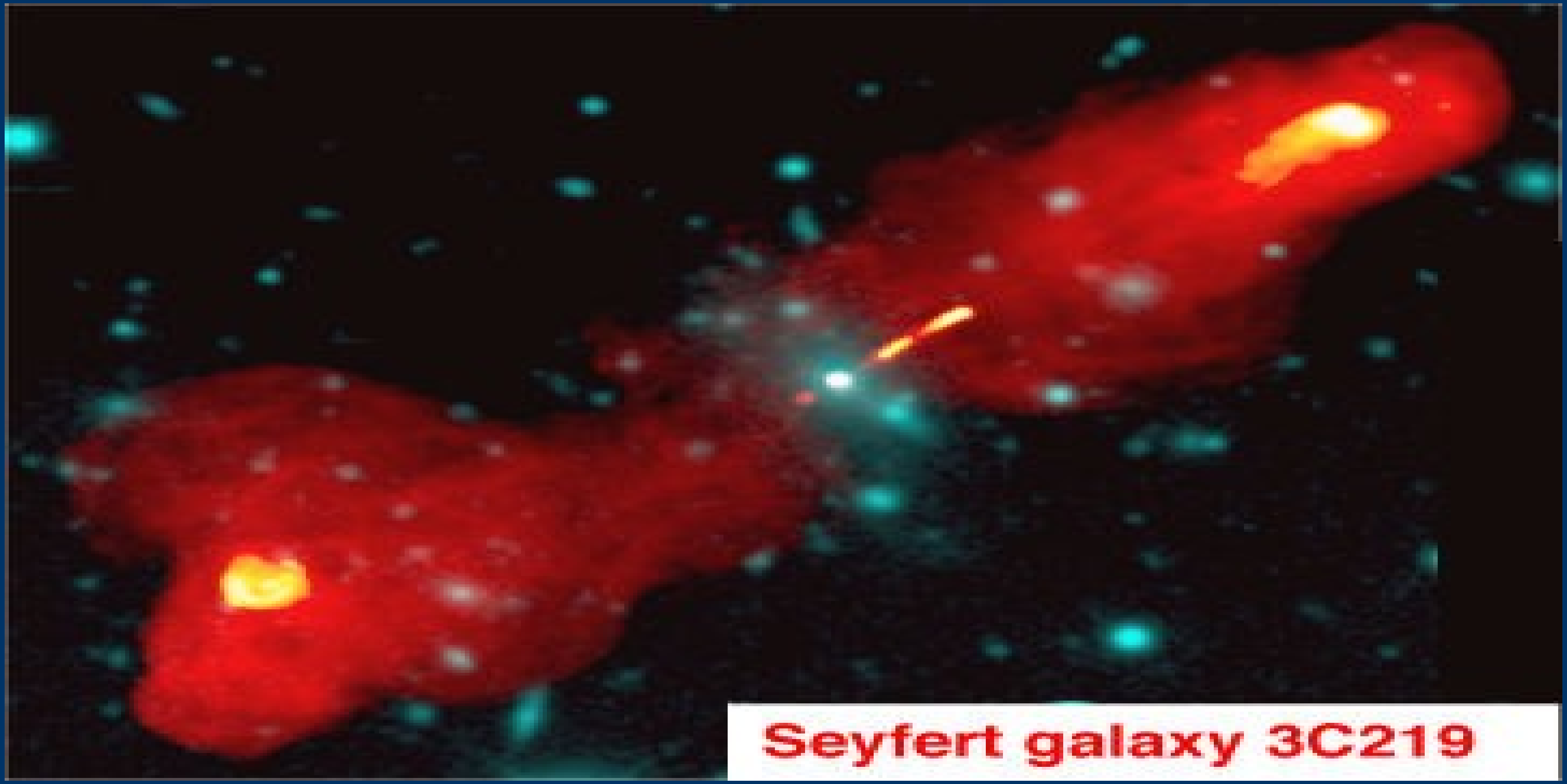
Astrophysical Jets from accreting Black Holes



by Max Häberlein

Outline

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III. Deceleration Mechanisms
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I.Description of astrophysical jets

- Jets are a tremendous, elongated outflows of plasma
- Jets can be observed in a huge spatial and energetic scale reaching from stellar size to galaxy size
- There are many sources for jets
- Our universe is full of jets

I.1 Sources of Jets

Stellar

Object	*Physical System*
Young Stellar Objects	*Accreting* Star
HMXBs	*Accreting* NS
LMXBs	*Accreting* NS
Pulsars (?)	Rotating NS
Planetary Nebulae	*Accreting* Nucleus or Interacting Winds

Extragalactic

Object	*Physical System*
AGN	Accreting Supermassive BH
GRBs	Accreting BH

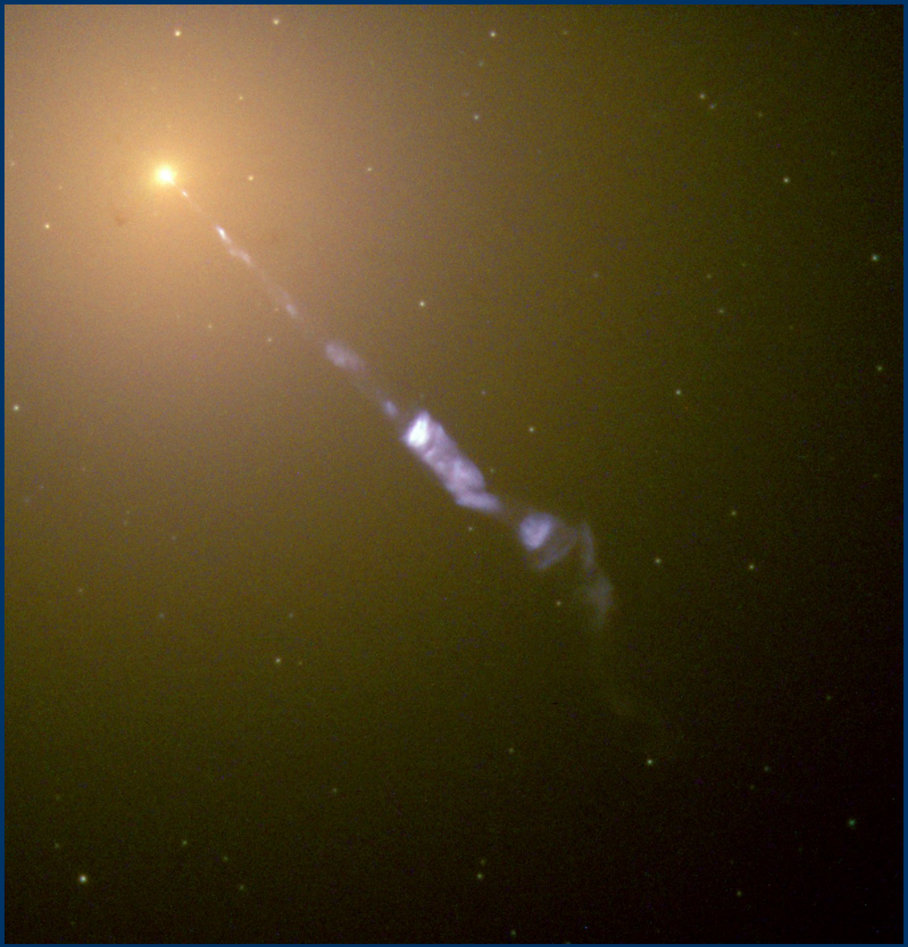
I.1 Sources of Jets
Active Galaxy Nuclei (AGN)

- supermassive black hole in the core of a galaxy

  $M \sim 10^6 M_{Sun}$

- there are 3 types:
  1. Seyfert galaxies
  2. Quasars
  3. Blazars
- emits ulrarelativistic jets

$$V_{escape} \simeq V_{jet} \simeq c \,;\, \gamma \sim 3$$



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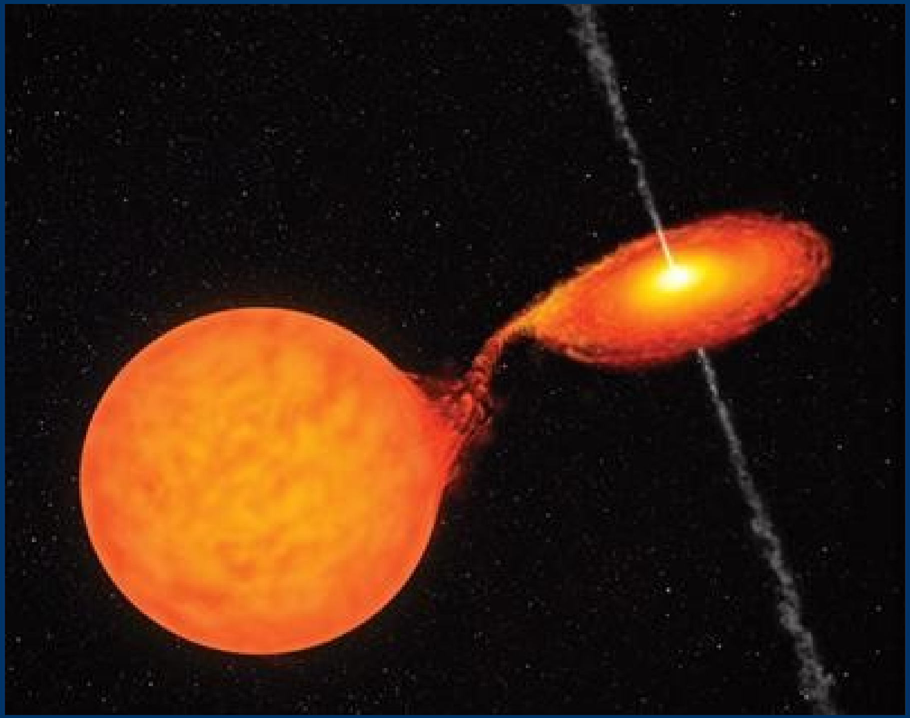
I.1 Sources of Jets
Microquasars

- binary star system consisting of a massive normal star and a black hole bzw neutron star
- timescale proportional to M -> evolution of the jets within days (quasars take years)
- jet velocity

$$V_{escape} \simeq V_{jet} \simeq 0.6c$$

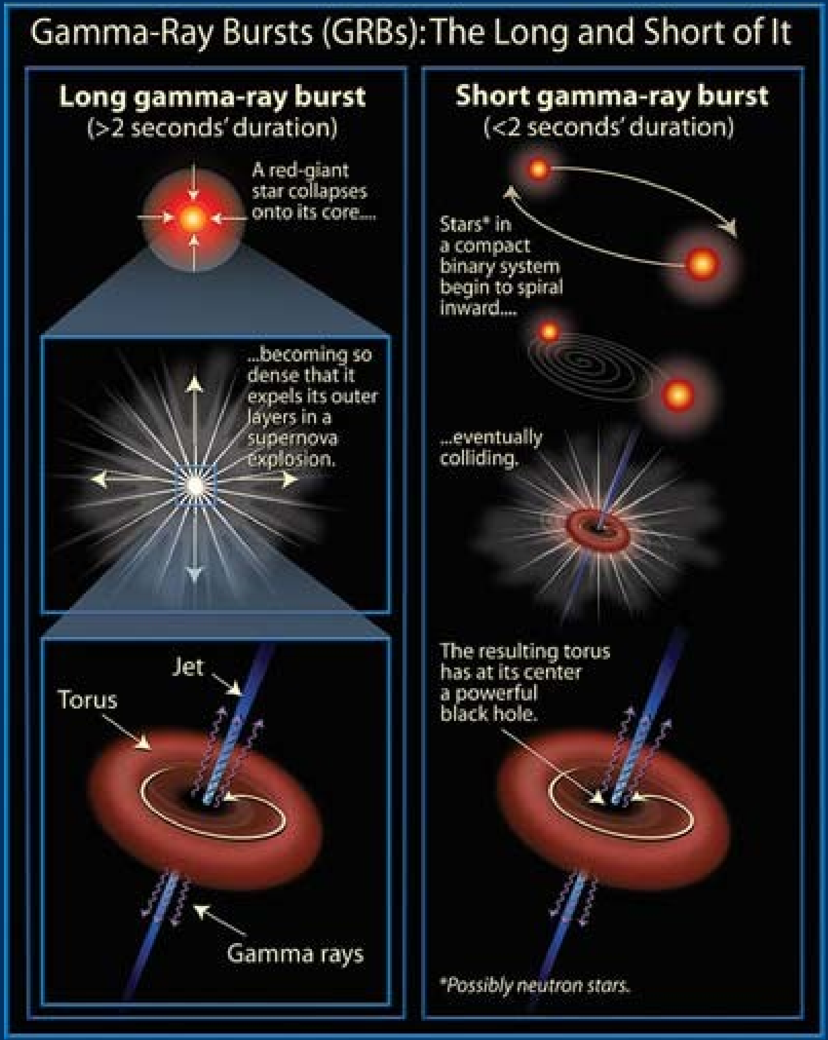


artists view of a microquasar

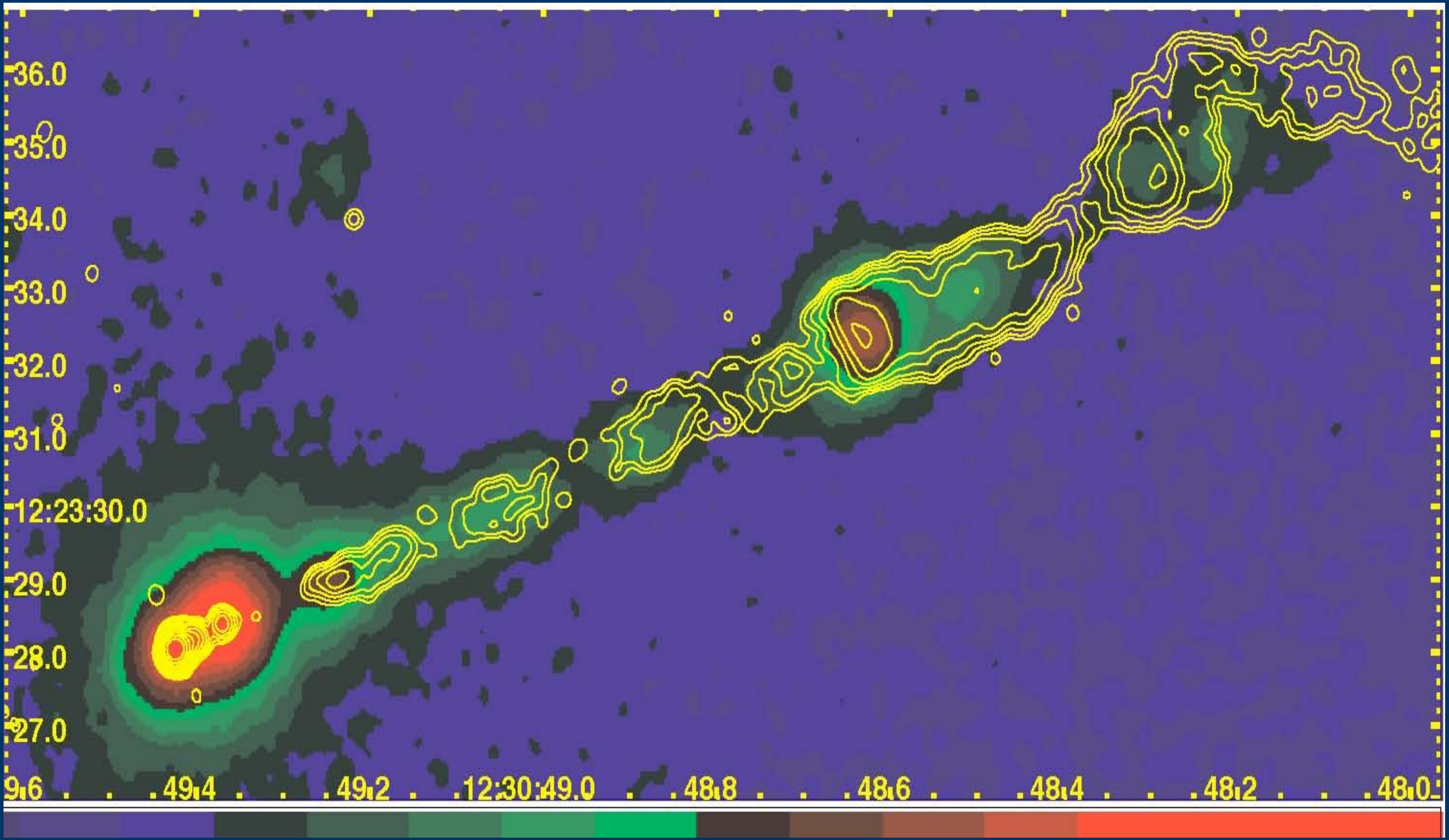
I.1 Sources of Jets
Gamma Ray Bursts (GRB)

- flashes of gamma ray emitted by heavy stars that collapse
- lifetime ~ s
- followed by a longer-lived afterglow
- most luminous events in the sky
- jet velocity

$$V_{escape} \simeq V_{jet} \simeq c\,;\gamma \sim 100$$

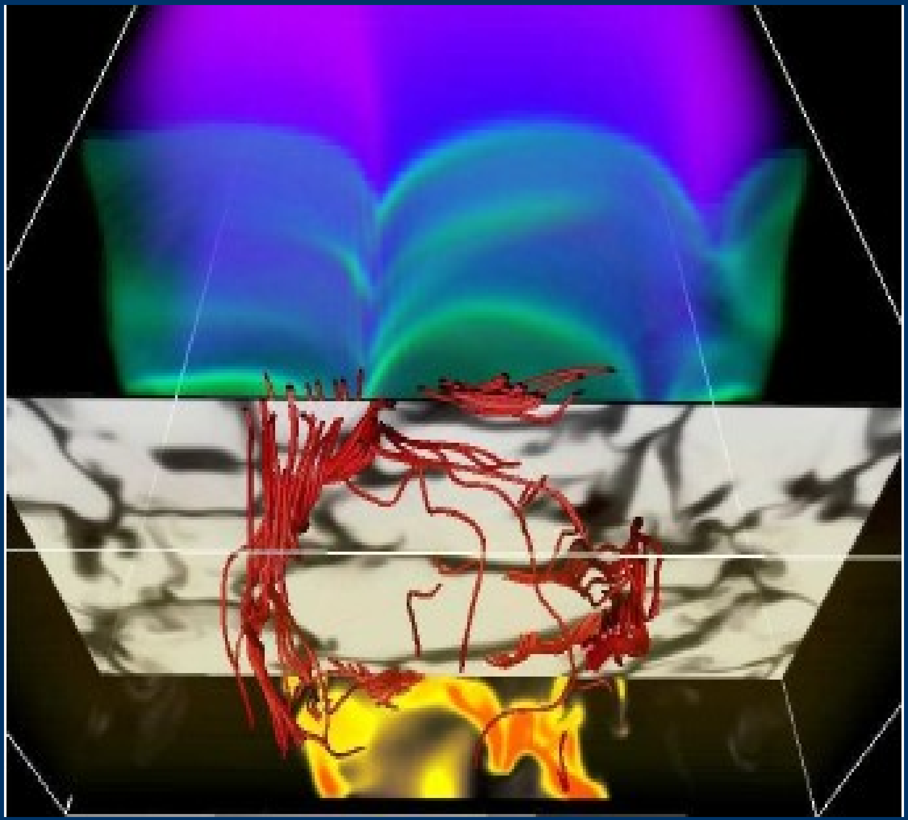


I.2 Structure of Jets

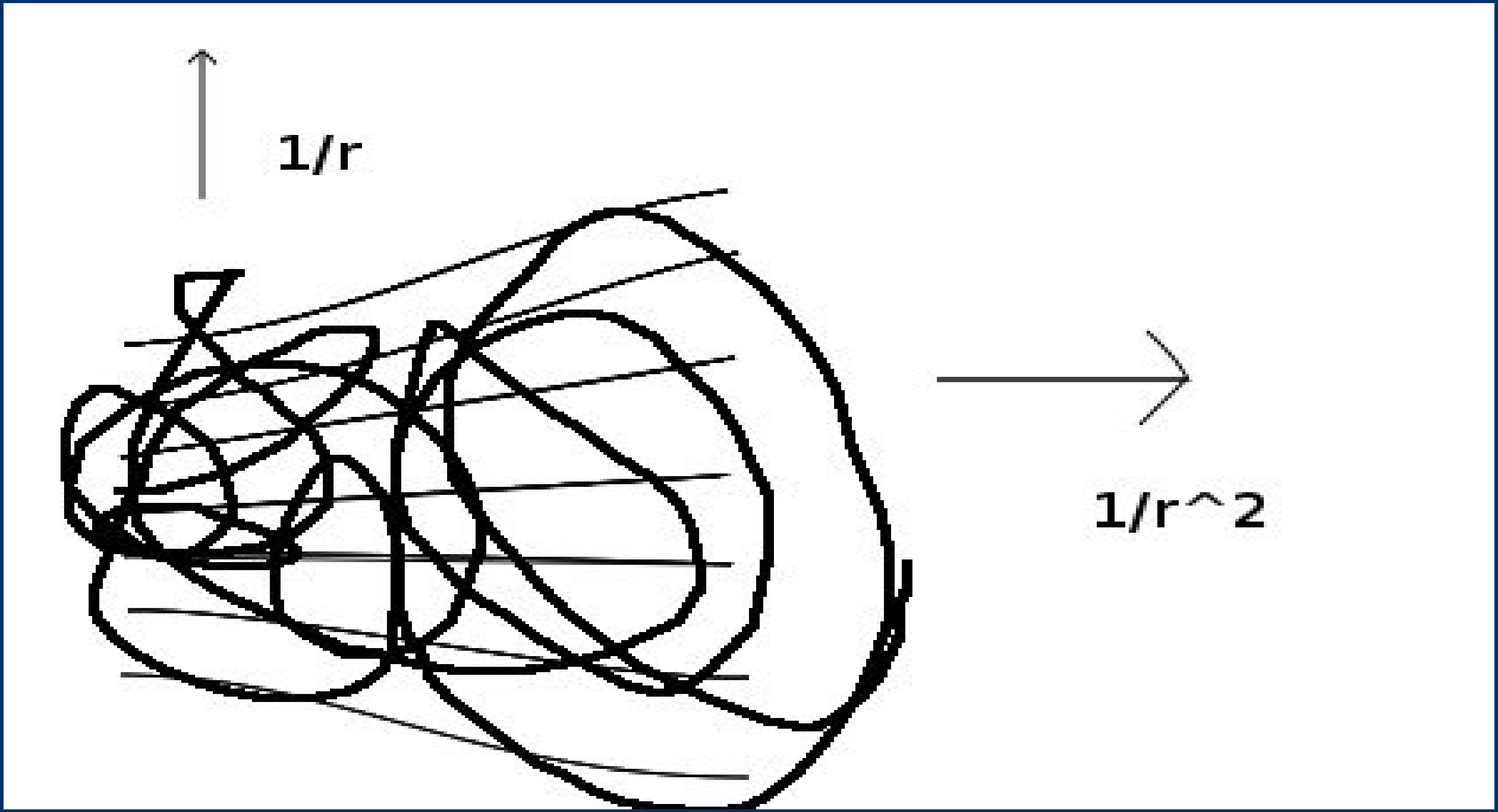


I.3 Formation Mechanism

- not known exactly
- there mainly two different theories
- most popular:
  the magnetic field lines spin with the BH. As you go to outer regions they get faster than light. This can be handled by a non-stationary model where field lines can be twisted -> jet with extreme energy



I.4 Jet Collimination



II. Acceleration in Jets

II.1 Fermi Acceleration

- relativistic particle is reflected by a moving gas cloud
- transformations lead to energy gain

$$\frac{\Delta E}{E} \approx 2\left(\frac{u}{c} + \frac{u^2}{c^2}\right)$$

II.2 Diffusive shock acceleration

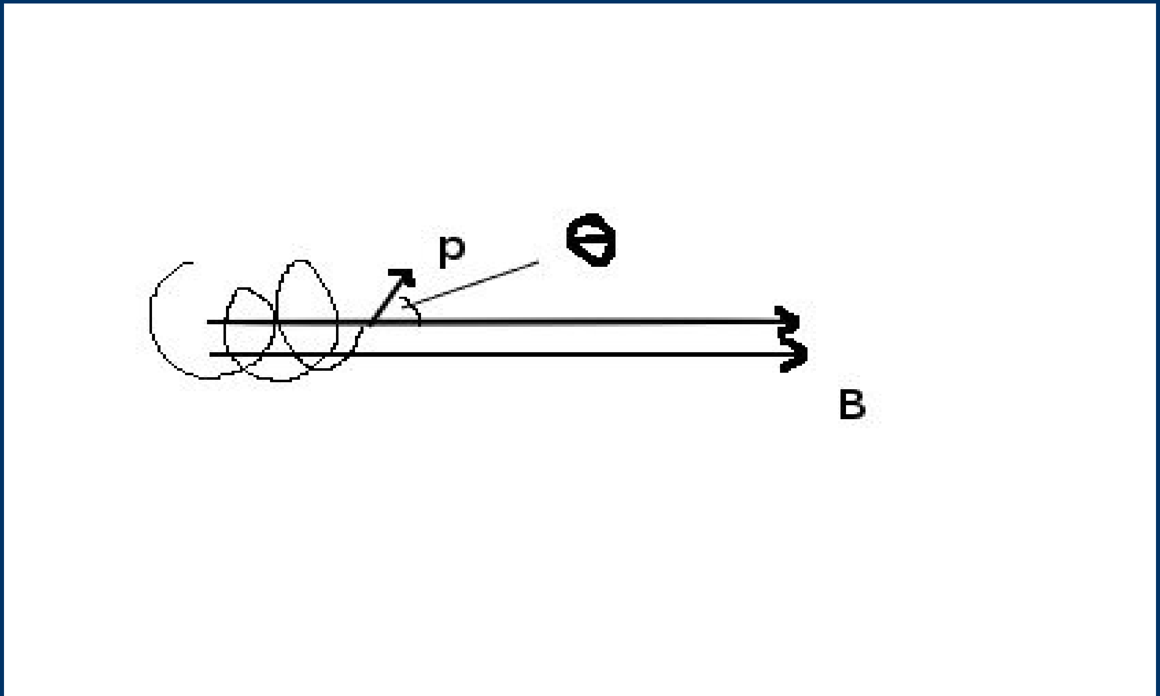
- In a uniform magnetic field a freely moving charged particle follows a helical trajectory. The particles pitch is defined as:

$$\mu = \frac{\vec{p} \cdot \vec{B}}{pB}$$

so its momenta are

$$p_{para} = \mu p$$

$$p_{perp} = (1 - \mu^2)^{0.5} p$$



II.2 Diffusive shock acceleration

- What happens if a small static irregularity is imposed on the uniform field?

- We are using some simplifications in the following slides
  1. shock normal is parallel to B-field
  2. shock is planar
  3. we are only considering staionary solutions
  4. individual particle velocity v is much greater than U, the velocity of the up- and downstream.

II.2 Diffusive shock acceleration

- Momentum is contained because the electric field is identically zero
- the pitch changes
- describable in phase space by a diffusion equation, which is, considered the scattering is sufficiently stochastic, isotropic

$$\frac{\partial f}{\partial t} = \nabla(\boldsymbol{\kappa} \nabla f)$$

II.2 Diffusive shock acceleration

- static irregularities are unrealistic
- There are two types of scattering centre motion

1. large-scale motions of the background which advects the scattering centres
2. motion of the individual centres relative to the background (Fermi II)

$$\frac{\partial f}{\partial t}=\vec{\nabla}(\boldsymbol{k}\vec{\nabla} f)\rightarrow\frac{\partial f}{\partial t}+\vec{U}\cdot\vec{\nabla} f=\vec{\nabla}(\boldsymbol{k}\vec{\nabla} f)$$

$$\frac{\partial}{\partial t} f(x,p)=\frac{\partial f}{\partial x}\frac{\partial x}{\partial t} \qquad \vec{U}\cdot\vec{\nabla} f=U\cdot\frac{\partial f}{\partial x}$$

II.2 Diffusive shock acceleration

- Liuovilles theorem: phase space density has to be constant along any trajectory
- for every convergence in position space you will need a divergence in momentum space

$$\frac{\partial f}{\partial t} = \vec{\nabla}(\boldsymbol{k}\vec{\nabla} f) \rightarrow \frac{\partial f}{\partial t} + \vec{U} \cdot \vec{\nabla} f = \vec{\nabla}(\boldsymbol{k}\vec{\nabla} f) + \frac{1}{3}\vec{\nabla} \cdot \vec{U} p \frac{\partial f}{\partial p}$$

1 1

II.2 Diffusive shock acceleration

- motion of the individual centres relative to the background (Fermi II)

$$\frac{\partial f}{\partial t}=\vec{\nabla}(\boldsymbol{k}\vec{\nabla}f)\rightarrow\frac{\partial f}{\partial t}+\vec{U}\cdot\vec{\nabla}f=\vec{\nabla}(\boldsymbol{k}\vec{\nabla}f)+\frac{1}{3}\vec{\nabla}\cdot\vec{U}\,p\frac{\partial f}{\partial p}+\frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D\frac{\partial f}{\partial p})$$

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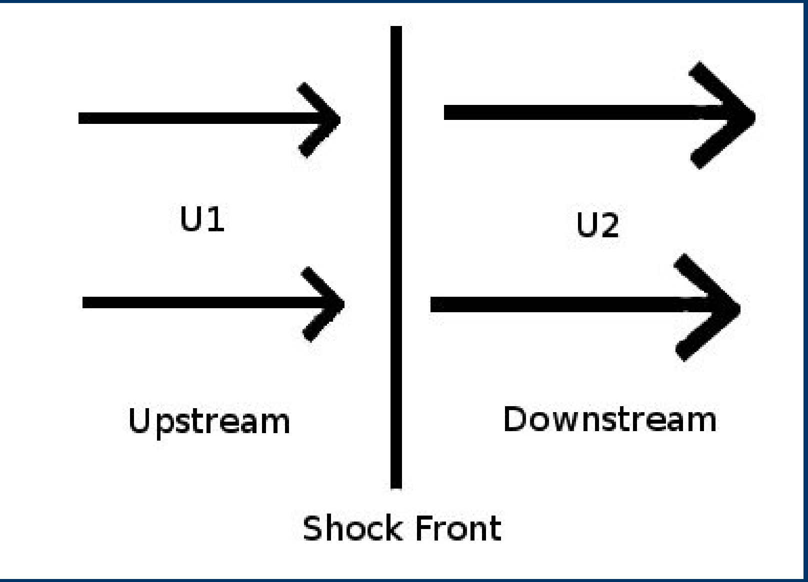
II.2 Diffusive shock acceleration

- U(x) = U1 for x < 0
  U(x) = U2 for x > 0

  $$\Rightarrow U\frac{\partial f}{\partial x}=\frac{\partial}{\partial x}\left(\kappa_{xx}\frac{\partial f}{\partial x}\right)$$

  as a steady solution except for x = 0



II.2 Diffusive shock acceleration

- boundary conditions:
  1. $x \to -\infty \Rightarrow f(x,p) \to f_1(p)$
  2. $x \to \infty \Rightarrow |f(x,p) < \infty|$
  3. the momentum space distribution has to be continuous
  4. phase space density is invariant under Lorentz-transformations

II.2 Diffusive shock acceleration

- 1+2 gives

$$f(x,p) \sim \begin{cases} f_1(p) + g_1(p)\exp\left(\int_0^x \frac{U\,dx'}{\kappa}\right) \\ g_2(p) = f_2(p) \end{cases}$$

II.2 Diffusive shock acceleration

- The anisotropic phase space density $F(x,p,\mu)$ can be expanded:

$$F(x,p,\mu) \sim f(x,p) - \mu\lambda \frac{\partial f(x,p)}{\partial x}$$

where

$$\kappa = \frac{\lambda v}{3}$$

II.2 Diffusive shock acceleration

- Then 3+4 lead to

$$F(x,p,\mu) \sim \begin{cases} f_1 + g_1 - \mu \dfrac{3U}{v} g_1 & x = 0^- \\ f_2 & x = 0^+ \end{cases}$$

II.2 Diffusive shock acceleration

- it follows with $r = \frac{U_1}{U_2}$

$$(r-1)p\frac{\partial f_2}{\partial p} = 3\mathrm{r}(f_1 - f_2)$$

and hence with $a = \frac{3\mathrm{r}}{r-1}$

$$f_2 = a\, p^{-a} \int_0^p p'^{a-1} f_1(p')\, dp'$$

- if a “softer” power law is incoming, a power law with slope a will come out

II.2 Diffusive shock acceleration

- From shock theorie it follows for the compression ratio

$$r = \frac{\gamma + 1}{\gamma - 1 + M^{-2}}$$

that means for $M \rightarrow \infty$ and $\gamma = \frac{5}{3}$ as for a non-relativistic plasma

$$r = 4 \Rightarrow a = 4 \Rightarrow N(x) = \int \frac{1}{4\pi p'^2} f(x, p') dp' \sim \epsilon^{-2}$$

and for $\gamma = \frac{4}{3}$ in a relativistic plasma

$$r = 7 \Rightarrow a = 3.5 \Rightarrow N(x) = \int \frac{1}{4\pi p'^2} f(x, p') dp' \sim \epsilon^{-1.5}$$

II.2 Diffusive shock acceleration

- Problem: One doesnt know how the acceleration works on physical grounds
- Answer: Microscopic derivation

II.2 Diffusive shock acceleration

- What is the probability for a particle of escaping downstream towards ∞?

$$N_{esc} = n U_2$$

- What is the probability of crossing the shock front?

$$N_{uptodown} = \int_0^1 \mu v n \frac{d\mu}{2} = \frac{n}{2}\frac{v}{2}$$

$\Rightarrow$ probability of not returning

$$\frac{n U_2}{n v / 4} = \frac{4 U_2}{v}$$

II.2 Diffusive shock acceleration

- What is the average momentum gain when crossing the shock front?

$$p_{shockfront} = p(1 + \mu \frac{U_1}{v}) \quad \rightarrow \quad p_{downstream} = p(1 + \mu \frac{(U_1 - U_2)}{v})$$

$$\langle \Delta p \rangle = p \int_0^1 [\frac{\mu (U_1 - U_2)}{v}] 2 \mu d \mu = \frac{2}{3} p \frac{(U_1 - U_2)}{v}$$

II.2 Diffusive shock acceleration

- In reality p is a random variable, but for v >> U and initial momentum identically p_0

$$p_n \sim \Pi_{i=1}^{n} p_0 [1+\frac{4}{3}\frac{(U_1-U_2)}{v_i}] \Rightarrow \ln(\frac{p_n}{p_0}) \sim \frac{4}{3}(U_1-U_2)\Sigma_{i=1}^{n}\frac{1}{v_i}$$

- The probability of crossing the shock front n times is

$$P_n \sim \Pi_{i=1}^{n}(1-\frac{4U_2}{v_i}) \Rightarrow \ln(P_n) \sim -4U_2\Sigma_{i=1}^{n}\frac{1}{v_i} = -3\frac{U_2}{U_1-U_2}\ln(\frac{p_n}{p_0})$$

$$\Rightarrow P_n = (\frac{p_n}{p_0})^{-3U_2/(U_1-U_2)} = (\frac{p_n}{p_0})^{-3/(r-1)}$$

II.2 Diffusive shock acceleration

- With $$N(x.p) = \int_p^\infty 4\pi p'^2 f(x, p') dp'$$

$$N(-\infty, x) = \begin{cases} 0 & p > p_0 \\ N_0 & p < p_0 \end{cases}$$

$$\Rightarrow N(\infty, x) = \frac{U_1}{U_2} N_0 \qquad p < p_0$$

II.2 Diffusive shock acceleration

- it follows

$$N_2(p_n) = P_n N(p_0) = \frac{U_1}{U_2}\left(\frac{p_n}{p_0}\right)^{-3/(r-1)}$$

$$f_2(p) = \frac{-1}{4\pi p^2}\frac{\partial N_2}{\partial p} = \frac{N_0}{4\pi}\frac{3U_1}{U_1 - U_2}\left(\frac{p}{p_0}\right)^{-3r/(r-1)} = \frac{N_0}{4\pi} a \left(\frac{p}{p_0}\right)^{-a}$$

II.2 Diffusive shock acceleration

- We again obtain a power law, but unlike other Fermi processes the slope is fixed
- to verify the slope a, we can look at the synchrotron emission
  - if the initial spectum is a power law, the synchrotron spectrum will be a power law with slope

$$\alpha=\frac{a-1}{2}=0.5$$

II.2 Diffusive shock acceleration

Hotspot	Spectal index α_0
3C 20 west(B)	-0.53 ± 0.05
3C 33 south	-0.75 ± 0.04
Hs only	-0.59 ± 0.08
3C 111 east	-0.54 ± 0.05
3C 123 east	-0.52 ± 0.05
min cutoff	
Pictor A west	-0.39 ± 0.02
3C 273 A	-0.45 ± 0.10

III. Deceleration Mechanisms

- Synchrotron Emission $X \rightarrow X' + \gamma$
- Inverse Compton Scattering $X + \gamma \rightarrow X' + \Sigma \pi$
- proton – proton collision $p + p' \rightarrow \Sigma \pi$
- Bremstrahlung

III.1 Synchrotron Emission

- particles gyrating in the plasma field can emit photons
- Synchrotron Loss Time:

$$\tau_{sync} = \frac{6\pi m_{p,e}^3 c}{\sigma_T \gamma_{p,e} m_e^2 B^2}$$

- Average Acceleration Time:

$$\tau_{acc} = \frac{80}{3\pi} \left(\frac{c}{U^2}\right) \frac{r_g}{b(\beta-1)} \left(\frac{r_{g,max}}{r_g}\right)^{\beta-1}$$

III.1 Synchrotron Emission

- With $\tau_{acc} = \tau_{sync}$

$$\Rightarrow \gamma_{max} \Rightarrow f_{max} = 3 \cdot 10^{14} (3b(\frac{U^2}{c^2}))\,Hz$$

III.2 Inverse Compton Scattering

- particles interact with the photonic background
- similar as for the sychrotron emission it follows considering both effects:

$$f_{max} = 3 \cdot 10^{14} (3 b (\frac{U^2}{c^2})) f(a) Hz$$

where a is the ratio of photonic to magnetic energy density

III.2 Inverse Compton Scattering

III.3 Other Processes

- 1. proton – proton collision lead to a very fast deceleration
  2. the probability only gets dominant if the jet for example crosses a gas cloud
- particles emit bremsstrahlung when they cross electric fields

IV Conclusion

- My aim was
  1. to present a short overview about the theoretical methods used in jet physics and especially to explain fermi acceleration in a more simple way
  2. to show where the 2 in the power law spectrum comes from
  3. to show that there are many things still to be done regarding jets
- My aim for myself was to make a talk about theory interesting, which I found is a hard thing to do and probably will not have worked.. this time

II.2 Diffusive shock acceleration

- 3+4 with $p \rightarrow p' = p(1 - \mu \frac{U}{v})$ gives

$$f_1 + g1 = f_2$$

$$U_1 p \frac{\partial}{\partial p}(f_1 + g_1) + 3 U_1 g_1 = U_2 p \frac{\partial}{\partial p} f_2$$