GRMHD simulations of relativistic jets

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Frankfurt seminar 16-02-2016
Content

- Introducing a new code: HARM-GPU
- Introduction to AGN jet physics
- Simulations setups
- Results
Trends in astrophysical MHD

- Use fewer assumptions/include more physical effects
- Resolve all relevant distance scales in 3D simulations
- Study systems over multiple orders of magnitude in time
- We need high performance MHD codes to move on!

Credit: SCO

Credit: McKinney, 2012
New code: HARM-GPU

• Based on well tested HARM GRMHD code
• Makes use of GPUs
• Various algorithmic enhancements such as better numerical solvers (HLLC) and staggered grid in work
• Adaptive grid will be implemented as well
Why GPUs

- Non vectorised single core performance reached state of perfection in CPUs and accelerators.
- Speedup lies in more cores and use of vectorization for CPUs/Accelerators.
- Vectorization is very difficult in HARM (20,000 instructions per cycle).
How do GPUs work?

• Goal is not to complete a single task very fast, but $10^5$ - $10^7$ tasks
• Trade circuitry/cache space for more ALU space, but retain huge register size
• Rely on 10+ threads per core to keep stream processors busy
• Necessitates usage of specialised programming languages (OpenCL/CUDA)
Code performance

Relative performance CPU/GPU

- AMD R9 Fury X: 177
- AMD R9 290X: 169
- Nvidia K80 (1 core): 121
- Nvidia K40: 135
- Nvidia K20X: 101
- Intel Core i7 5960x HT on: 19.8
- Intel Core i7 5960x HT off: 15.8
- Intel Xeon Phi: 10.5
- Intel Xeon E5 2670 HT off: 9.4
- AMD Interlagos 8 FPUs (16 threads): 7
- AMD Interlagos 8 FPUs (8 threads): 5
- AMD Interlagos 1 FPU (2 threads): 1

Speedup vs 1 AMD Interlagos FPU
Code scaling
My goal: Understanding jet acceleration

- Jets convert their magnetic energy (Poynting) flux into mass-energy flux through acceleration, but how and on which scales?
- What is the effect of the ambient medium on jet acceleration and shape?
Applications: Cosmic Rays

- AGN jets could be a significant contributor to extragalactic cosmic rays and neutrinos (CTA/IceCube)

Hubble image of M87
Credit: NASA
Applications: BH feedback

- How do jets influence galactic structure formation?

AREPO cosmological simulation

Hubble image Virgo cluster
When are jets launched?

<table>
<thead>
<tr>
<th>Condition</th>
<th>State</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h/r \sim 1$</td>
<td>Radiatively-Inefficient (super-Eddington)</td>
<td>100%</td>
</tr>
<tr>
<td>$\tau \gg 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h/r \ll 1$</td>
<td>Thin Disk (High/Soft or Thermal state)</td>
<td>10%</td>
</tr>
<tr>
<td>$\tau \gg 1$</td>
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\[ \lambda = \frac{L}{L_{edd}} \]
Blandford & Znajek jets

Credit: Alexander Tchekhovskoy
Jet acceleration theory

• Situation a bit different when jets get superfast \((v > v_{FMS})\)
• Conversion of magnetic energy into kinetic energy by reordering of field lines past FMS (fast magnetosonic surface)
• Reproducing a realistic collimation profile in simulations is a challenge
Acceleration and collimation of jets

Credit: Asada & Nakamura, 2012
Simulations

• Assumes a radiatively inefficient sub-eddington rate torus
• Assumes axisymmetric ideal MHD
• Adds viscosity and resistivity through use of Riemann solver (HLL)
• Uses density floors to mass-load the jet
• Uses grids that can resolve the substructure of the jet over 5 orders of magnitude
Movie: Toroidal pinch instabilities forming
Configuration

- Giant ADAF extending till the Bondi radius of $5 \times 10^5 R_G$
Results: Jet’s core resolved properly

• The inner core (cusp in $B_p$) is resolved due to high resolution focusing of a static grid → Important for differential collimation
Jet structure
Results: Low res model (left); High res model (right)

- $\mu$ gives the jet’s theoretically maximum Lorentz factor $\gamma$
- $\sigma$ gives jet’s magnetization
- $\delta>1$ means that the jet’s opening angle is larger than it’s Mach cone angle
Results: Collimated (left) vs Uncollimated (right)

• $\mu$ gives the jet’s theoretically maximum Lorentz factor $\gamma$
• $\sigma$ gives jet’s magnetization
• $\delta>1$ means a causally disconnected jet
My simulations vs other work

- Mckinney et al 2006 observed heating due to toroidal pinch instabilities and found inefficient acceleration.
- We observe the same toroidal pinch instabilities but no heat, instead the magnetization is higher and the jet becomes chaotic.
Origin of break: Toroidal pinch instabilities?

Credit: Walker et al, 2008

Credit: Mertens et al, in prep
Standing shock features in jets

Credit: NASA
Conclusion

• Axisymmetric jet solutions extended by an order of magnitude in distance due to GPU code
• Highly disordered magnetic field observed
• Toroidal pinch instabilities prevent the jet from accelerating efficiently
• Simulations will be extended to 3D, which is very challenging
Future work: Tilted disk simulations

- Computationally very challenging
- High tilt, long run time and very thin disks most rewarding but highly challenging
- Best opportunity to see (inner) disk precession in combination with alignment of inner disk and black hole
- Resolving the jet is doable as well in 3D
- Tidal disruption event simulations are even more challenging but provide a cleaner result out of first principles