Low angular momentum solutions, Bondi and Bondi-Hoyle-Lyttleton

Accretion disks are easy!

Radiated energy of accretion disks

Circular orbit

$$mv^2 = \frac{GMm}{r}$$

(Kepler problem, centrifugal force balance)

$$2E_{\mathrm{kin}} + E_{\mathrm{pot}} = 0$$

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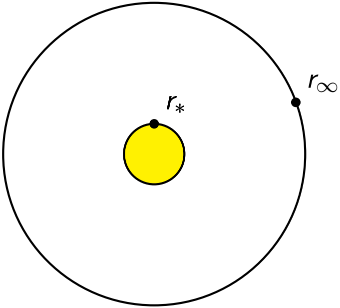
$$E_{\mathrm{tot}} = {}^1\!/_2\, E_{\mathrm{pot}} = -{}^1\!/_2 \frac{GMm}{r}$$

Loss of dynamic energy through accretion



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$$\Delta E_{\mathrm{tot}} = E_{\mathrm{tot},*} - E_{\mathrm{tot},\infty}$$

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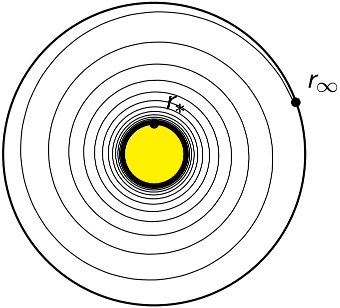

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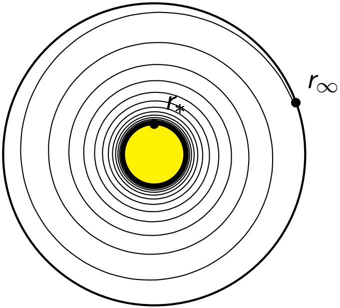

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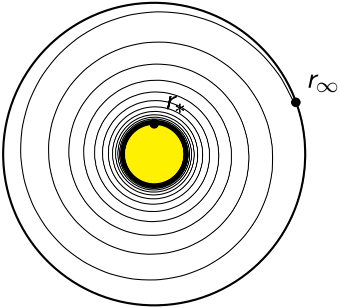

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In Physics, energy is conserved!

The energy lost from the dynamical system $\Delta E_{\mathrm{rad}} = -{}^1\!/_2 E_{\mathrm{pot},*}$ is emitted as radiation!

Accretion disks are hard!

Turbulence makes disks work

Reynolds number

$$R_e = \frac{inertial}{viscous} \sim \frac{Rv_\phi}{\nu} = \frac{Rv_\phi}{\lambda \tilde{v}}; \quad v_r \sim \frac{\nu}{R}; \;\; R_e = \frac{v_\phi}{v_r}$$

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Use molecular values: Thermal mean free path
$\lambda = \lambda_d = 7 \times 10^{-2} \left(\frac{T}{10^4 \mathrm{K}}\right)^2 \left(\frac{N}{10^{15} \mathrm{cm}^{-3}}\right)^{-1} \ln \Lambda^{-1} \mathrm{cm}$
Sound-speed: $\tilde{v} = c_s$

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Disks become turbulent

With molecular values $\frac{v_r}{v_\phi} < 10^{-14}$, a disk wouldn't work!
Turbulent viscosity $\nu = \alpha c_s H$ (Shakura Sunyaev (1973).

The Bondi solution

Bondi flow

Why study spherical accretion?

- Train intuition with exact accretion solution
- Predict accretion rate (and luminosity)
- Quantify influence of a gravitating object
- The role of the sound-speed

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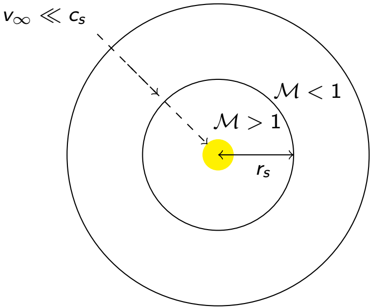

Sketch of the spherical geometry, a subsonic flow at $r = \infty$ becomes supersonic before impacting on the central object.

Bondi flow

Seek: stationary solution that smoothly accelerates from $v_\infty = 0$ to the central object ($dv/dr < 0$).

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Total differential $d\dot{M} = 0 = \frac{2}{r} + \frac{d\rho}{\rho} + \frac{dv}{v}$

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Isothermal (for now)

$$c_s^2 = \frac{P}{\rho}; \quad \frac{dP}{dr} = c_s^2 \frac{d\rho}{dr}$$

Bondi flow

Eliminate P, ρ and shake:

$$\frac{r}{v}\frac{dv}{dr} = \frac{2}{v^2/c_s^2 - 1}\left(1 - \frac{GM/(2c_s^2)}{r}\right)$$

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$dv/dr < 0$ requires:

- $v < c_s$ $(r \to \infty)$
- $v > c_s$ $(r \to 0)$

The solution traverses a "sonic point" at $r = r_s = \frac{GM}{2c_s^2}$ where $v^2 = c_s^2$.

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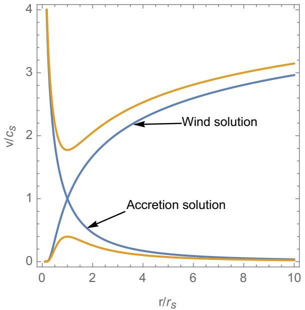

The accretion solution uniquely goes through the sonic point with $dv/dr < 0$.

What is the accretion rate for $c_{s,\infty}, \rho_\infty$?

$$\dot{M} = 4\pi r_s^2 \rho(r_s) c_s(r_s)$$

Integral of the momentum equation: Bernoulli

$$\int v dv = -\int \frac{GM}{r^2} dr - \underbrace{\int \frac{1}{\rho} dP}_{c_s^2/(\gamma-1)}$$

$$\Rightarrow B = \frac{v^2}{2} + \frac{c_s^2}{(\gamma-1)} - \frac{GM}{r} = const.$$

Compare B at $r \to \infty$ with B at $r = r_s$

$$\frac{c_{s,\infty}^2}{\gamma - 1} = c_s^2 \left(\frac{1}{2} + \frac{1}{\gamma - 1} - 2 \right) \Rightarrow c_s^2 = c_{s,\infty}^2 \left(\frac{2}{5 - 3\gamma} \right)$$

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Putting it together

$$\dot{M} = \pi \frac{G^2 M^2}{c_{s,\infty}^3} \rho_\infty f(\gamma); \quad f(\gamma) \in [1, 4.5]$$

$$\dot{M} \simeq 1.4 \times 10^{11} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{\rho_\infty}{10^{-24}\mathrm{g\,cm^{-3}}}\right) \left(\frac{c_{s,\infty}}{10\mathrm{km s^{-1}}}\right)^{-3} \mathrm{g\,s^{-1}}$$

$$\dot{M}c^2 \sim 10^{32} \mathrm{erg\,s^{-1}}$$

ISM accretion onto e.g. neutron star barely detectable!

What is the accretion rate for $c_{s,\infty}, \rho_\infty$?

Exercise: Galactic center

$M = 4 \times 10^6 M_\odot; \quad c_{s,\infty} = 500 \mathrm{km\,s^{-1}}; \;\; \rho_\infty = 10^{-24}\,\mathrm{gcm^{-3}}$

$$\dot{M}c^2 =$$

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$$\begin{aligned} \dot{M}c^2 &= 10^{21} \times 10^{11} \times 10^{13} \times 50^{-3} \mathrm{erg\,s^{-1}} \\ &\simeq 10^{40}\,\mathrm{erg\,s^{-1}} \end{aligned}$$

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$$\simeq 10^{40}\,\mathrm{erg\,s^{-1}} \gg 10^{37} \mathrm{erg\,s^{-1}}\ \text{observed!}$$

Galactic center extremely radiatively inefficient! Or are we loosing mass somewhere?

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The radius of influence

Investigate Bernoulli:

$$\frac{c_{s,\infty}^2}{\gamma - 1} = \frac{v^2}{2} + \frac{c_s^2}{\gamma - 1} - \frac{GM}{r}$$

c_s increases only slowly $c_s^2 \simeq c_{s,\infty}^2 \Rightarrow$ Term balancing grav.: $v^2/2$.
Becomes noticeable when $v^2 \approx c_{s,\infty}^2$

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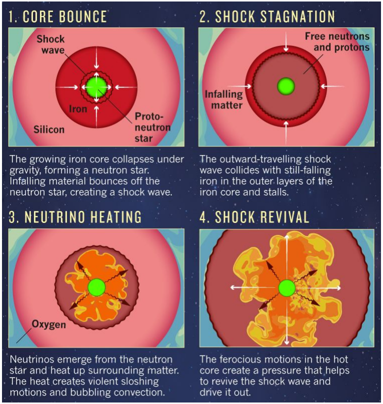
$$= 7 \times 10^5 r_{\mathrm{g}}$$

Applications of the theory

- **Stellar collapse and Supernovae**
- Low luminosity AGN (Sgr A* is $\sim 10^3$ times under-luminous though!!)
- Cosmological simulations
- Star and planet formation



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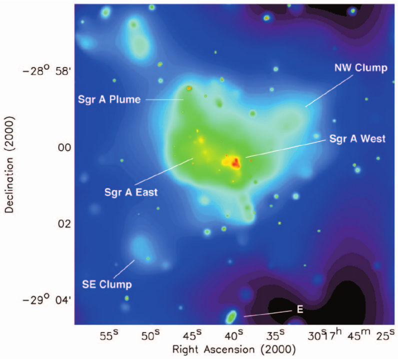

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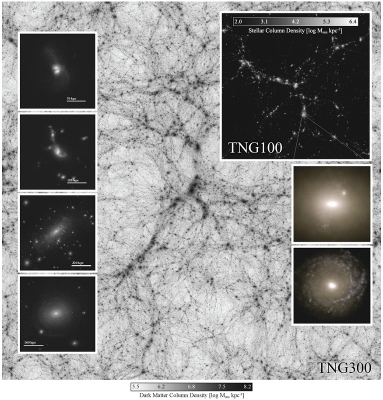

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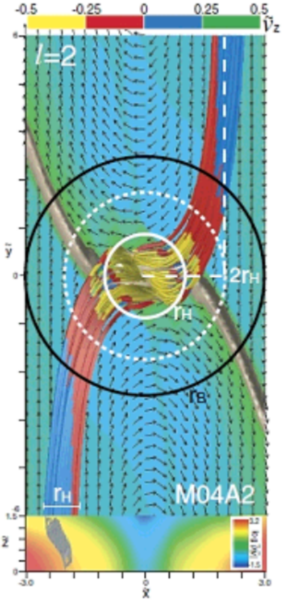
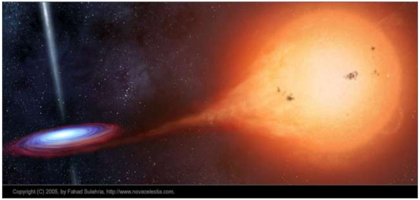


Accretion onto a moving target

Motivation



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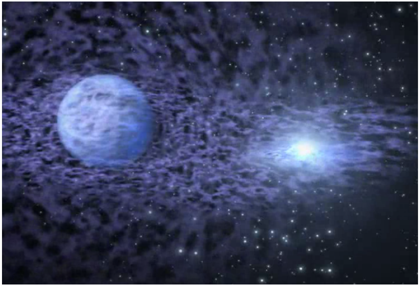

- Low mass X-ray binary (LMXB): massive compact object (BH) and less massive star; **Roche-lobe filling**
- High mass X-ray binary (HMXB): massive star and (less massive) compact object companion; **Wind accretion**

Vela X-1: prototypical HMXB

$18M_{\odot}$ Supergiant and $2M_{\odot}$ neutron star

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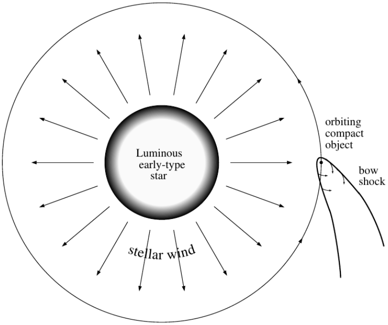

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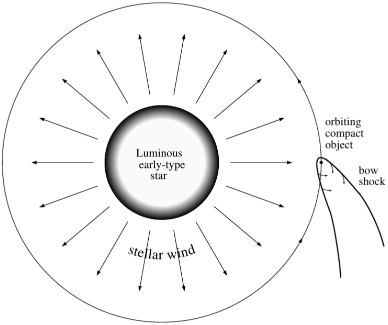

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Vela X-1

$18M_\odot$ Supergiant and $2M_\odot$ neutron star.
Stellar wind: $\approx 1000 \mathrm{kms}^{-1}$;
sound-speed: $\approx 10 \mathrm{km\,s}^{-1}$
$\Rightarrow$ Mach 100! Highly **supersonic**.

The Ballistic approximation

Unimportance of pressure gradients: back to momentum equation

$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \frac{1}{\rho}\frac{dP}{dr}$$

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Equation of motion

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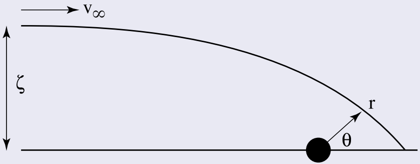
just like test-particles!

Hoyle-Lyttleton accretion rate

Actual equation of motion

$$\ddot{r} - r\dot{\theta}^2 = -\frac{GM}{r^2}$$

$$r^2\dot{\theta} = \xi v_\infty$$



Capture radius

When the flow hits the axis behind the accretor:

$$v_\theta = 0; \quad v_r = -v_\infty$$

Bound material:

$$\frac{1}{2}v_\infty^2 - \frac{GM}{r} < 0$$

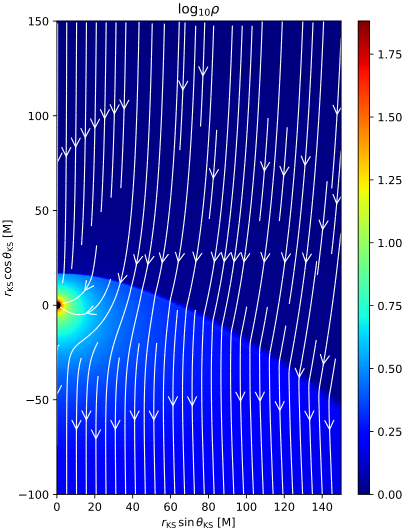
Solve for critical impact parameter $\xi_{\rm HL}$: $\xi_{\rm HL} = \frac{2GM}{v_\infty^2}$

Hoyle-Lyttleton accretion rate: cross-section of $\pi\xi_{\rm HL}^2$

$$\dot{M}_{\rm HL} = \pi\xi_{\rm HL}^2 v_\infty \rho_\infty = \frac{4\pi G^2 M^2 \rho_\infty}{v_\infty^3}$$

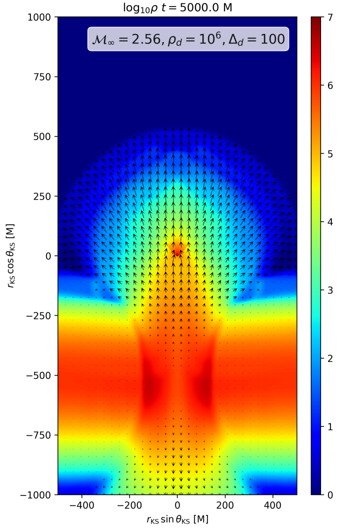
Outlook on the exercises - Part 1

- Simulate a BHL flow onto a black hole with HARM
- Initialize a completely new problem!
- Visualize the results
- Check the ballistic approximation against the 2D simulation
- Check resolution dependence of the solution
- Scale the simulation to physical values and calculate accretion luminosity



Outlook on the exercises - Part 2

- Simulate how a black hole impacts on an accretion disk with HARM
- Modify your BHL setup
- Visualize the results
- Vary parameters of the disk
- See how the accretion rate goes up as the black hole gobbles up matter from the disk

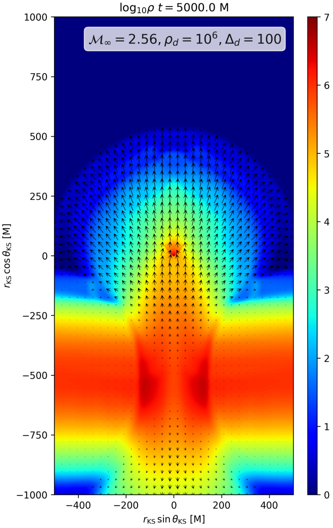


How to go about it - 1

Make sure you are comfortable with:

- compiling harmpi on cartesius
- submitting jobs using slurm
- copying data from cartesius to the VM (or your laptop)
- Visualize the results on the VM
- Change parameters and do it all over again!

Try not to overwrite results from previous runs (we have 300 GB per user on /data on the VM)



Modify HARMPI

watch out for these:

```
/*#########################################################################################*/
/*#########################################################################################*/
/*#########################################################################################*/
/*#########################################################################################*/
/*######### In the following part of 'init_BHL' the initial conditions are defined ########*/
/*#########################################################################################*/
/*#########################################################################################*/
/*#########################################################################################*/
/*#########################################################################################*/
```

Files to modify:

- init.c
- bounds.c
- decs.h

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- Spherical accretion: sonic point, expressions for acc. rate and radius of influence
- Accretion onto a supersonically moving target: ballistic approximation, expressions for accretion rate
- We have calculated: the bondi radius in the galactic center and the accretion luminosity