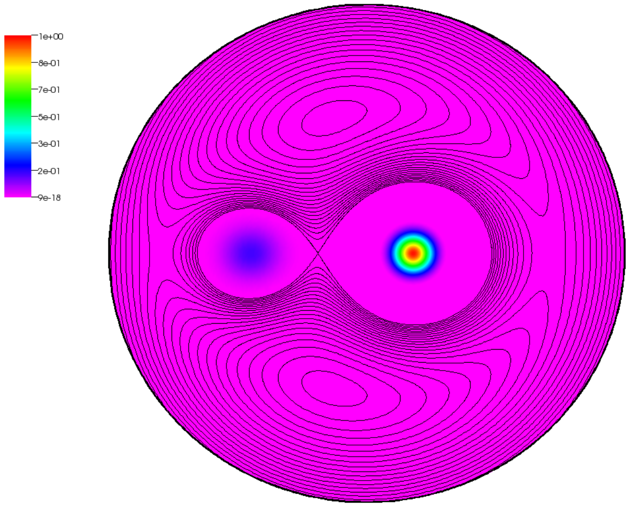
- The accretion flow of interacting DWD's is much more complicated and requires 3D modeling
- Mass driven from accretor may not be driven out of system and may remain in a common envelope
- Radiation may escape interaction with the accretion column
- Our model is an attempt to see what happens



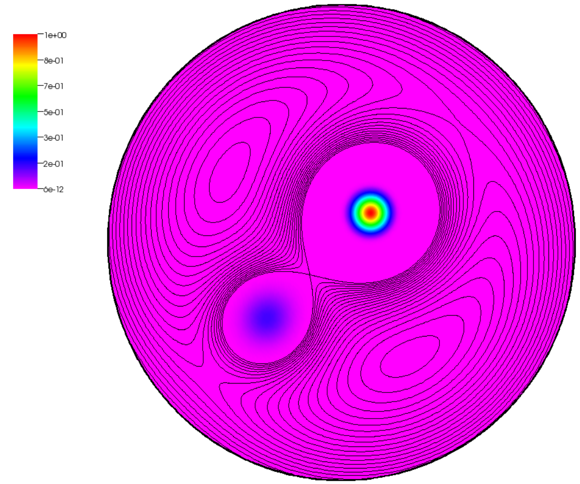
- Equatorial slice of initial model w/ effective potential contours

Model Requirements

$$\frac{t_p}{t_d} \approx 20\sqrt{1+q^{-1}}$$



0 orbits

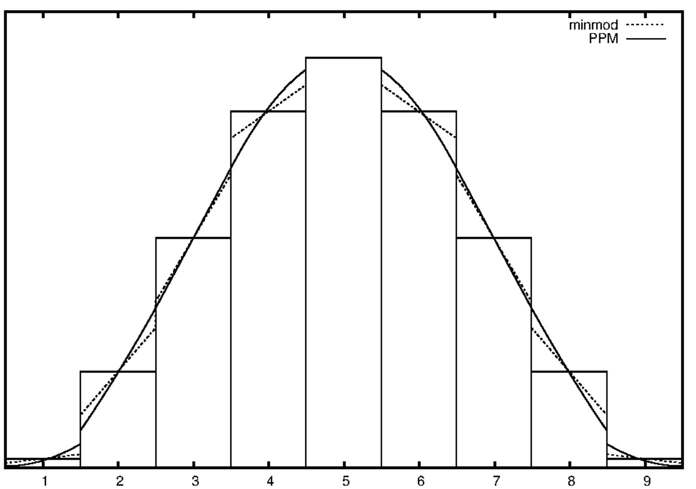


20 orbits (looks similar)

- The evolution takes hundreds of donor dynamical times and most of the grid is in near-equilibrium (until possible merger)
- To accurately model over these time periods we want numerical conservation of
  - Mass
  - Inertial Frame Angular Momentum
  - Energy
- We also want radiation transport to account for *possible* radiation driven mass loss

Numerical Method (abridged)

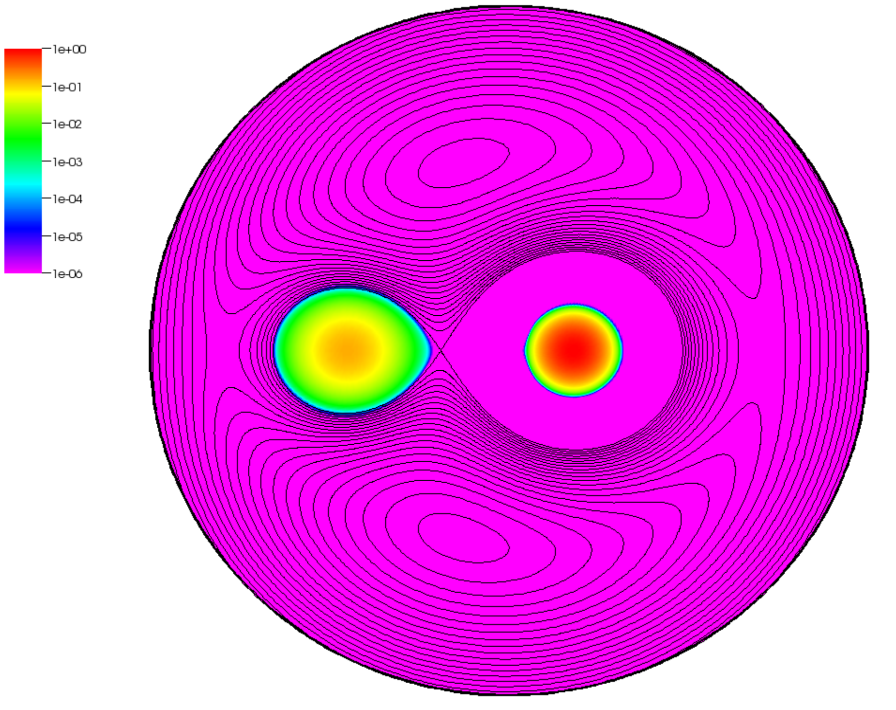
- Ideal inviscid fluid dynamics using Eulerian finite volume with semi-discrete central scheme of Kurganov & Tadmor (1999)
- Shock heating by dual energy formalism of Bryan et al. (1995)
- Newtonian self-gravitation (Cohl & Tohline 1999)
- Radiation energy transport using flux limited diffusion (FLD) (Levermore & Pomraning (1981))
  - Advects gray field radiation energy density
  - Hybrid implicit-explict scheme
- Reflection on z-plane



- We have incorporated the gravitational potential energy into the K-T scheme in a way that conserves kinetic+internal+potential energy (Marcello & Tohline, 2012)
  - Prevents 'potential creeping' and allows for an equilibrium state model star
- NCSA Teragrid and Louisiana Optical Network Initiative resources

Three Q=0.4 Model Evolutions

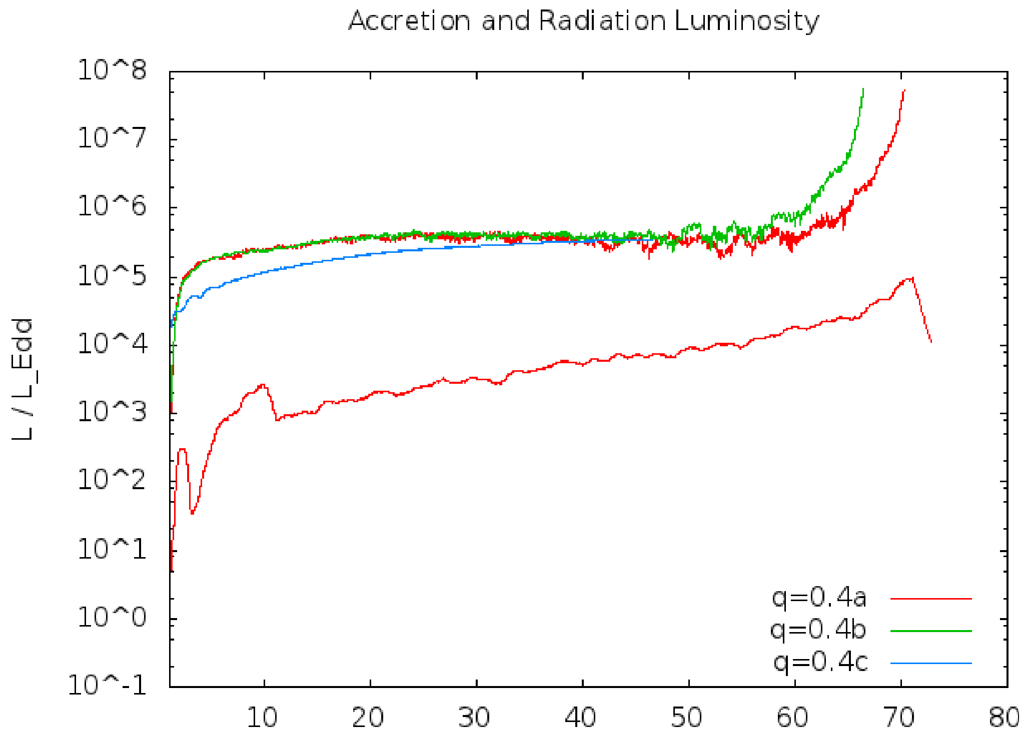
- Initial model
  - Begin with two spherical polytropes in Roche pote
  - Radiation field is set internal to stars by setting radiation and gas temperatures equal
  - Hold stars in place, evolve with velocity damping terms
  - If RLOF occurs, iterate with larger separation

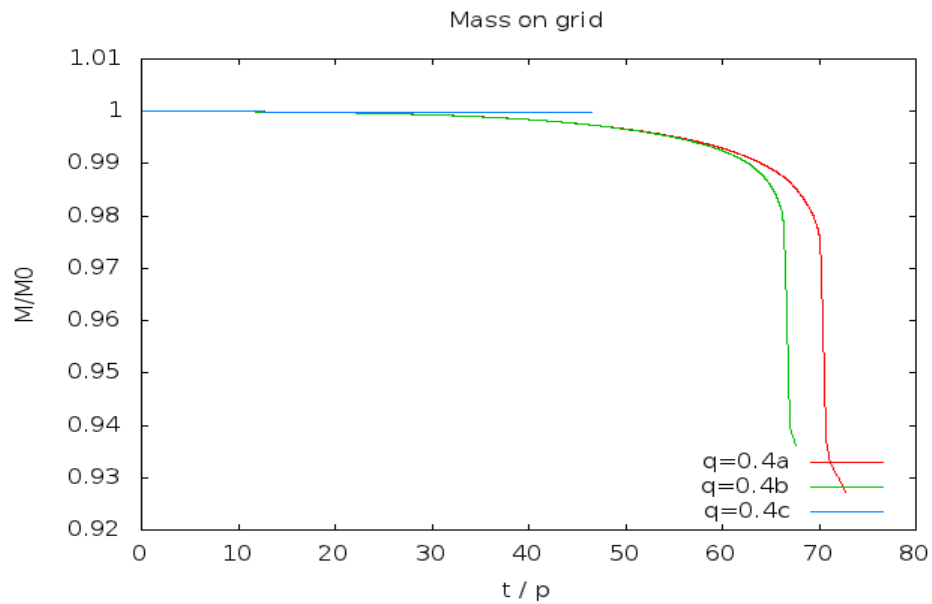


- q=0.4a
  - Evolves radiation energy density
  - Includes shock heating
- q=0.4b
  - Same as q=0.4 but without radiation
- q=0.4c
  - No radiation or total energy
  - Entropy is conserved, so no shock heating
  - Equivalent to assuming all the shock heat is immediately lost to radiation

Q=0.4 (preview)

- All models begin with direct-impact accretion
- Flow quickly becomes highly super-Eddington
- Q=0.4ab runs are very similar
  - Stream detaches from impact point and hot accretion torus forms for q=0.4ab
  - Mass flows off grid but none of it has above zero binding energy
  - Some mass returns to donor and L2 overflow causes tidal disruption
- Q=0.4c has no hot torus, the simulation is still progressing





Links to movie files

(YouTube Links and direct links)

- Equatorial Slices
  - Q=0.4a
    http://youtu.be/yFY4bqawqjw http://phys.lsu.edu/~dmarcel/q4/q4a_d.mpeg
  - Q=0.4b
    http://youtu.be/KWs2TXH15is http://phys.lsu.edu/~dmarcel/q4/q4b_d.mpeg
  - Q=0.4c
    http://youtu.be/gRaMk4sZ3Pw http://phys.lsu.edu/~dmarcel/q4/q4c_d.mpeg
- Vertical Slices
  http://youtu.be/O__sSYwnoLk http://phys.lsu.edu/~dmarcel/q4/vert.mpeg

Mass Transfer Rate and Separation

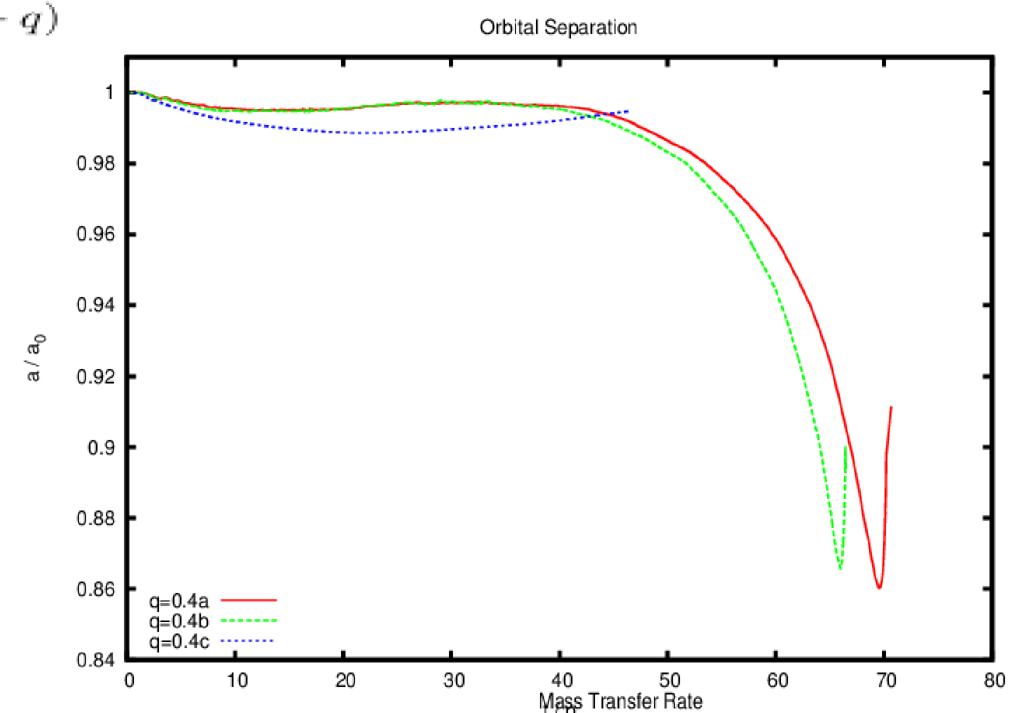
- Q=0.4ab runs $\frac{\dot{a}}{a} = \frac{2\dot{J}}{J} + \frac{-2\left(\dot{M}_2\right)}{M_2}(1-q)$

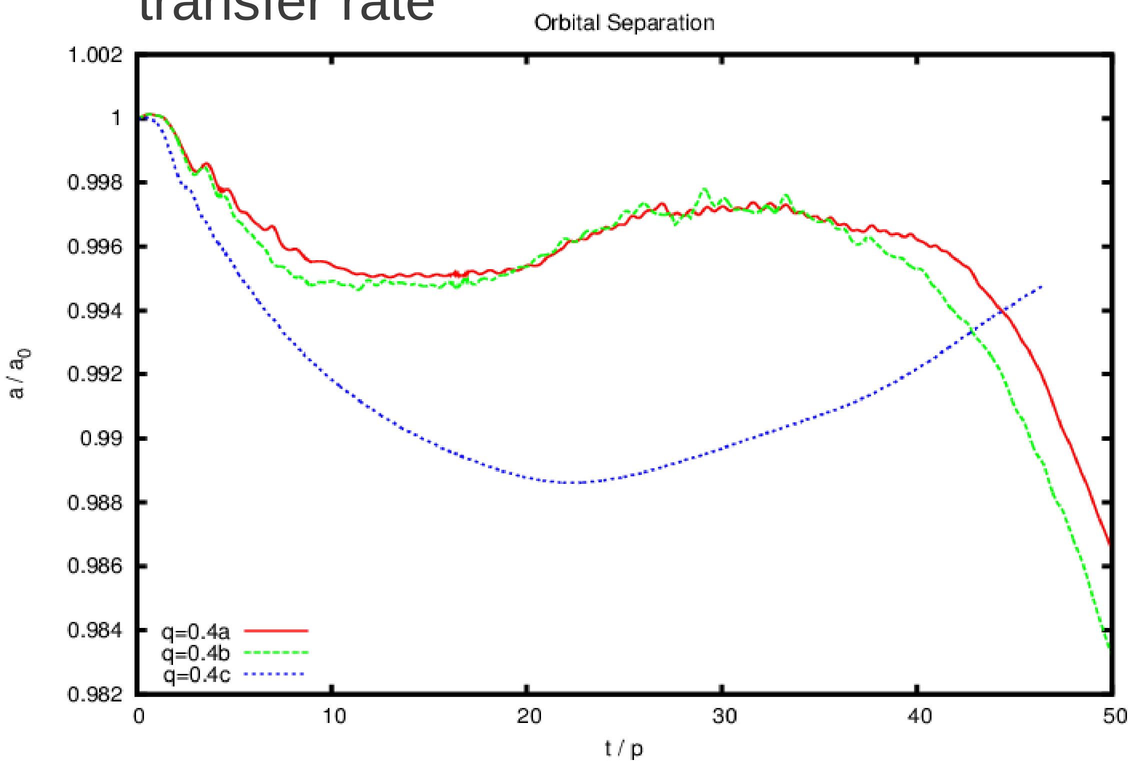
  1) Orbital angular momentum loss drives binary closer

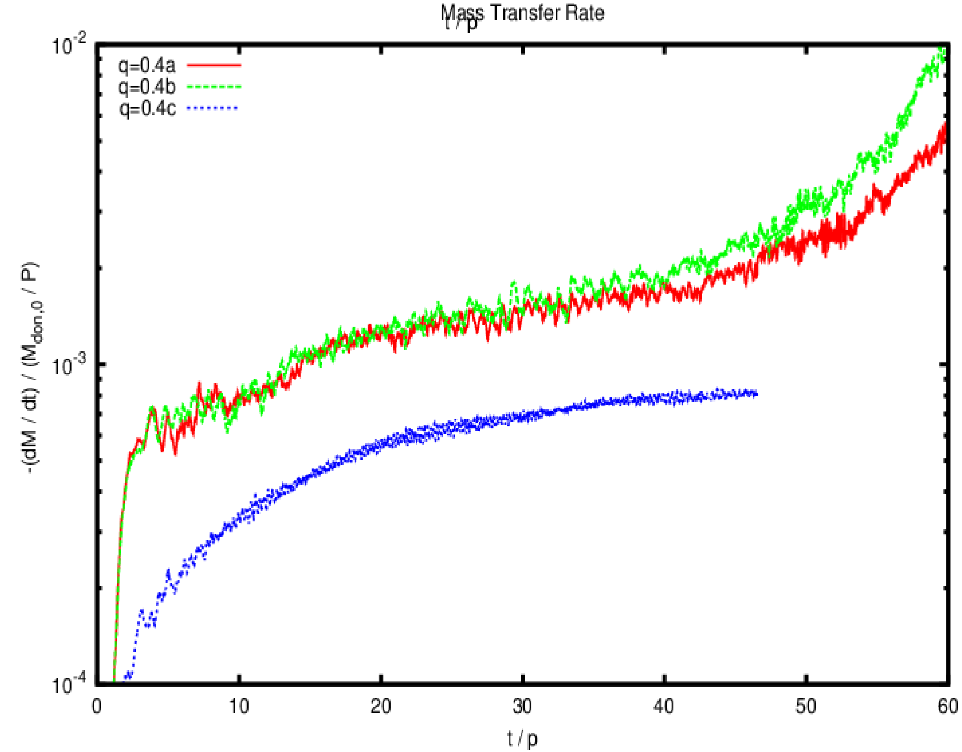
  2) The mass transfer increases and acts to stabilize the orbit

  3) The hot accretion matter flows back to the donor and overflows L2, driving the binary to tidal disruption

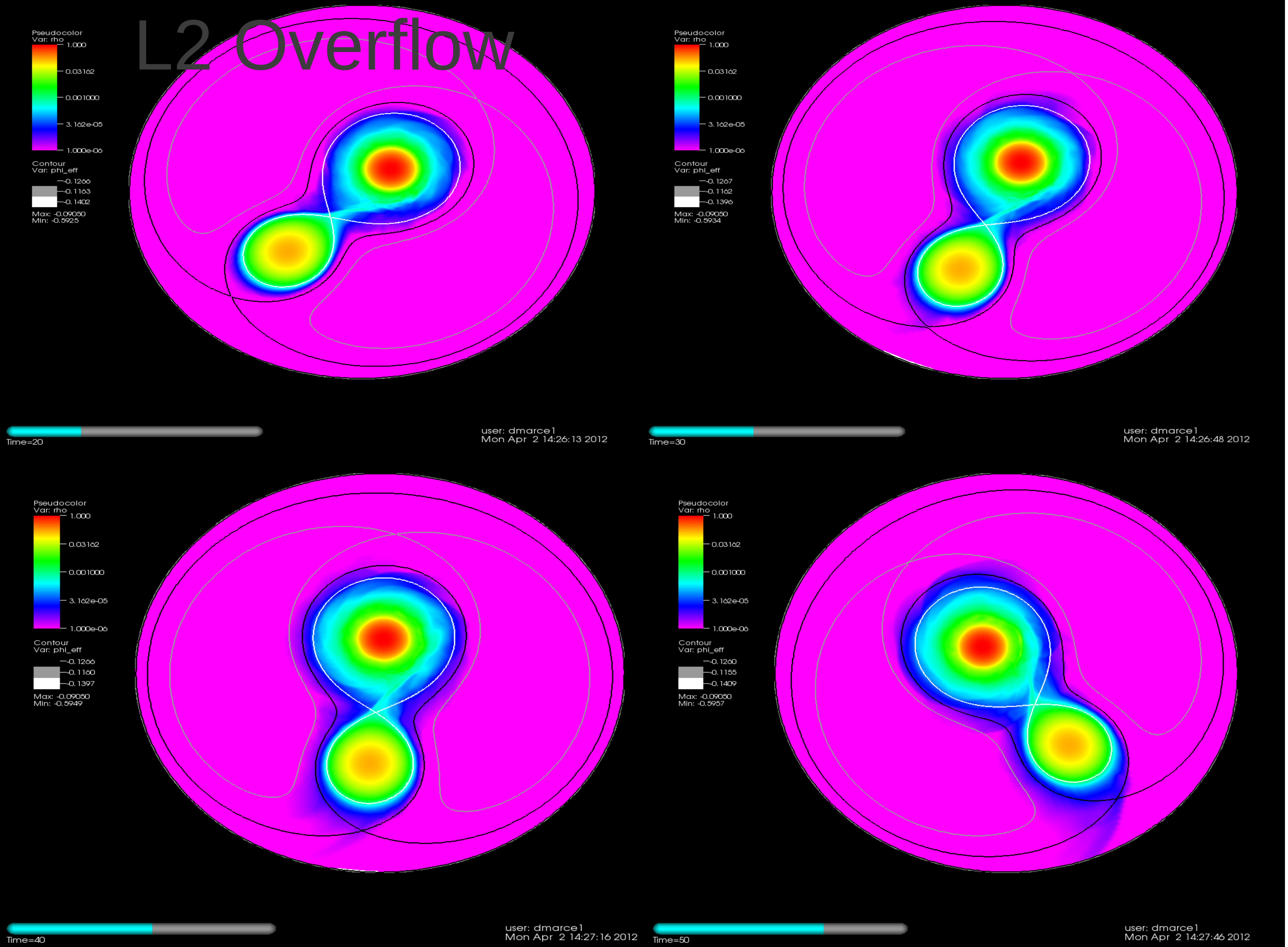
- Q=0.4c goes through first phase slower because of lower mass transfer rate







L2 Overflow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1.000e-06
Contour
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Mon Apr 2 14:26:13 2012
Pseudocolor
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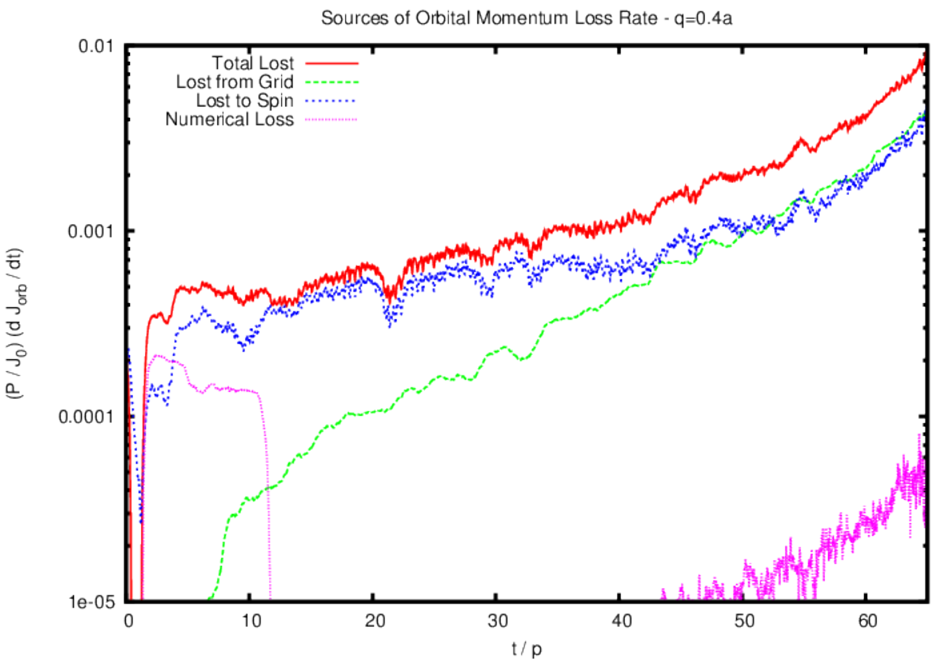
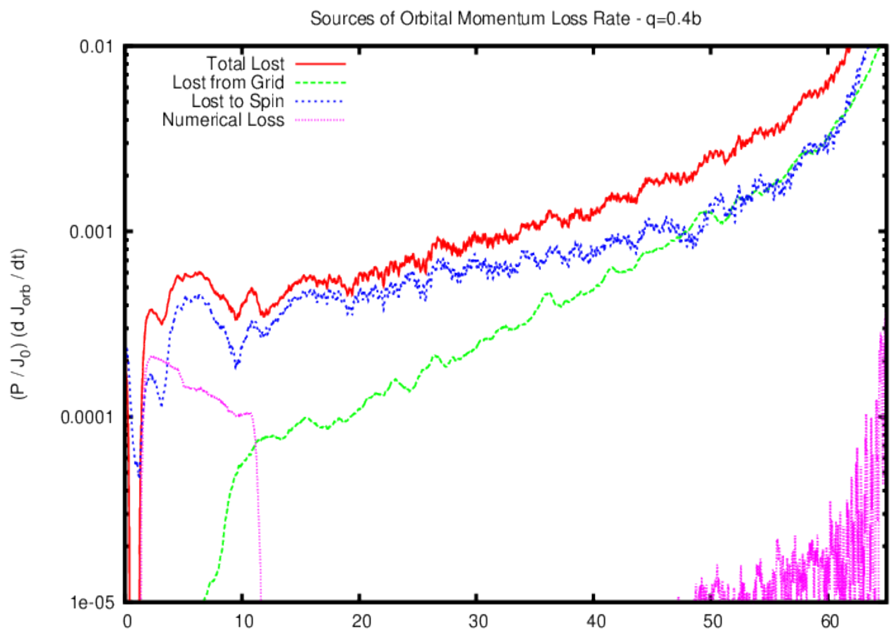
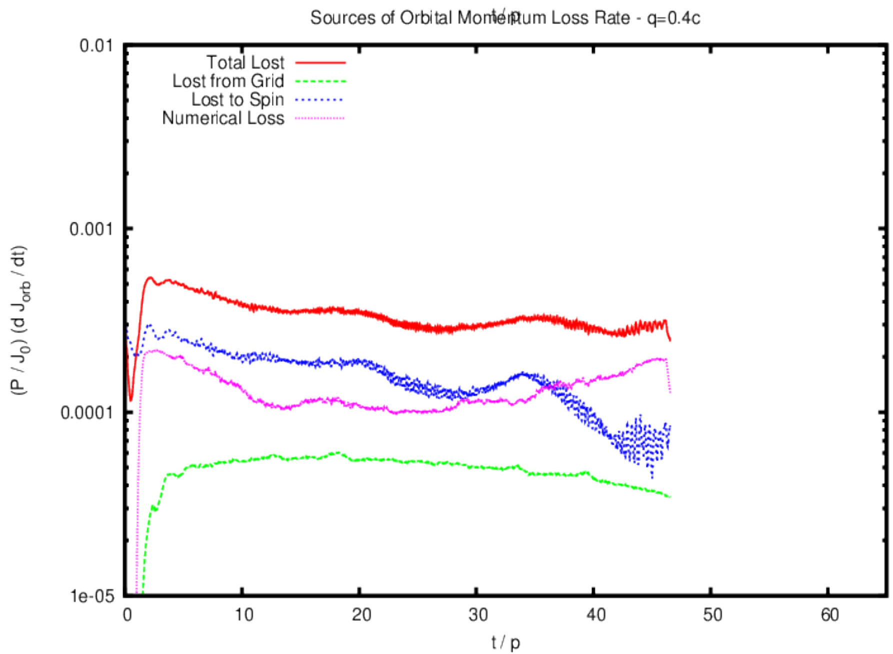
Sources of Rate of Orbital Momentum Loss

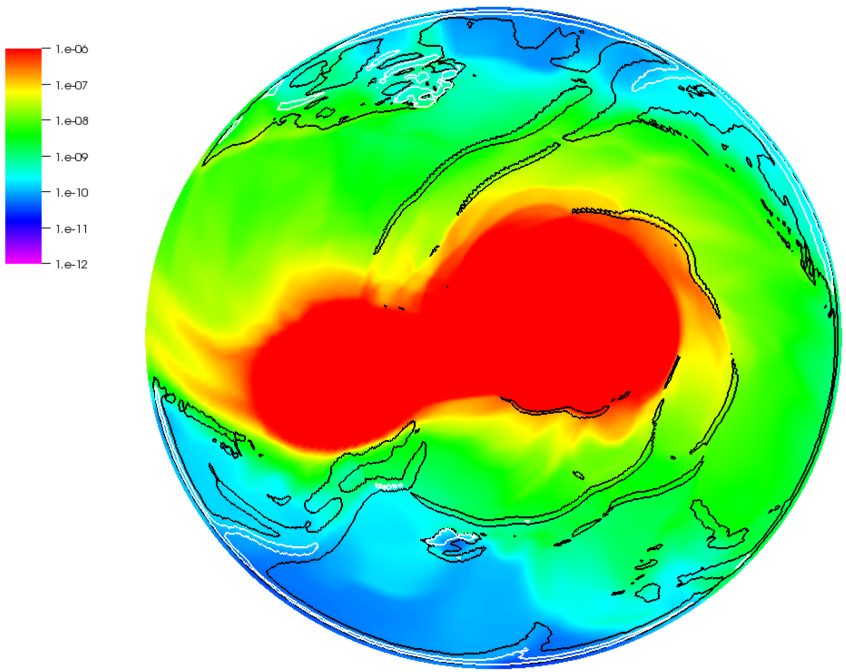






- For q=0.4ab there is initially numerical driving which is damped by tightening the tolerance for the Poisson solver
- Loss of orbital angular momentum is initially goes to spin
- As the atmosphere around the donor puffs of, loss of OA through L2 for q=0.4ab becomes as significant as loss to spin

Super-Eddington?



- Very little of the flow is ever super-Eddington in the sense that the force of radiation exceeds the force of gravity
- The radiation is swamped by the optically thick accretion flow
- This may not occur for lower transfer rates

Next: The Trans-Eddington Model

- In the model above, the mass transfer rate crosses from sub to super-Eddington very quickly, so we may be missing physics that occurs in this phase
- Its possible there is a regime where radiation is not swamped by flow and is strong enough to affect flow
- Presently we are unable to model realistic mass transfer rates – AMR is needed (at a minimum)
- An alternative is to adjust the physical constants so that the model has a trans-Eddington phase of significant length
- We have taken the above model and are now evolving it with lower speed of light and Thomson cross section
- We are also working towards an AMR model using High Performance ParalleX (HPX) (*Kaiser, et. al. (2009)*)

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