The efficiency of the magnetic acceleration in relativistic outflows

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Outline:

- σ_∞ in exact relativistic-MHD solutions with applications to AGN and GRB jets, and Crab-like pulsar winds
- how the efficiency depends on the conditions near the central object
- conclusion

- The observed pc-scale acceleration in AGN outflows (e.g., Sudou et al. 2000 for the NGC 6251, Unwin et al. 1997 for the 3C 345) supports magnetic driving.

- A recent measurement of a high ($80 \pm 20\%$) linear polarization in the prompt emission in GRB 021206 has been interpreted as evidence that the outflow was magnetically driven (Coburn & Boggs 2003).

Is the flow still Poynting-dominated after the end of the magnetic acceleration? Which is the value of σ_∞?

$$\sigma = \frac{\text{Poynting flux}}{\text{particle energy flux}}$$

Could ideal MHD explain the value $\sigma_\infty = 0.003$ (Kennel & Coroniti 1984) in the Crab-pulsar wind?

Known solutions of the ideal MHD equations

Michel's solution gives $\gamma_\infty = \mu^{1/3}$ and $\sigma_\infty = \mu^{2/3} >> 1$
($\mu c^2 = \frac{\text{total energy flux}}{\text{mass flux}}$; μ is the maximum possible γ).

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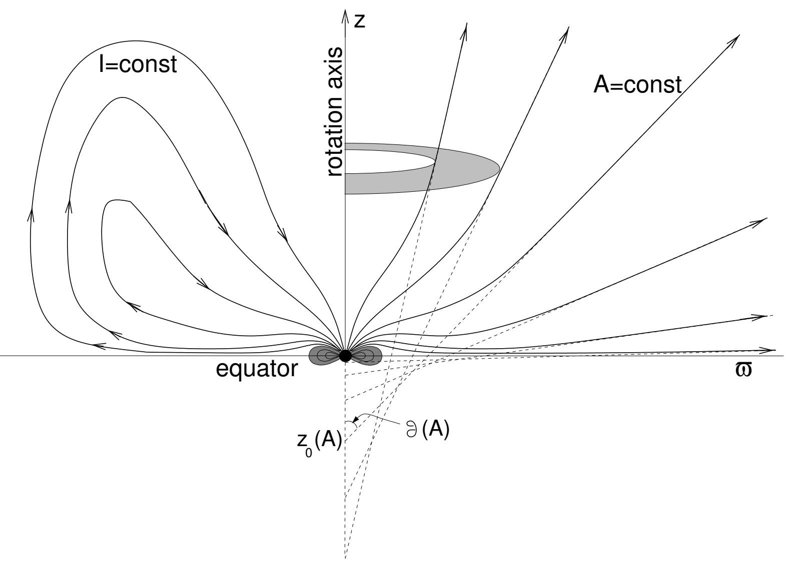
Necessary to solve the transfield because the line shape controls the acceleration:



$\gamma \uparrow$ when $\varpi |B_\phi| \downarrow$

$E = |\mathbf{V}/c \times \mathbf{B}| \approx |B_\phi|$, $E = (\varpi\Omega/c)B_p$

So, $\varpi |B_\phi| \propto \varpi^2 B_p = (\varpi^2/\delta S)\delta A$

($A =$ magnetic flux function).

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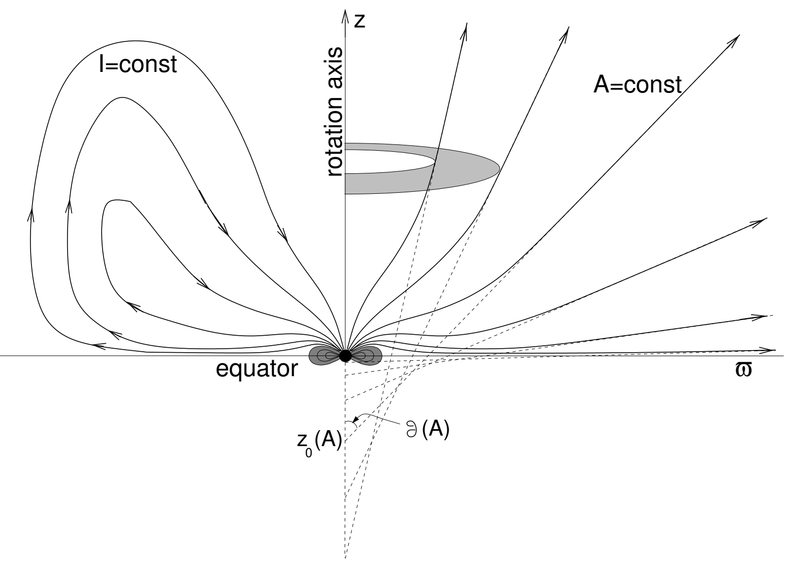

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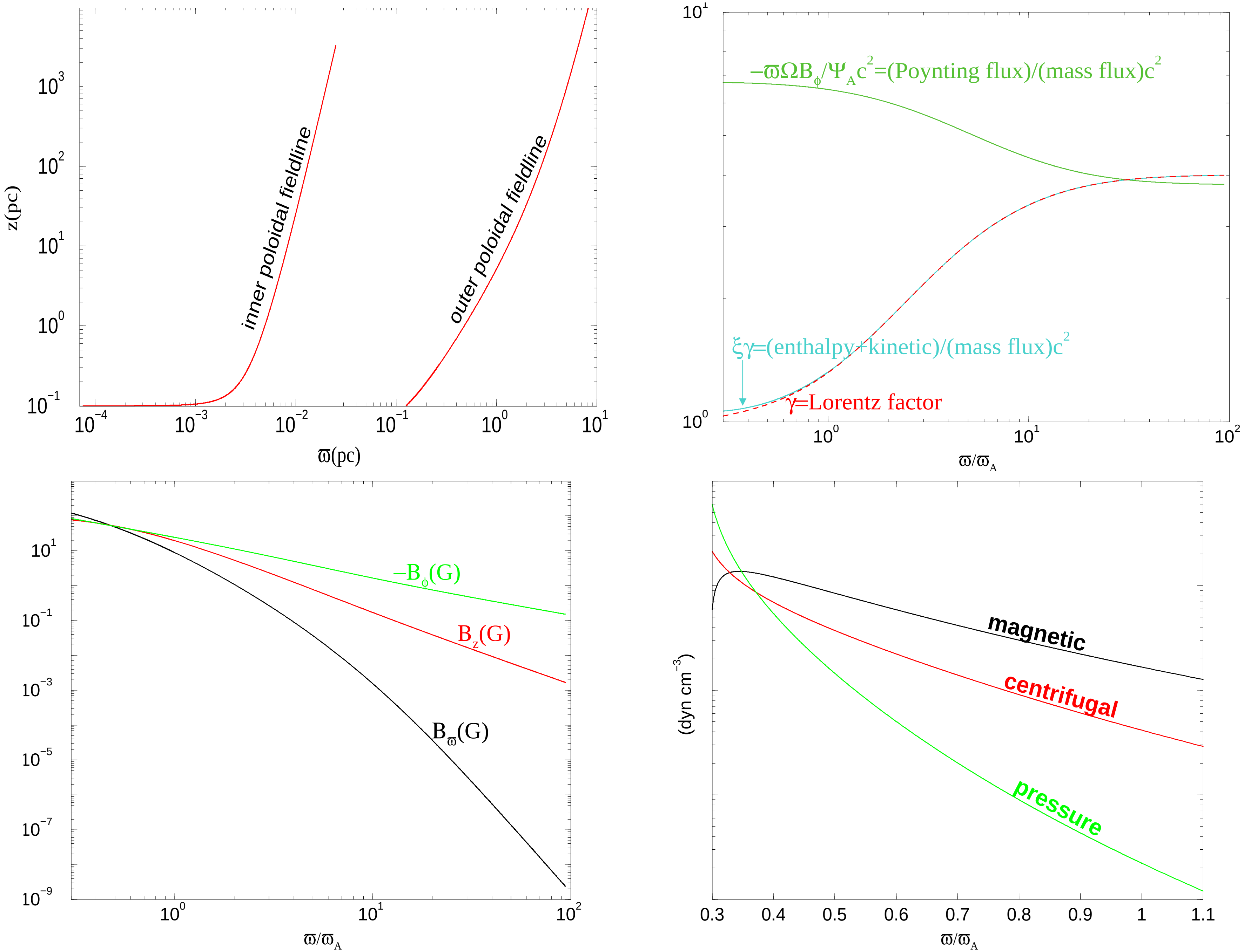
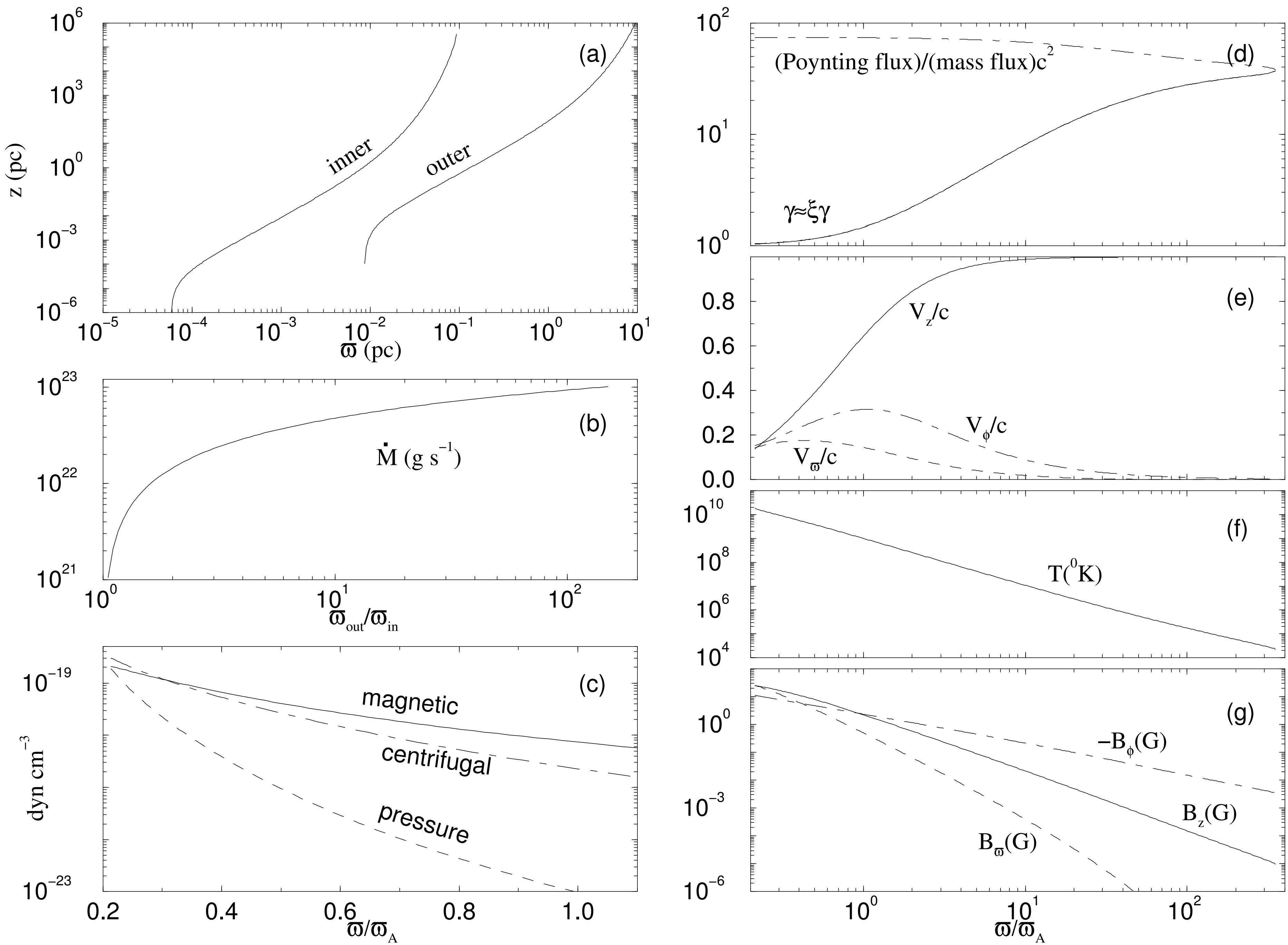
Transfield: $$\underbrace{f_E + f_B}_{\propto \nabla(\varpi B_\phi/\gamma)} = \underbrace{f_I}_{\propto \varpi/\mathcal{R}} + f_C + f_P$$

Important to keep small terms even in asymptotic analysis!

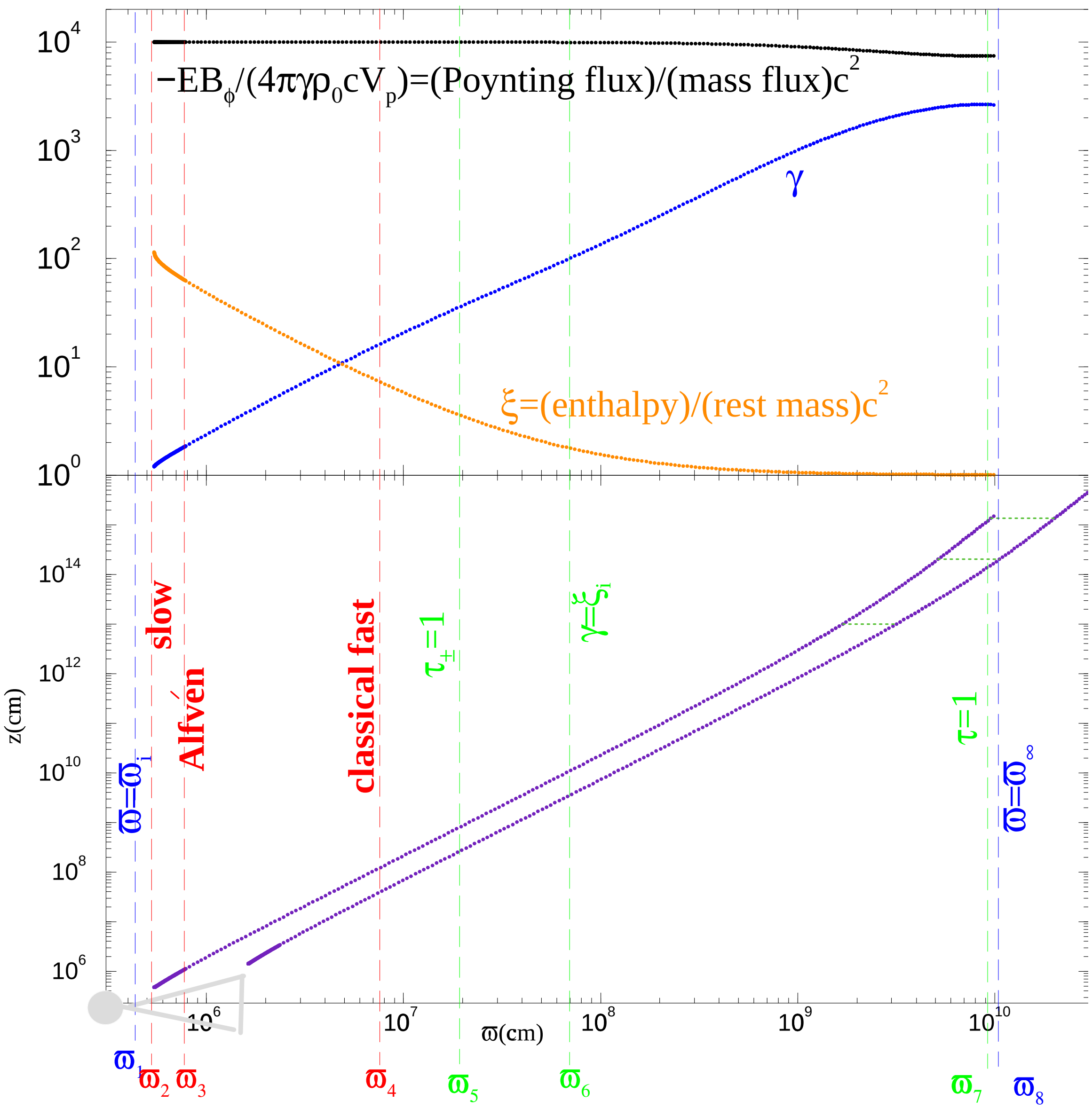
AGN outflows (Vlahakis & Königl to be submitted)

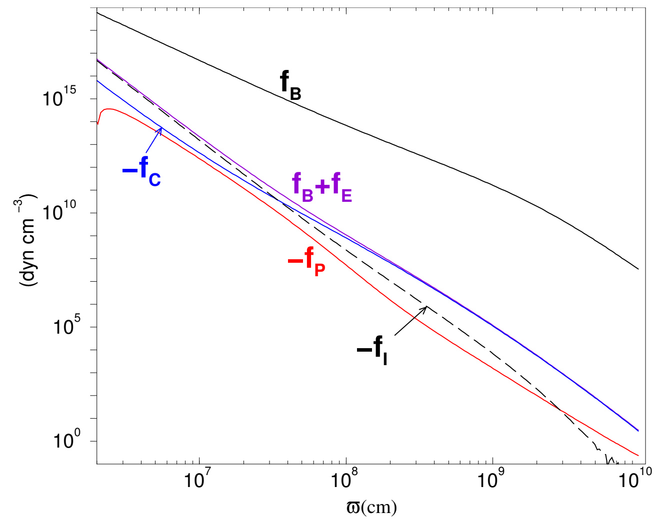


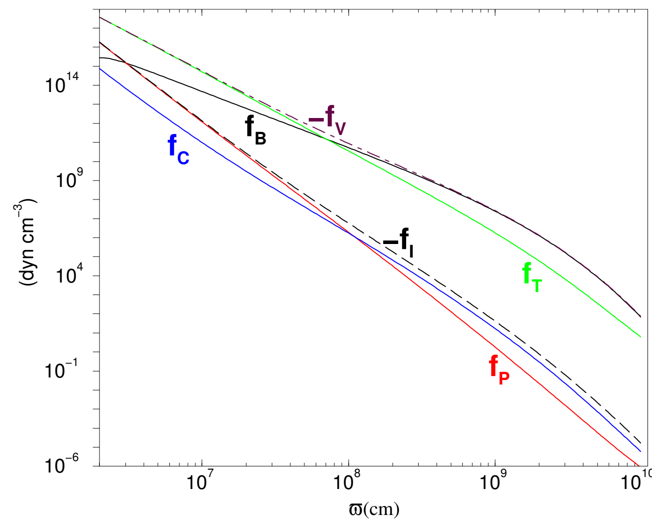


(a)
inner
outer
z (pc)
ϖ (pc)
(b)
Ṁ (g s^-1)
ϖ_out/ϖ_in
(c)
magnetic
centrifugal
pressure
dyn cm^-3
ϖ/ϖ_A
(d)
(Poynting flux)/(mass flux)c^2
γ≈ξγ
(e)
V_z/c
V_φ/c
V_ϖ/c
(f)
T(^0K)
(g)
−B_φ(G)
B_z(G)
B_ϖ(G)
ϖ/ϖ_A

GRB outflows (Vlahakis & Königl 2003, ApJ, 596, 1080 and 1104)



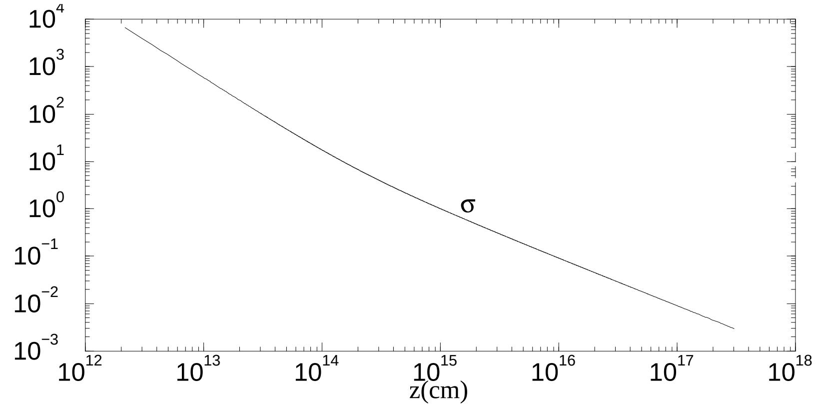




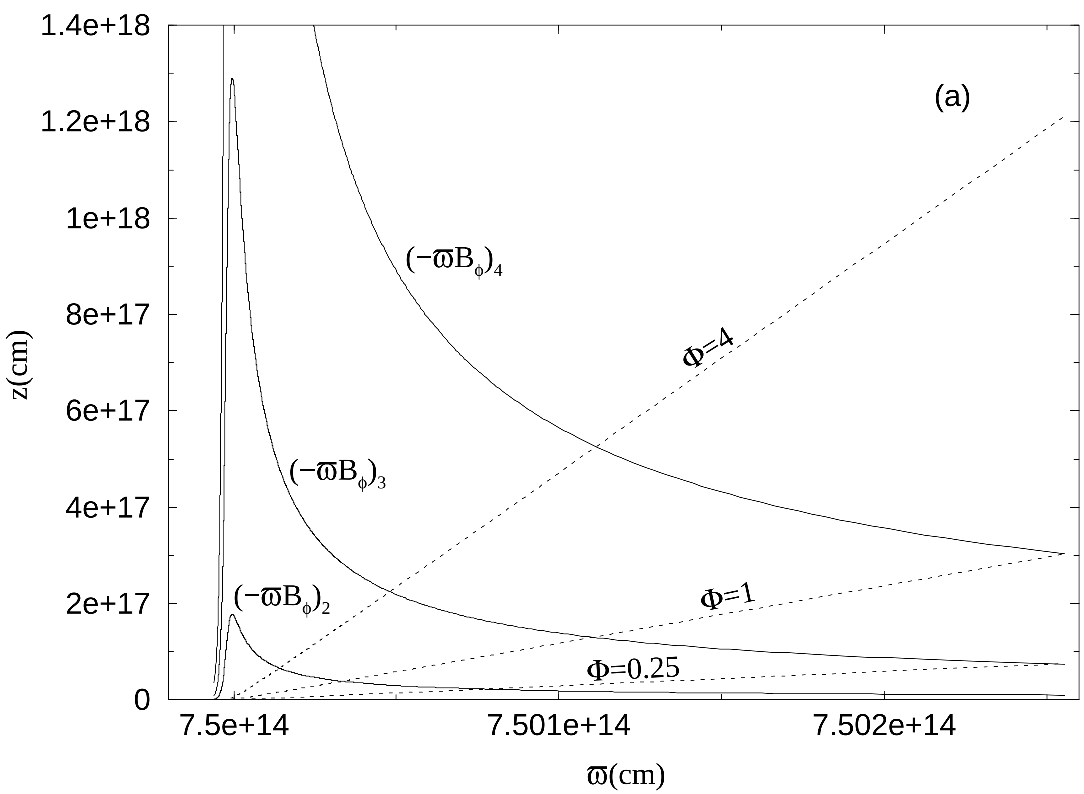
$$\sigma_\infty \approx 1$$

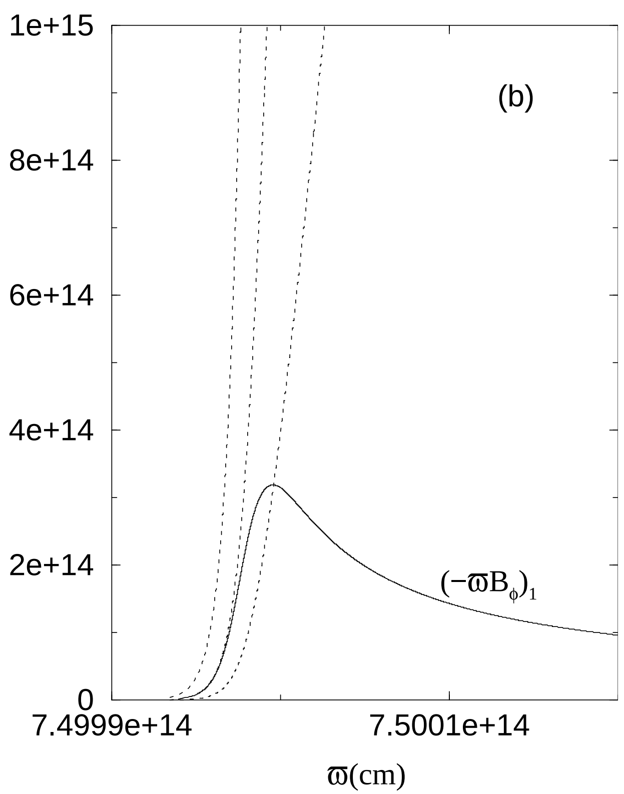
equipartition between Poynting and kinetic energy fluxes

Crab-like pulsar winds
(Vlahakis, ApJ, 600, January 2004 issue [preprint astro-ph/0309292])



$\sigma_\infty << 1$ **is possible !**





Chiueh, Li, & Begelman 1998:

Transfield $\rightarrow \varpi/\mathcal{R} \approx 1/\gamma^2 << 1 \Leftrightarrow$ straight lines.

So, $\varpi^2 B_p =$ const, and no acceleration to $\sigma_\infty << 1$ is possible.

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NO!

Straight lines are not always $z \propto \varpi$ (conical I).

The general case is (conical Ia)

$$z = z_0(A) + \frac{\varpi}{\tan\vartheta(A)} \Rightarrow \frac{\varpi^2 B_p}{A} = \frac{1}{A\vartheta'/\sin\vartheta - Az_0'\sin\vartheta/\varpi} \downarrow$$

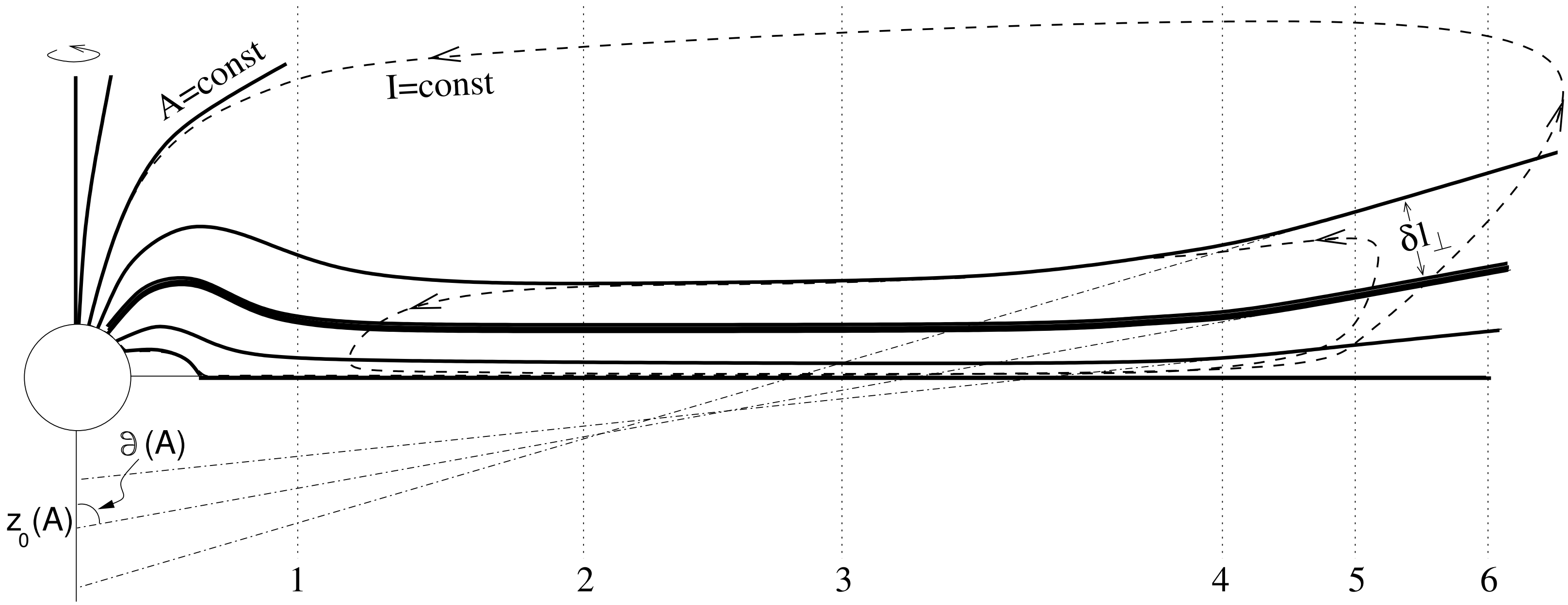
This gives $\sigma_{\rm min} = \frac{\sin\vartheta}{A\vartheta'}\frac{\sigma_{\rm M}}{\mu}$

$\sigma_{\rm M} =$ Michel's parameter $= \mu\left(\frac{A}{B_p\varpi^2}\right)$ base of the superAlfvénic regime

So, $\sigma_{\rm min} = \frac{\sin\vartheta}{A\vartheta'}\left(\frac{A}{B_p\varpi^2}\right)$ base of the superAlfvénic regime ,

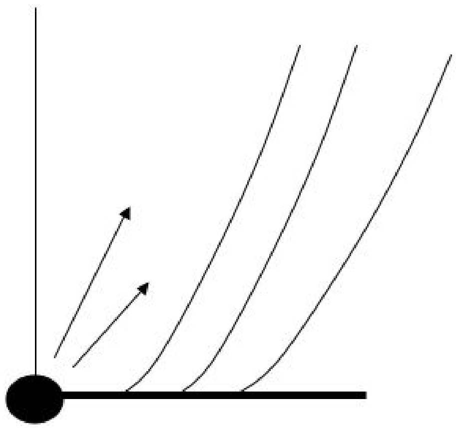
or, $\sigma_{\rm min} = \frac{\sin\vartheta}{\underbrace{A\vartheta'}_{\sim 1}}\left(\frac{A\Omega}{2|I|}\right)$ base of the superAlfvénic regime .

• A scenario for equatorial pulsar winds



• AGN and GRB jets

almost parallel poloidal fieldlines ⇒
$\frac{\varpi^2 B_p}{A} = \frac{\varpi^2}{\delta S}\frac{\delta A}{A}$ increases $\propto \varpi$.



Conclusion

- In order to solve for the acceleration it is absolutely necessary to solve for the line shape as well.
  - ⋆ Michel's (1969) solution is not exact $\rightarrow$ the σ_∞ in MHD outflows in principle is (and has been found) $<< \mu^{2/3}$.
  - ⋆ Models with prescribed fieldlines are meaningless.

- In the case of a smooth magnetic flux distribution near the source ($B_p \varpi^2 \sim A$), the efficiency is close to 50%, or, $\sigma_\infty \sim 1$ (confirmed by self-similar solutions).

- If bunched fieldlines are somehow created near the source ($B_p \varpi^2 >> A$), the efficiency could be close to 100%, or, $\sigma_\infty << 1$ (confirmed by self-similar solutions).