Role of large scale magnetic fields in AGN jets

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What carries bulk of energy in ultra-relativistic jets?

Ultra-relativistic jets

- *Pulsars, $\Gamma \sim 10^6$*
- ***AGNs , $\Gamma \sim$ 10-30***
- *GRBs , $\Gamma \sim$100-1000*
- *Microquasars , $\Gamma \sim 2$*
- *X-ray binaries , $\Gamma \sim 10$*

Prime mover

- *Ions*
- *Pairs*
- ***Large scale B-field***

$$B_\varphi \sim \frac{1}{r} \Rightarrow B_\varphi^{\ 2} \sim \frac{1}{r^2}; \qquad \rho c^2 \sim \frac{1}{r^2}$$

$$\sigma = \frac{B_\varphi^{\ 2}}{8\pi\,\Gamma \rho c^2} \sim \mathrm{const}$$

- ***What is σ in AGN jets?***

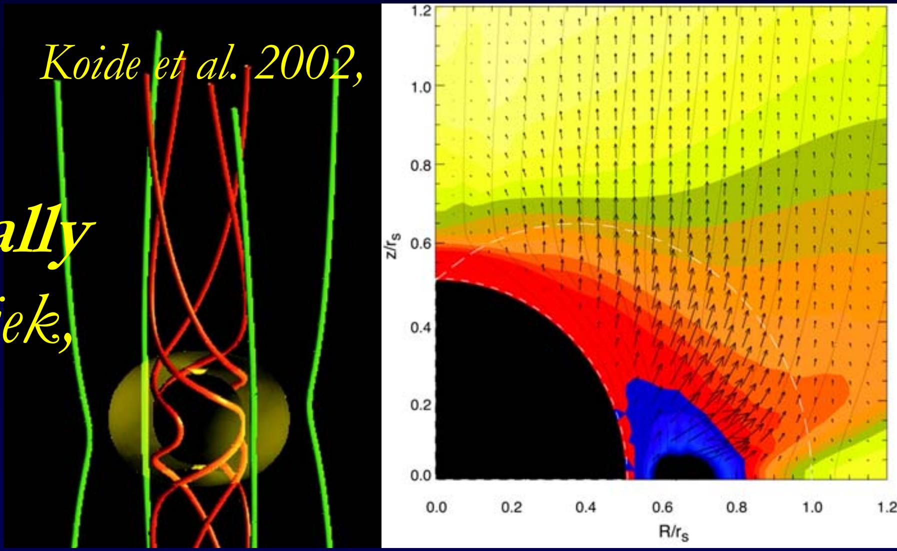
- ***Π of parsec scale AGN jets imply that σ is non-negligible, $\sigma \geq 1$, and may be >> 1***

Jet launching: large scale B-field

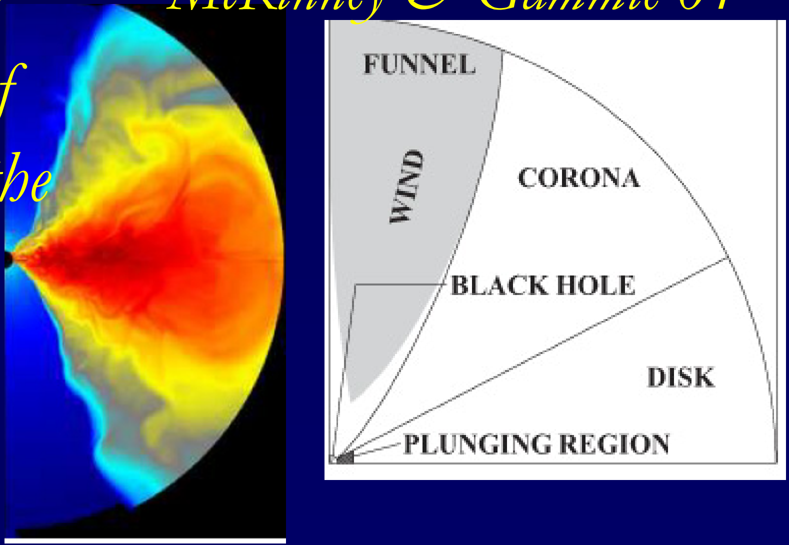
- ***Jets are launched and collimated electromagnetically*** *(Lovelace et al., Blandford & Znajek, Blandford & Payne, Camenzind, Fendt; Koide, Shibata and others).*
- *Numerical simulations: McKinney & Gammie: "low density polar regions of the numerical models agree well with the Blandford-Znajek model ".*

  Similar results by Hawley &Krolik

Koide et al. 2002,



McKinney & Gammie 04

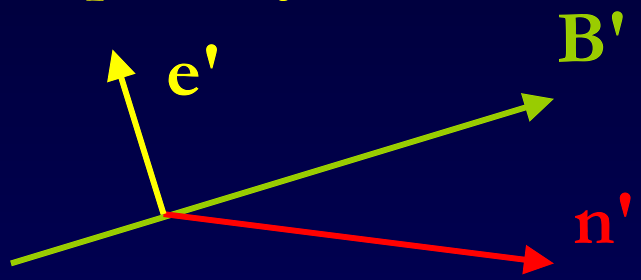


Π in AGN jets

- *Π at pc scale is produced at internal shocks by compression of random B-field (?) (Lang 80)*
- ***Is Π at pc scale consistent with large scale B-field?***
  - *in radio: synchrotron*
  - *consider optically thin regions*

Synchrotron emission by *relativistic* sources: Lorentz transformation of Π

- *In plasma frame*



$$\mathbf{e}' \perp \mathbf{B}', \mathbf{n}'$$

$$n \sim \gamma^{-p}, \Pi_{\max} = \frac{p+1}{p+7/3}$$

- *In laboratory frame*

$$\mathbf{e} = \frac{\mathbf{n} \times \mathbf{q}}{\sqrt{\mathbf{q}^2 - (\mathbf{n} \bullet \mathbf{q})^2}}$$

$$\mathbf{q} = \hat{\mathbf{B}} + \mathbf{n} \times (\mathbf{v} \times \hat{\mathbf{B}})$$

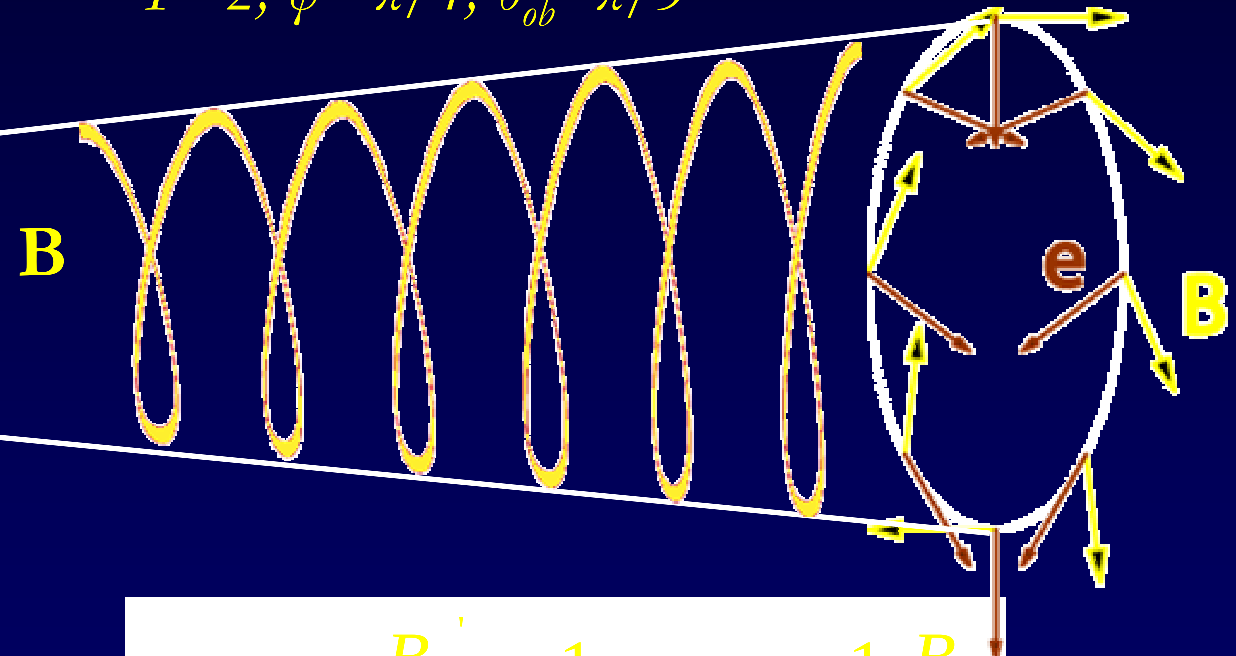
$$(\mathbf{e} \bullet \hat{\mathbf{B}}) = (\mathbf{e} \times \mathbf{n})(\hat{\mathbf{B}} \times \mathbf{v}) \neq 0$$

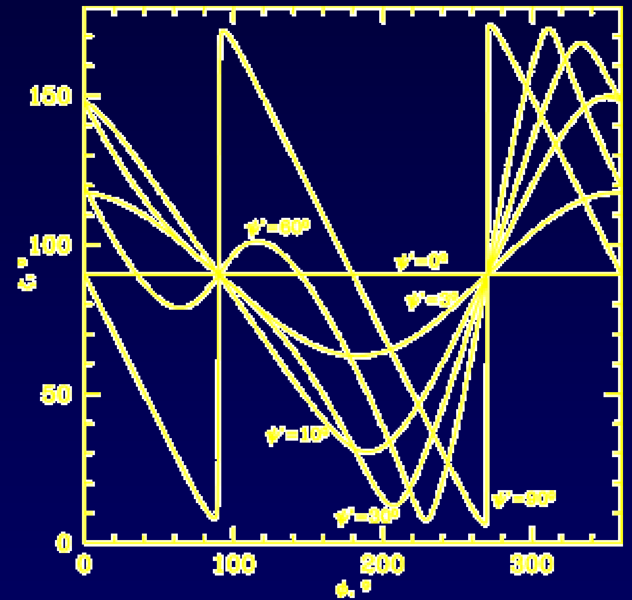
Both B-field and velocity field are important for Π

(Blandford & Konigl 79; Lyutikov,Pariev,Blandford 03)

Π from relativistically moving shell with helical B-field

$\Gamma=2,\ \psi'=\pi/4,\ \theta_{ob}=\pi/3$



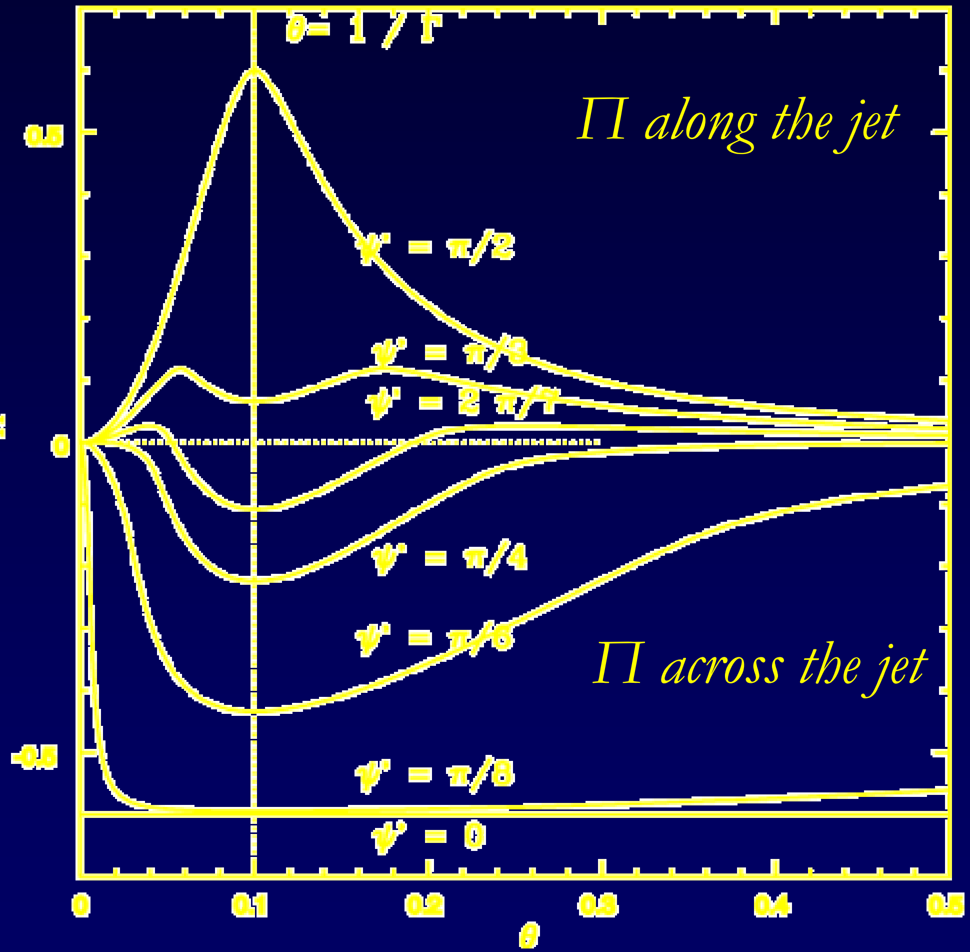


$$\tan\psi' = \frac{B_\varphi'}{B_z'} = \frac{1}{\Gamma}\tan\psi = \frac{1}{\Gamma}\frac{B_\varphi}{B_z}$$

Π from relativistically moving source

- ***B*** *not orthogonal to* ***e***
- *Observers: always plot* ***e****, not "inferred"* ***B****-field*
- *One needs to know* ***v****-field to infer* ***B****-field from* ***e****-field*
- ***symmetry of the system*** *(e.g. axial) and* ***assumptions about v****-field (e.g. sheared cylindrical motion with $v_z(r)$) may still provide information about intrinsic* ***B****-field*

Π from cylindrical shell



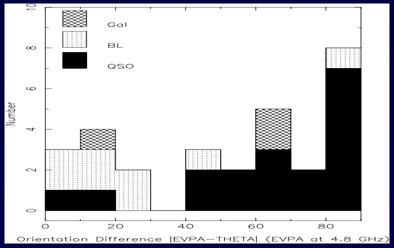
- *Π depends on p*
- *Even co-spatial populations with different p may give different Π (eg radio & optical)*

$$\tan\psi' = \frac{B'_{\varphi}}{B'_{z}}$$

Γ=10, p=1, different rest frame (emissivity –averaged) pitch angles

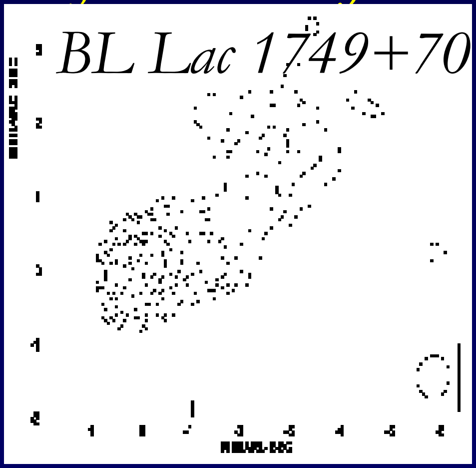
Large scale B-field in AGNs

- *Bimodial distribution of PA*



(Aller et al)

- *PA follows the jet as it bends*



(Gabuzda 03)

- *Sometimes a bend gives 90 change of PA*
- *For cylindrical jet U=0, average Π along or across the axis*
- *For fixed ψ, Π mostly keeps its sign*
- *Sometimes a change does occur*

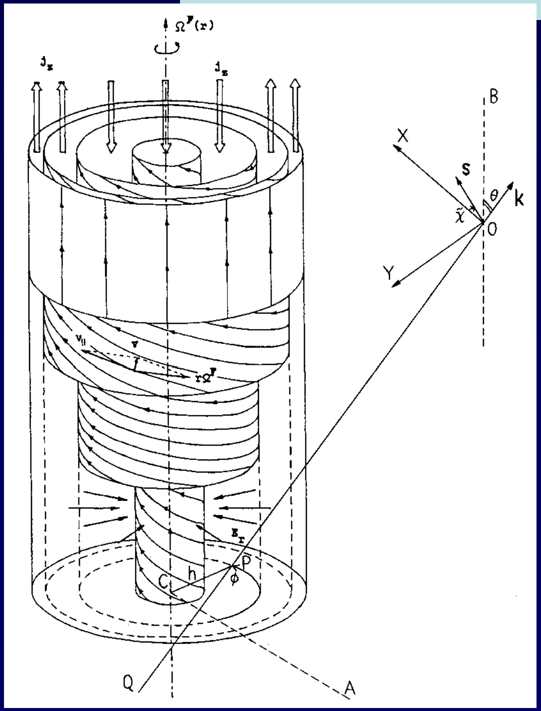
Resolved jets: B-field, E-field, v-field and emissivity profiles

- *Relativistic jet structures: cylindrical force-free equilibria*
- *E-field may be important: rotation: Bφ, Bz, Er:*

$$\Omega = \frac{E_r \times B_z}{r(B_z{}^2 + B_\phi{}^2)}$$

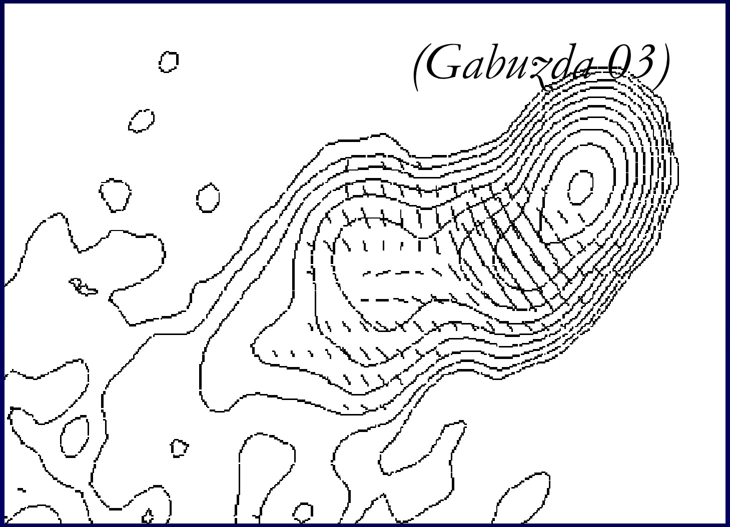
$$B_z^2 = \frac{1}{2r}\partial_r(B_z^2 + B_\varphi^2 - E_r^2)$$

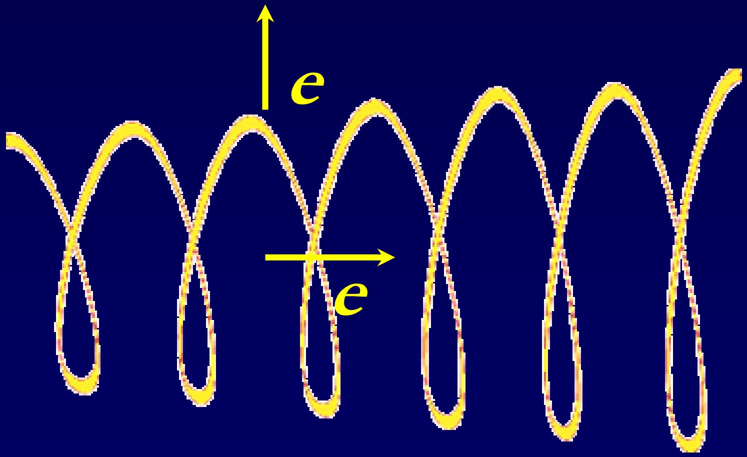
- *Need to specify force-free equilibria, $\beta_z(r)$*
  - *Diffuse pinch*
  - *Zero poloidal flux pinch*
  - *Multiple reversal, B~J(ar)*
- *Emissivity $\varkappa(r)\sim j^2$, B'^2*



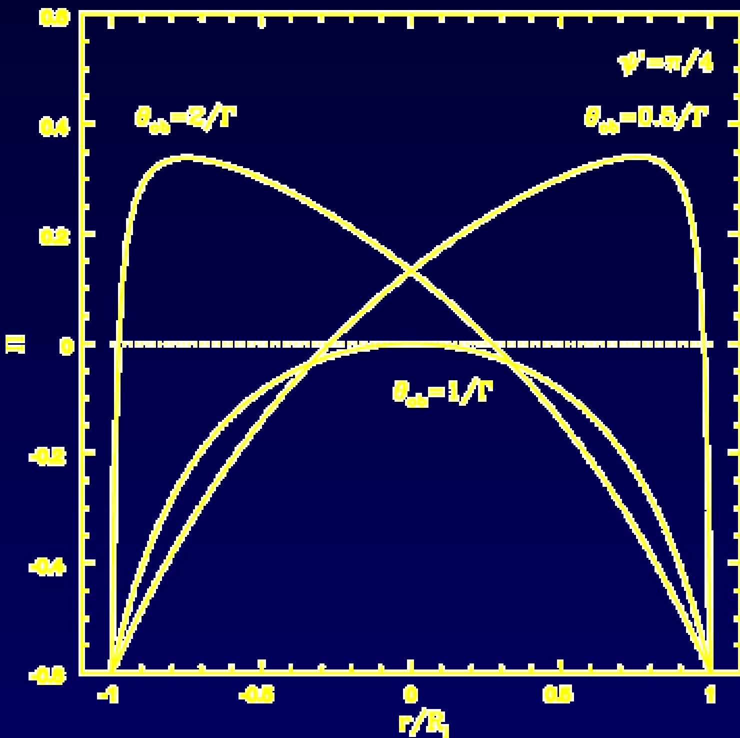
Resolved jets

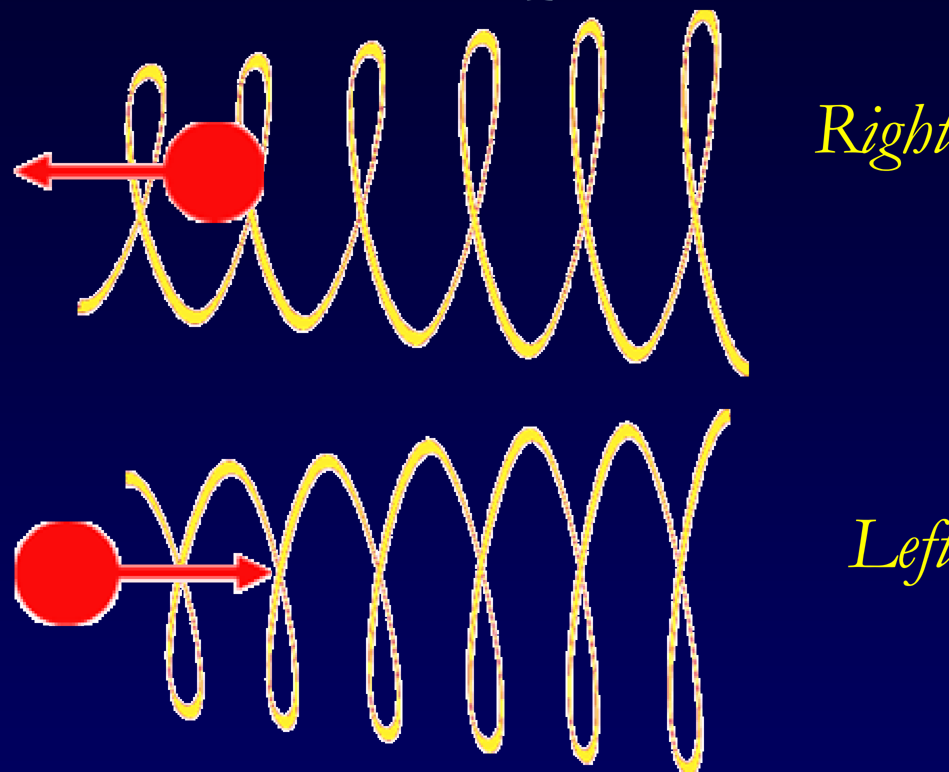
- *Resolved jets: center: PA along, edges: PA across*
- *If emission is generated in small range of radii $\Delta r < r$*





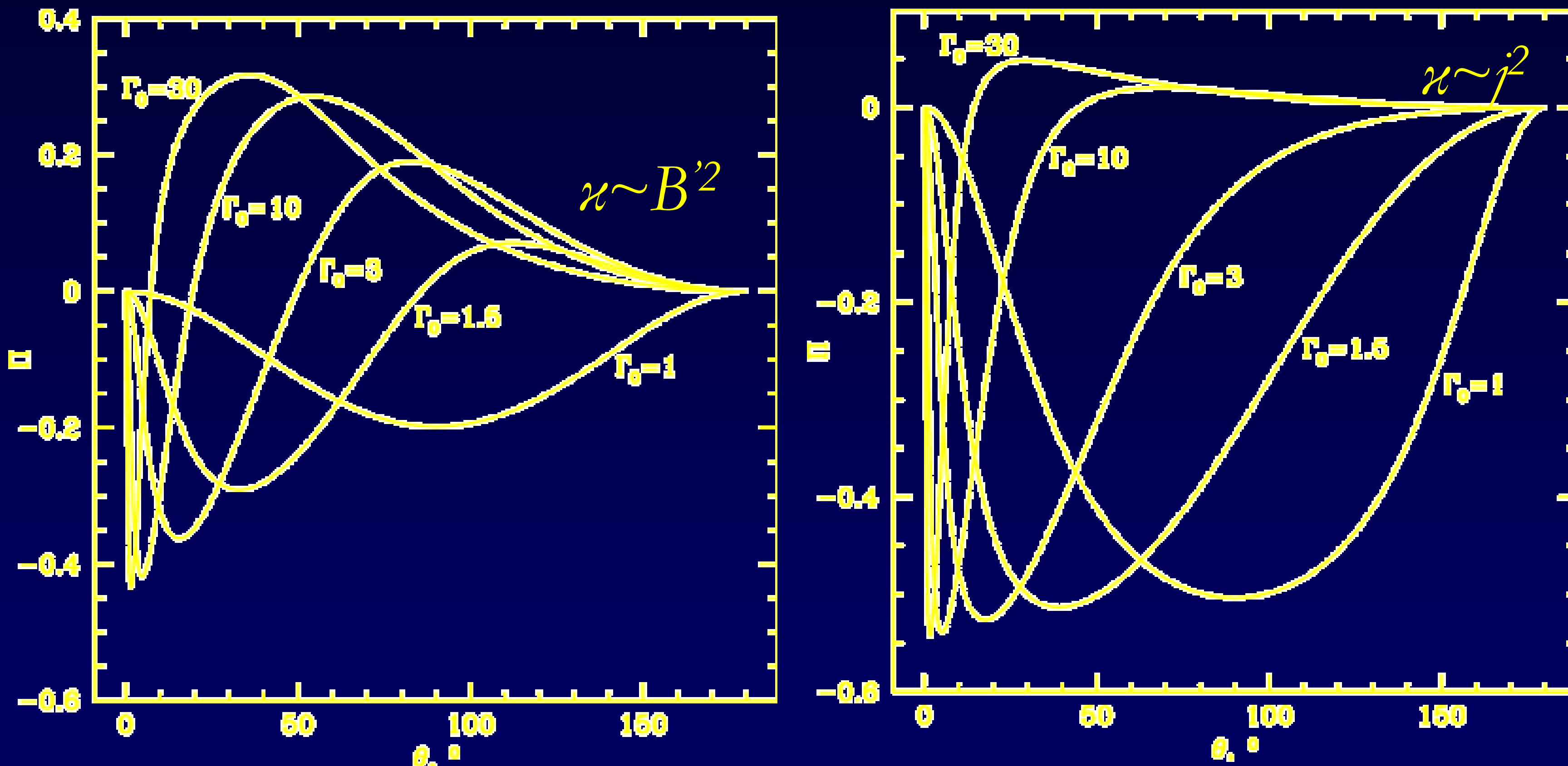
Jet polarization may tell the spin of BH





- *Left & Right helixes look different*
- *Different Π signature*
- *May tell direction of BH or disk spin (if θΓ >< 1 is known)*

Π from relativistic sheared jet $\Gamma_z(r)$



- *At θΓ< 1 Π is across jet (Bφ⟶0 on the axis)*
- ***Need emission from Δr << r: limb brightening***

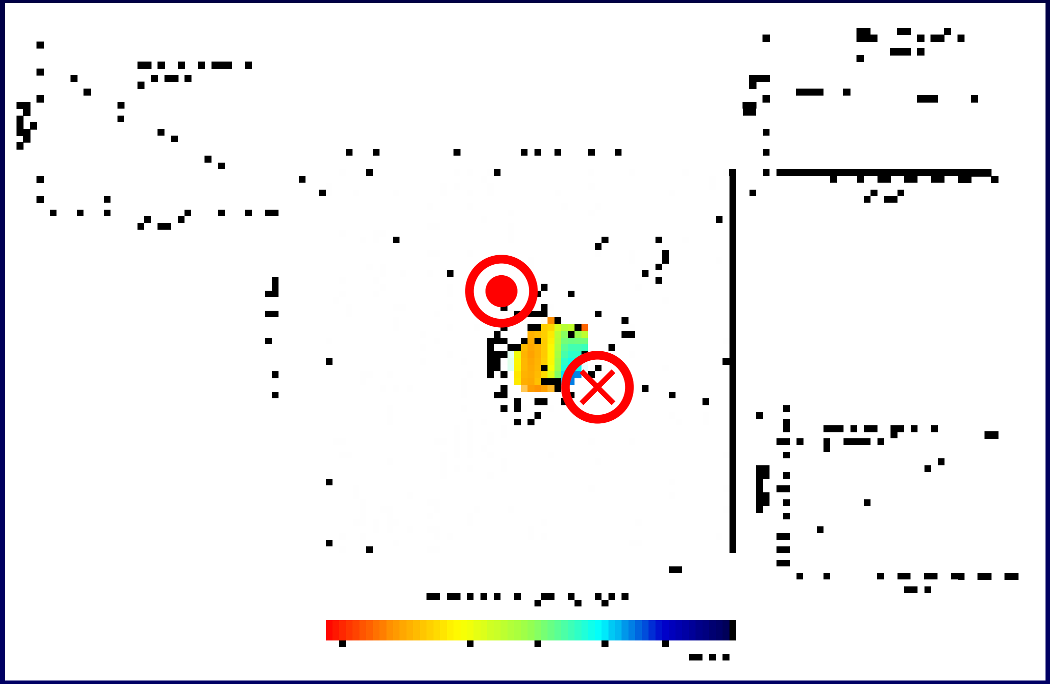
Faradey Rotation across the jet

- *Gradient of Rotation*

  Measure across the jet

- *Helical field*

  RM ~ ∫*Bndl – sign-dependent*



(Gabuzda 03)

Self-regulation $B'_\varphi \sim B'_z$?

- *Small $\Pi \sim$ 3-5%: $\psi' \sim \pi/4$ -- $\pi/3$, ($B'_\varphi \sim B'_z$)*
- *$B'_\varphi >> B'_z$ – unstable.*
- *Over-expansion $\longrightarrow$ large $B'_\varphi / B'_z \longrightarrow$ instability $\longrightarrow$ dissipation of poloidal electrical current $\longrightarrow$ reduce $B'_\varphi / B'_z \sim 1$*
- *Poloidal flux problem?*
  - *BH cannot carry enough Bz flux seen in pc-scale jets*
  - *Disk may, but not at kpc scale*

pc-scale AGN jets are *strongly* dominated by Bφ

- *In a relativistic jet, $\Gamma \gg 1$, in order to have PA along the jet, it is needed $B'_\varphi / B'_z \geq 1 \rightarrow B_\varphi / B_z \sim \Gamma \gg 1$*
- *BL Lac jet are **strongly** dominated by Bφ*
- *This is expected for jets launched from disks, expanding from $\sim 500\, R_{BH} \sim 10^{16}$ cm to ~ 0.1 pc, $B_\varphi \sim 1/r_c$, $B_z \sim 1/r_c^2$*
- *Internal stability depends on B'_φ / B'_z - stable*
- *Relativistic effects (rotation) stabilize jet on large scales (Istomin94)*

Conclusion for AGN jets

- ***Large scale B-fields may explain polarization of pc-scale AGN jets***
- ***σ is not small, $\sigma \geq 1$*** *(Lyutikov,Pariev,Gabuzda 04)*

How important B-field energertically?

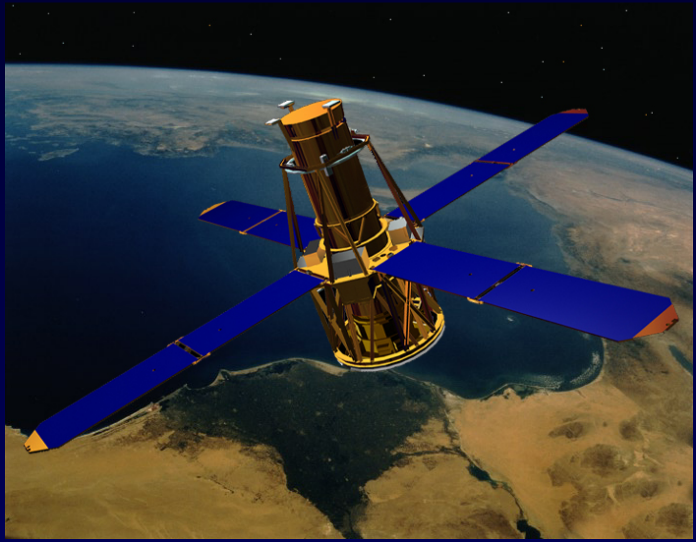
Magnetization parameter $\sigma = \dfrac{B^2}{4\pi\,\Gamma\,\rho_b\,c^2} = \dfrac{b'^2}{\rho_b'\,c^2} = \dfrac{F_{Poynting}}{F_{matter}}$

- *For $\sigma \geq 1$ B-field is more important than matter*
- ***Extract energy in B-field, propagate, dissipate***
- *Hard to prove: in the emission region (= dissipation) ~ equipartition*
- *B-field dissipation due to current instabilities –("reconnection")*
- ***Alternative to shock acceleration***
- *$B^2/8\pi >> \rho c^2, p$* – ***new plasma regime, new acceleration schemes*** *(no hydro or non-relativistic analogues)*
  - *Relativistic reconnection (Lyutikov&Uzdenski02, Lyutikov 03)*
  - *Charge-starved plasma, turbulent EM cascade (Thompson&Blaes,Lyutikov&Blackman01, in prog)*

Conclusion

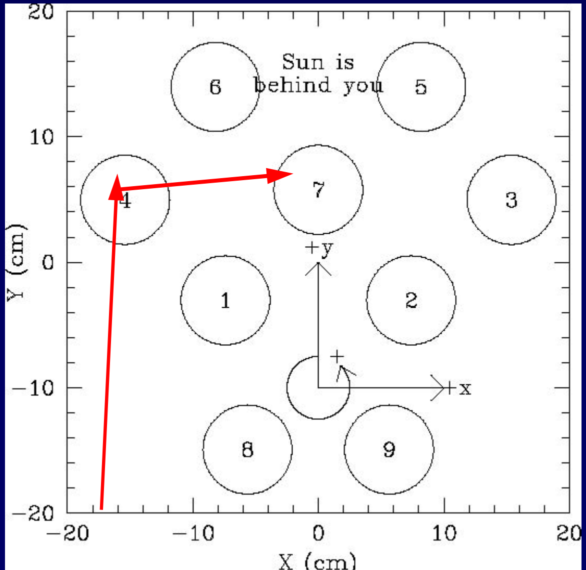
- *Technical issues: be careful with Π in relativistic sources*
- *Π indicate presence of large scale B-fields in pc-scale jets*
- *Paradigm of Poynting flux dominated flows may to be able to consistently explain jet generation, collimation, propagation, relative stability of jets, and particle acceleration.*

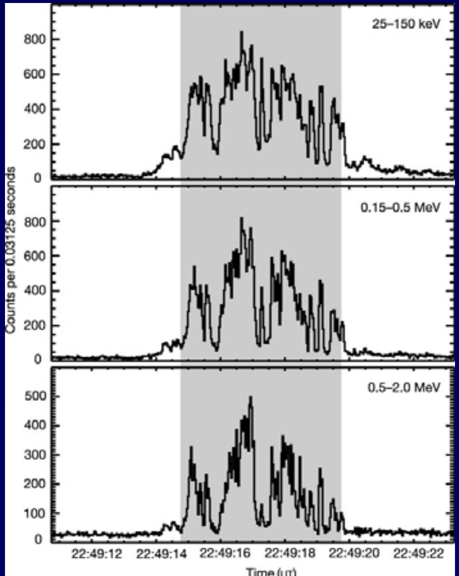
RHESSI Polarization in GRB021206

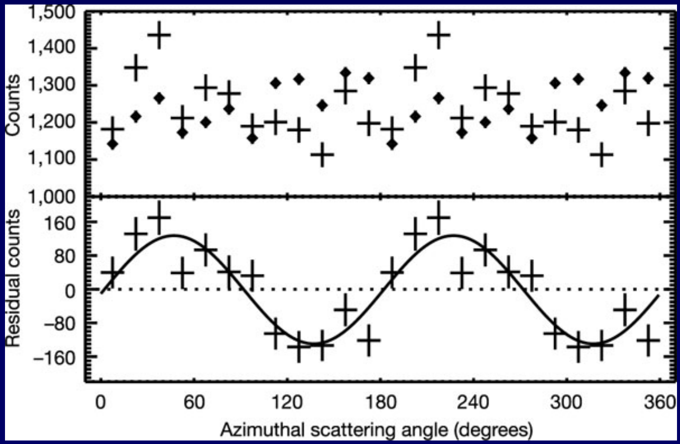


- *Solar X-ray satellite, revolves t=4 sec*
- *Bright, hard burst ,18º off-axis*
- *Π=80±20% (Coburn & Boggs 03)*
- *Result contested (Ruttledge & Fox 03, Wigger etal 04)*

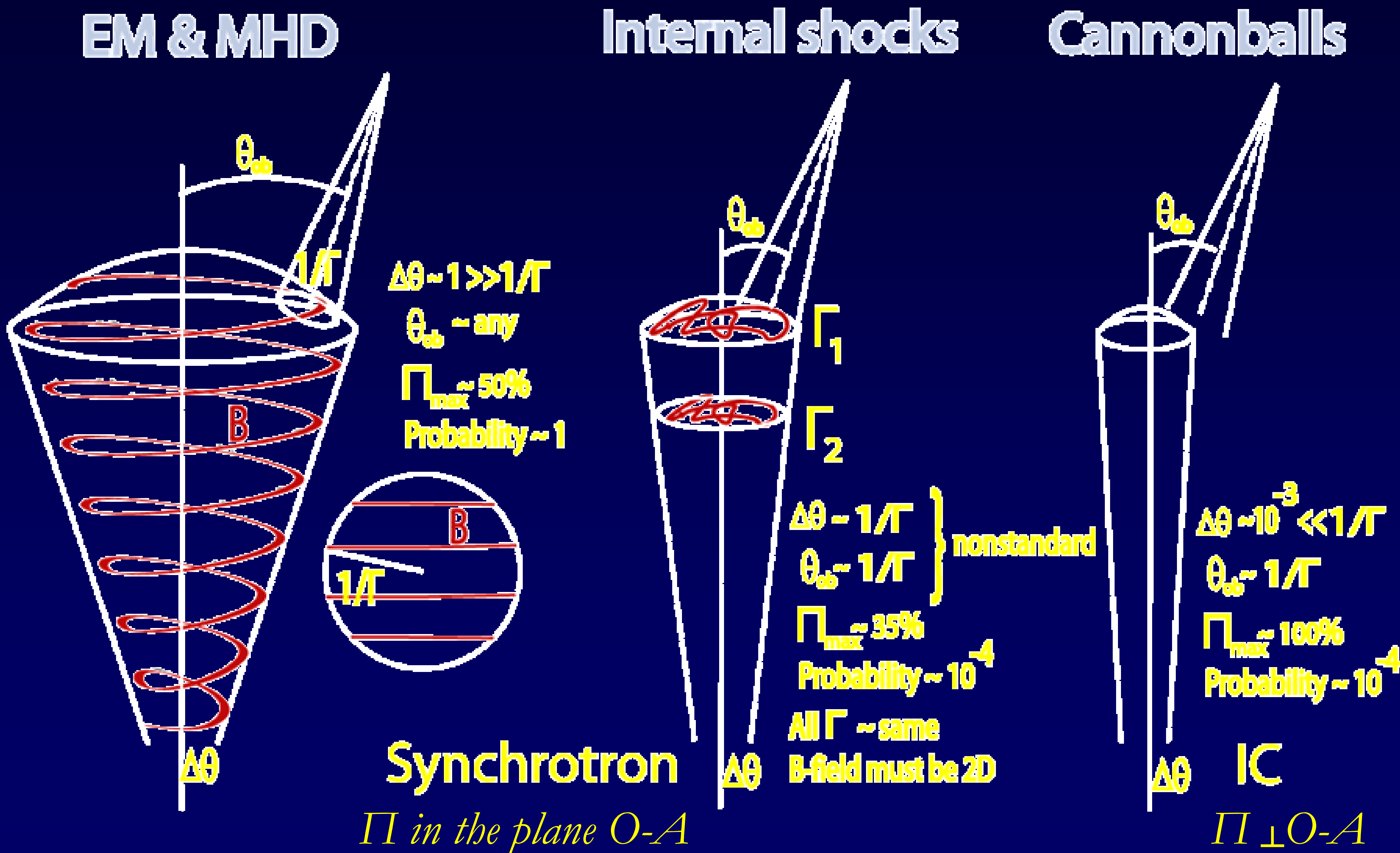
If confirmed, what are the implications of Π?







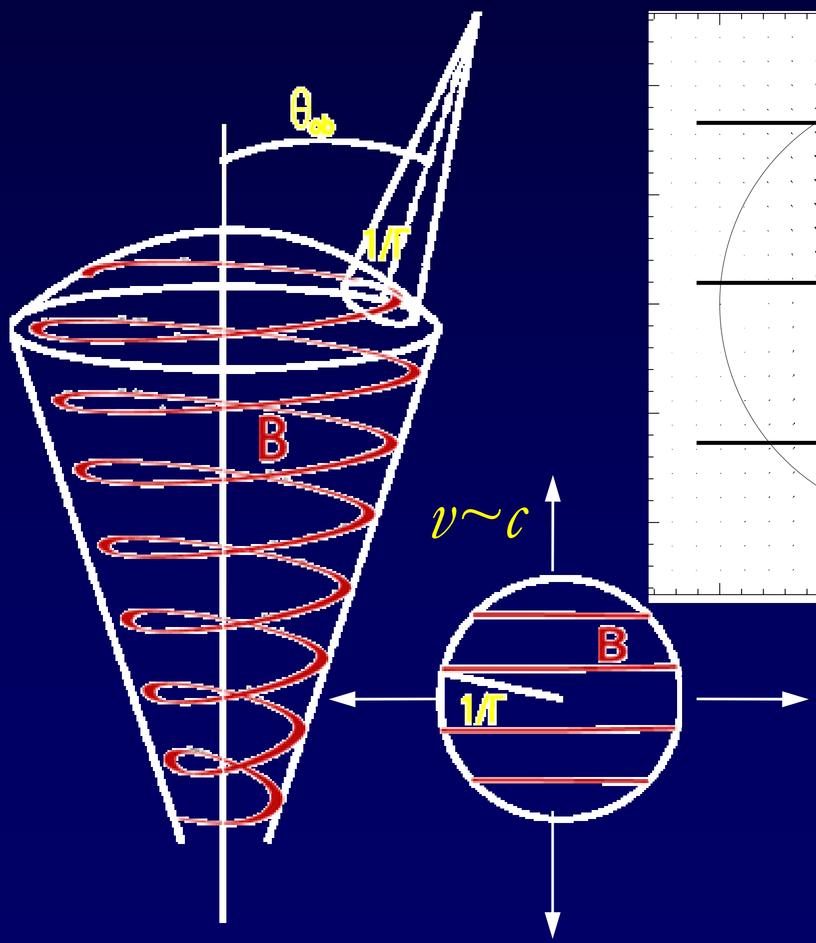
Different GRB models

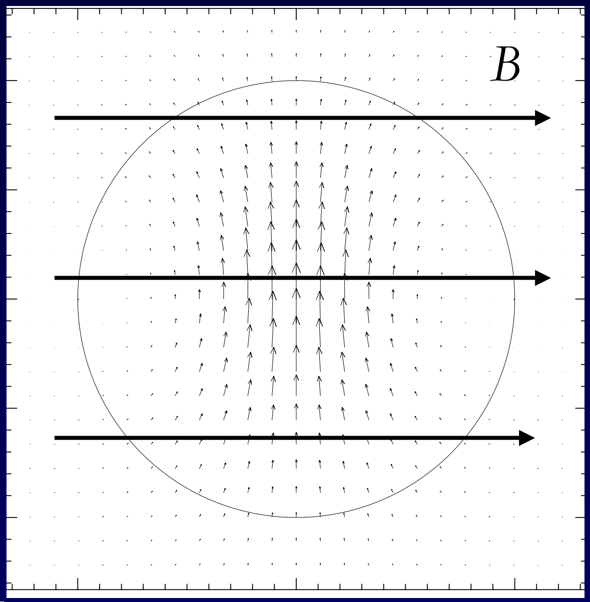


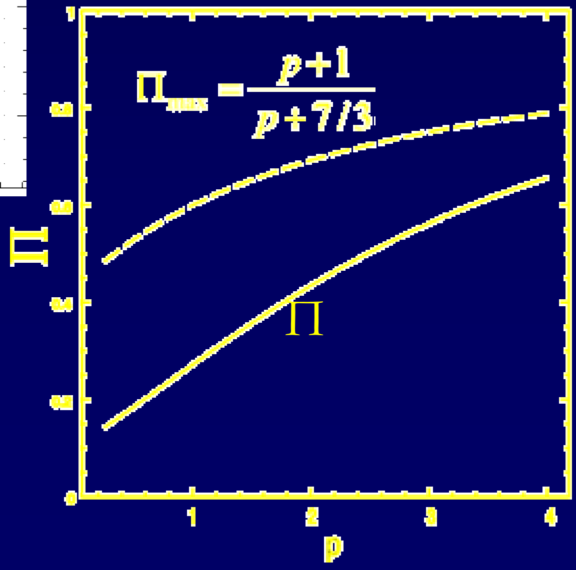
Polarization from expanding sources

- ➢ *Large scale B-field ($l_{corr} >> R/\Gamma$)*

(Lyutikov,Pariev,Blandford 03)







horrors of war. And it seems ... amnesia, as well as the memory formation, is in some way a result of the stress hormones.

What is undoubtedly true is that memory, like everything else in biology, is an evolved, functional response. If individuals tend to be better off by not remember-

... thing that was not there to start with. That is something of which the courts should be acutely aware when they assess the credibility of witnesses. It is also something psychiatrists may care to ponder when they are trying to dredge up "forgotten" childhood memories. ■

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Up close and personal

attach themselves to the knee, and then feed until they let go of their own accord, which they tended to do after about an hour. Everyone was asssessed in detail over the course of a month from the start of treatment, and more generally over the course of three.

The result was that leech therapy beat diclofenac for pain relief, particularly in the first week after application. It also seemed to bring longer-term benefits in the form of reduced stiffness and better joint function, probably because besides dulling pain, leech saliva also acts as an anti-inflammatory agent. Whether such benefits outweigh the disadvantages of having half a dozen leeches feasting from your knee for an hour is a matter of personal taste.

Gamma-ray bursts

Bursting with controversy

Arguments continue about the biggest explosions in the universe

GAMMA-RAY bursts (GRBS) are one of the most mysterious and controversial things astronomers can see. Mysterious, because until a few months ago, there was no consensus about what caused them. Controversial, because even though there is now agreement about the underlying cause—supernovas—there is an argument about how such stellar explosions actually generate gamma rays.

These rays are an energetic form of electromagnetic radiation. (More familiar forms of this radiation include radio, light and x-rays.) About once a day a spot in the sky lights up with a burst of them so intense that it is billions of times more powerful than anything else in the universe.

There are two theories about how the gamma rays in these bursts are generated. One is that they are a form of synchrotron radiation—the radiation produced when electrically charged particles are forced to travel in a curve by a magnetic field. The other is that they are formed by an interaction between low-energy electromagnetic radiation, such as light, and high-energy charged particles produced in the explosion. This is a process known as inverse Compton scattering.

In the past year, two satellite observations that bear on this and other questions about GRBS have been made. One, in late

March, was carried out by HETE-2, a multinational satellite explicitly designed to search for GRBS. Because this burst was one of the closest to Earth that has ever been observed, astronomers were able to see, in the position that HETE-2 predicted, the remains of a supernova. It was this that confirmed supernovas as the cause of GRBS, rather than colliding neutron stars or even more exotic ideas such as rents in the fabric of space.

The other observation, however, was in some ways more remarkable. It was made in December 2002 by RHESSI, an American satellite actually designed to observe the sun. Serendipitously, a burst occurred in the same part of the sky as the sun, and RHESSI saw it. But it is this accidental observation, not one made deliberately, that bears on the question of what causes the gamma rays. That is because it allowed researchers to try to measure their polarisation.

Trying, though, is not the same as succeeding. Wayne Coburn and Steven Boggs of the University of California, Berkeley, used the RHESSI data to assert, in a paper published in May in *Nature*, that around 80% of the gamma rays in this particular burst were "linearly polarised". According to a paper just published in *Astrophysical Journal* by Maxim Lyutikov of McGill University in Montreal, and his colleagues, that is because the magnetic fields of the supernova were carrying the bulk of the energy of the burst. This suggests the gamma rays are generated by synchrotron radiation.

Max!

But a few weeks ago Robert Rutledge and Derek Fox of the California Institute of Technology (CalTech), in Pasadena, came up with the opposite conclusion from the same set of data. They have written a paper in which they claim that Dr Coburn and Dr Boggs have made a mistake in their analysis. According to Dr Rutledge and Dr Fox, the data actually show negligible polarisation. Dr Coburn and Dr Boggs have since written another paper defending their analysis, and say a more thorough defence is forthcoming.

Bob!

A yardstick for the future?

The result from HETE-2 is remarkable enough, however, because it pinned the burst down so quickly and precisely. Before that, GRBS had been hard to locate. This was because they are so bright that they tended to overwhelm the available detectors. But HETE-2 is a recently launched satellite, with a better detector, and because the burst it saw was relatively close by, it was fairly easy to locate the remnants, and thus examine them.

Although GRBS themselves last at most a few hundred seconds (the shortest take mere milliseconds), they leave an afterglow. By understanding this, physicists hope they can understand the bursts themselves. Three papers in this week's *Nature* examine the afterglow of the March burst. Two go into details, such as the polarisation of light from the glow and the nature of a bump that appeared in that glow a few days after the explosion. But the third may ignite yet more discord. Edo Berger, of CalTech, and his colleagues dispute the claim, made by several researchers in the past few years, that all GRBS release the same amount of energy.

If that claim were true, it would mean that GRBS could be used as cosmic "yardsticks", since their distance could be worked out from their apparent brightness. Existing yardsticks, which include certain supernovas, are important because they provide ways of calculating how fast the universe is expanding. Because GRBS are so much brighter than anything else, they would be particularly useful in this context. However, Dr Berger argues that the size of the March GRB, whose supernova-of-origin is understood, rules out the idea of standard-energy GRBS. Different supernovas, he concludes, release different proportions of their energy as gamma rays, and those differences are not predictable. A shame. But though they may turn out to be less useful than hoped for in analysing the rest of the universe, GRBS still seem to be generating plenty of interest—and controversy—in their own right. ■

More on gamma-ray bursts

Perishing publishing

"Pre-printing" scientific papers electronically is a good idea. But it has its perils

GAMMA-RAY bursts (see previous article) have created more than just scientific debate. Sir Martin Rees, England's Astronomer Royal (these days an honorific title; Sir Martin is also a professor at Cambridge University), has become embroiled in a controversy that raises questions about the way that scientific papers are published.

In the olden days, a group of researchers would bang out their paper on paper. They would submit it to a journal. They would wait several months for it to be accepted (or not) and then several more for it to be published. Though long winded, this allowed time for reflection by both authors and the independent referees who the provide "peer review". This helped to keep the scientific process accurate.

The world wide web has changed that. Now, physics papers often get "pre-printed" on a website (www.arxiv.org) before they have gone through the grinding process of review and revision. This can lead to misunderstandings.

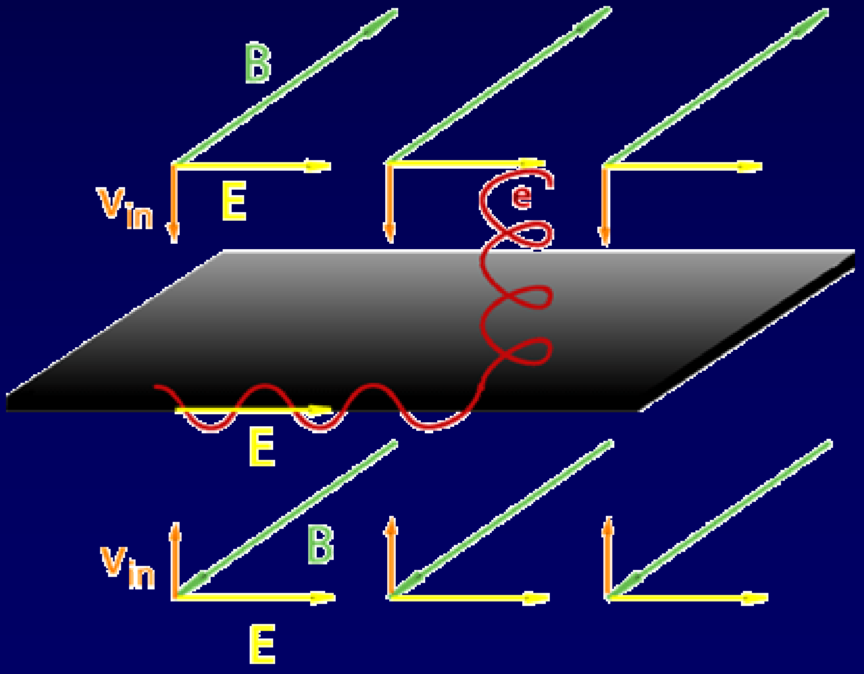
In the case of Sir Martin, the misunderstanding was over who first came up with the idea that the gamma rays in bursts are generated by inverse Compton scattering. In September, he and his colleagues pre-printed a paper on the subject which did not acknowledge the contribution to the field of two researchers called Arnon Dar and Nir Shaviv. This is the sort of omission that peer review is intended to correct, but Dr Dar got in touch anyway, and Sir Martin agreed to make the change in the published version, which is about to come out in a journal called *Monthly Notices of the Royal Astronomical Society*.

Several weeks later, however, another researcher named Alvaro De Rújula, who works with Dr Dar, posted a paper on the same website, pointing out the omission in what many might regard as immoderate language. Sir Martin revised the pre-printed version. But the incident raises questions, and not just about possible libels.

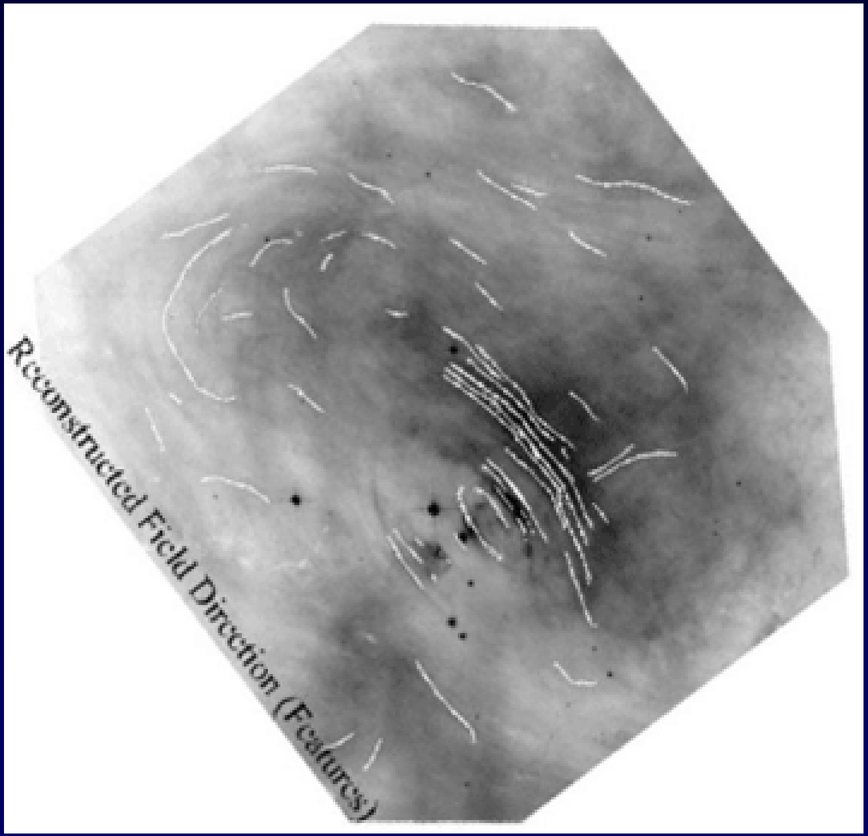
On the face of things, pre-printing is a good idea. It exposes a paper to wider scrutiny than the old system did, which should improve its accuracy—as happened in this case. But it also suggests that the price of getting one's ideas into the public domain rapidly is a need to keep them continuously revised in order to avoid criticism, however moderately or immoderately expressed. Like the Red Queen, in "Through the looking glass", today's physicists need to rush faster and faster merely to stay in the same place.

Acceleration in relativistic reconnection layers

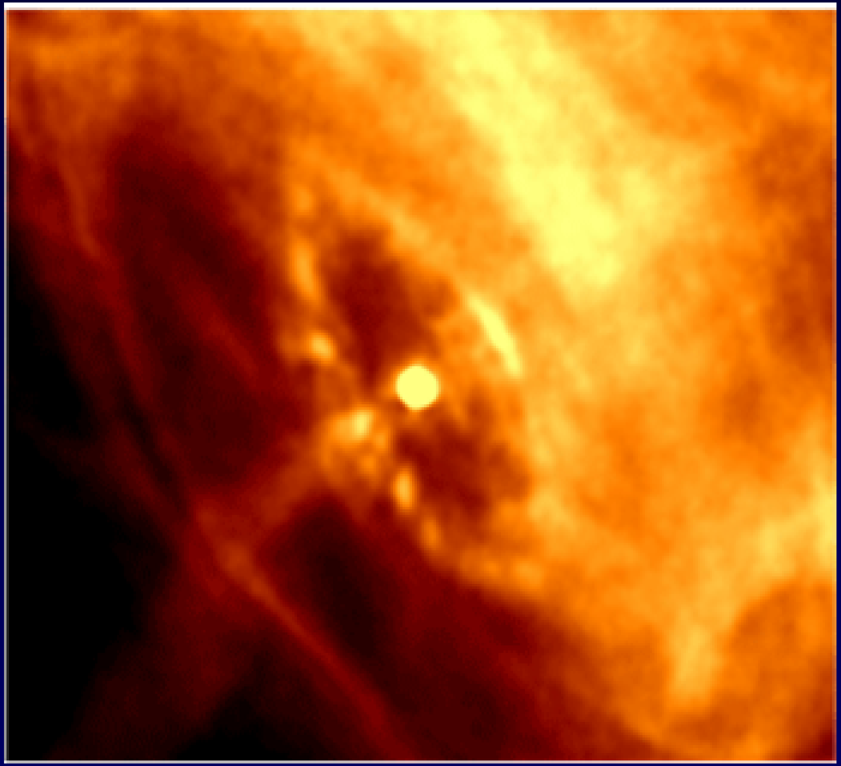
- *DC acceleration by E-field,* $\tau_{acc} \sim 1/\omega_B$
- *In* $\sigma >> 1$ *plasma,* β_{in} *can be* ~ 1 *(ML & Uzdensky 02)*



Pulsar winds: large scale B-fields are important (Crab)



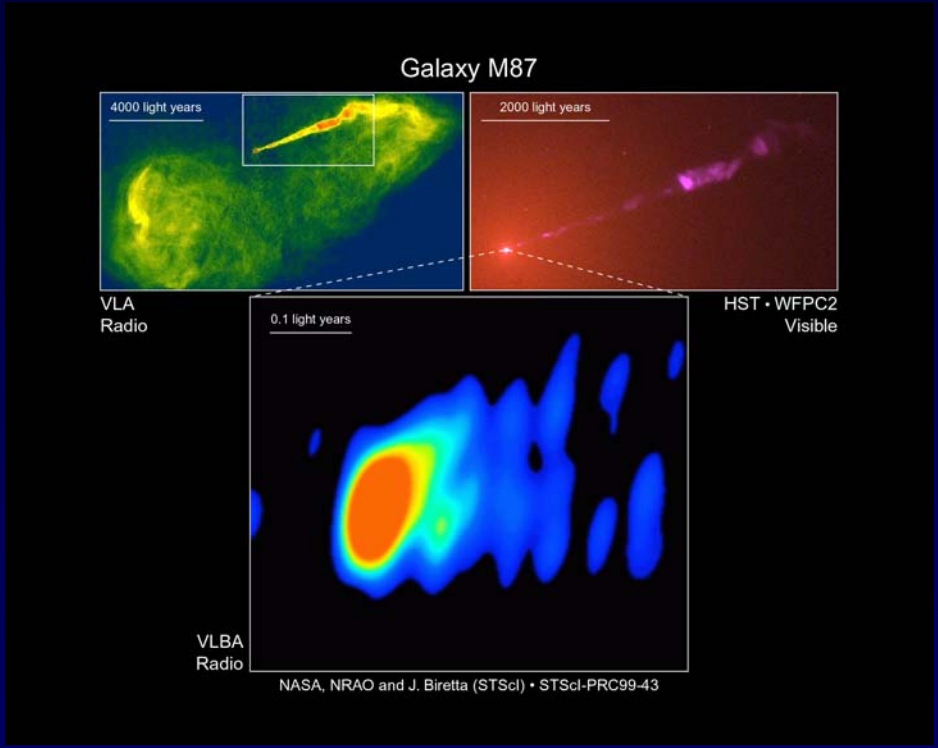
Optical: polarized intensity + directions of magnetic field (white lines)



X-rays intensity

(curtoucy of G. Pavlov)

AGN jets: from sub-pc to kpc



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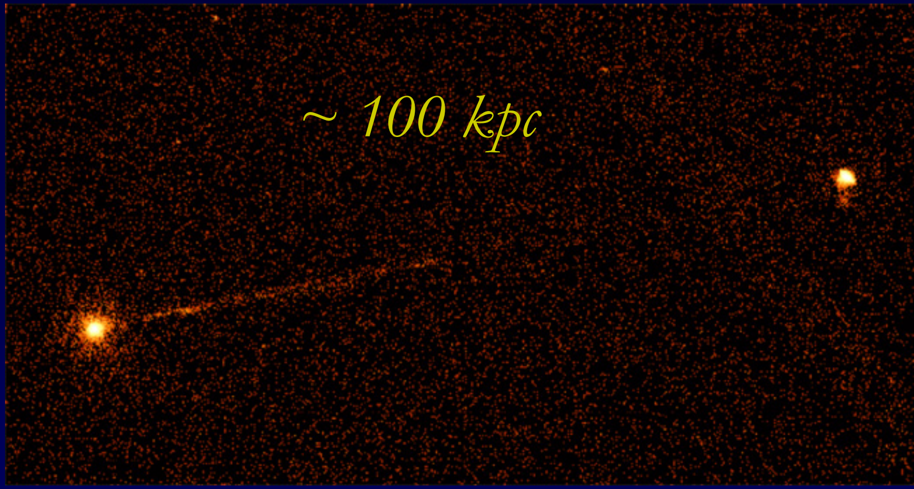

Pictor A (Chandra X-ray)