On the Magnetization and RM Gradients of AGN Jets

Lukasz Stawarz

Jagiellonian University, Poland

RM Gradients

$$c^2k^2 = \zeta\omega^2$$

$$\zeta = 1 - \frac{\omega_{\rm pl}^2}{\omega\left(\omega \pm \omega_{\rm L}\right)}$$

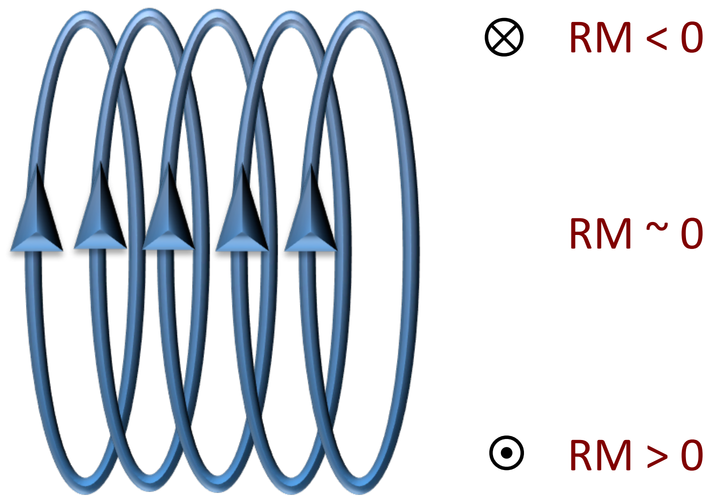
$$v_{\rm ph} = \frac{\omega}{k} \quad , \quad v_{\rm gr} = \frac{\partial\omega}{\partial k}$$

$$\Delta\chi = \frac{2\pi\, e^3}{m_{\rm e}^2 c^2\, \omega^2} \int_0^L n_{\rm th}\, B_{0,||}\, ds$$

$$\left(\frac{\Delta\chi}{\rm rad}\right) = RM \cdot \left(\frac{\lambda}{\rm m}\right)^2$$

$$RM = 0.81 \int_0^L \left(\frac{n_{\rm th}}{\rm cm^{-3}}\right) \left(\frac{B_{0,||}}{\mu{\rm G}}\right) \left(\frac{ds}{\rm pc}\right)$$

When propagating through a magnetized plasma (“external screen”), a polarized wave experiences rotation of a plane of polarization. That is because any plane polarized wave can be treated as a linear superposition of a right-hand and left-hand circularly polarized component; circularly polarized wave with positive helicity has different phase velocity than the wave with negative helicity within the magnetized environment.



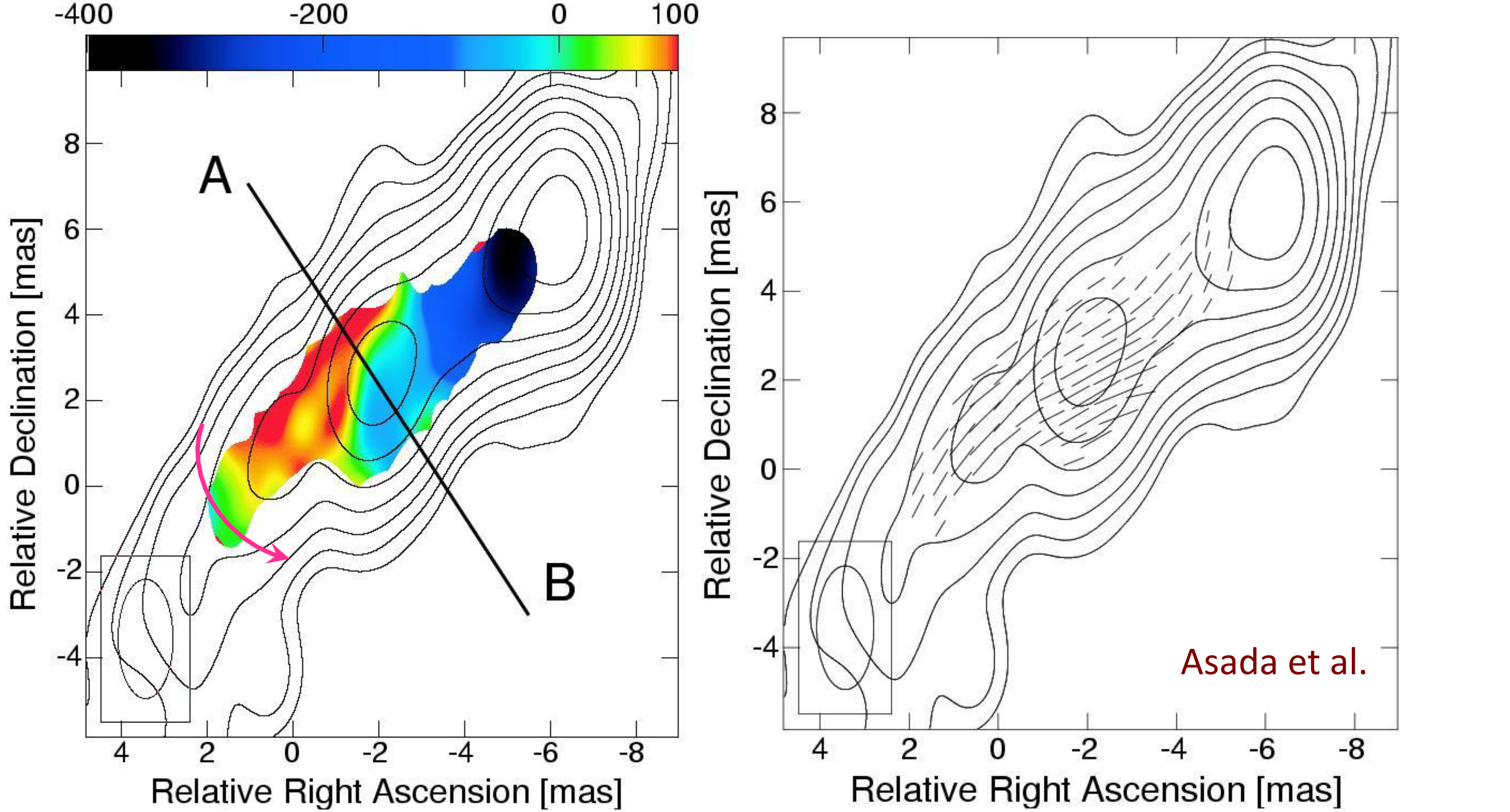
Observations

- Gradients of RM often observed on pc scales in AGN jets
- Faraday screen seems to be external to the emission region because

  (i) $\Delta\chi \sim \lambda^2$ dependence
  (ii) >45deg rotations observed
  (iii) RM gradients often seen around the jet/ISM interaction regions
  (iv) a decrease of RM along the jets sometimes observed
  (v) high fractional polarization from the RM gradient regions

- Faraday screen cannot be completely unrelated to the jets, since RM gradients vary on timescales of years
- RM gradients require toroidal MF in the depolarizing medium; meanwhile, polarization properties often imply that the MF within emitting regions contains a substantial poloidal component
- In the majority of cases RM gradients on pc scales are "clock-wise" (CW), and not counter clock-wise (CCW)!

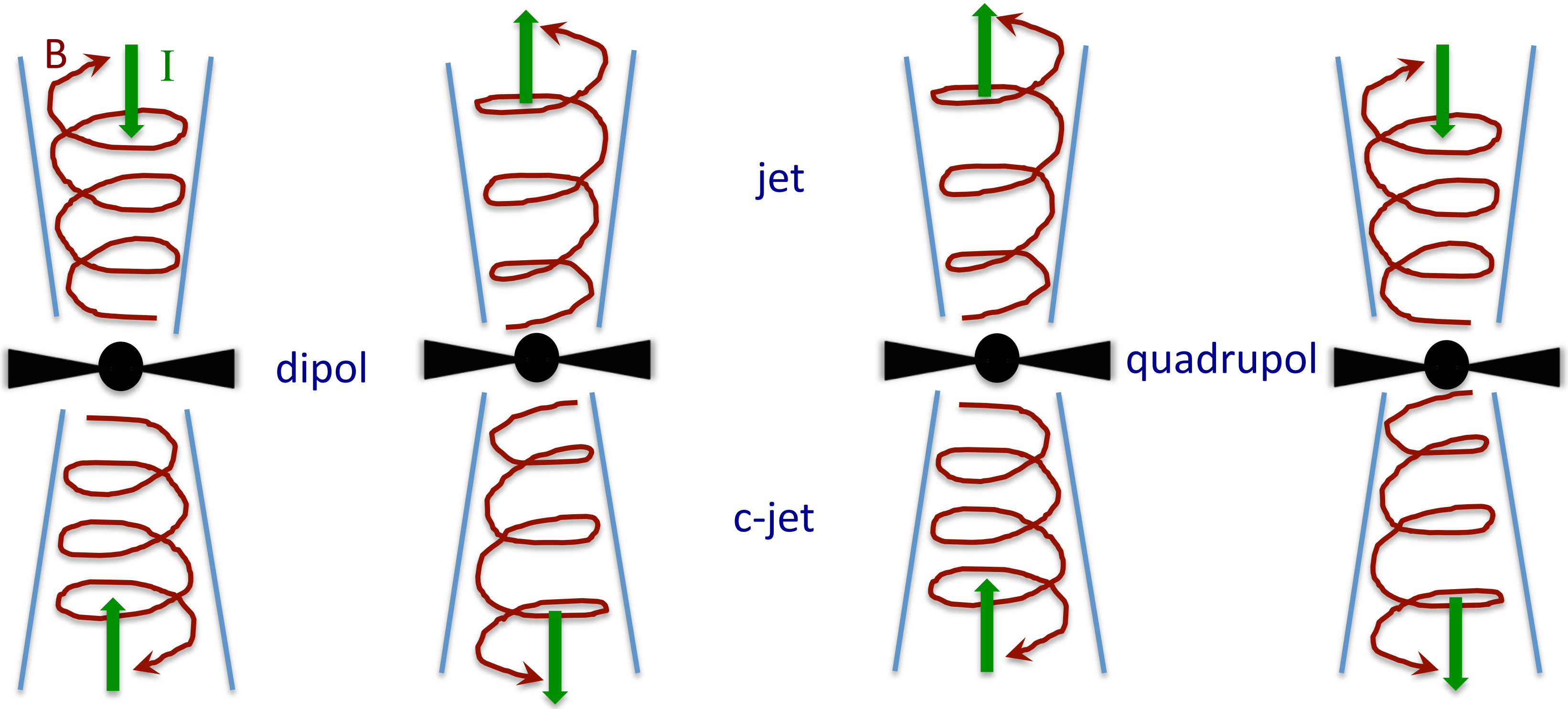
B_T (RM gradients) vs B_P (polarization)



Main Motivation

- Direction of RM gradient, if related to the jet MF, should be determined by the properties of the MF around SMBH (jet launching region);
- one should therefore expect equal number of CW and CCW gradients…
- … <u>**unless**</u> the "Poynting–Robertson Cosmic Battery" operating in AGN accretion disks is considered (Contopoulos et al. 2009, etc.)

“Standard” Model



jet: CW	jet: CCW	jet: CCW	jet: CW
C-jet: CCW	C-jet: CW	C-jet: CCW	C-jet: CW

Cosmic Ray Acceleration

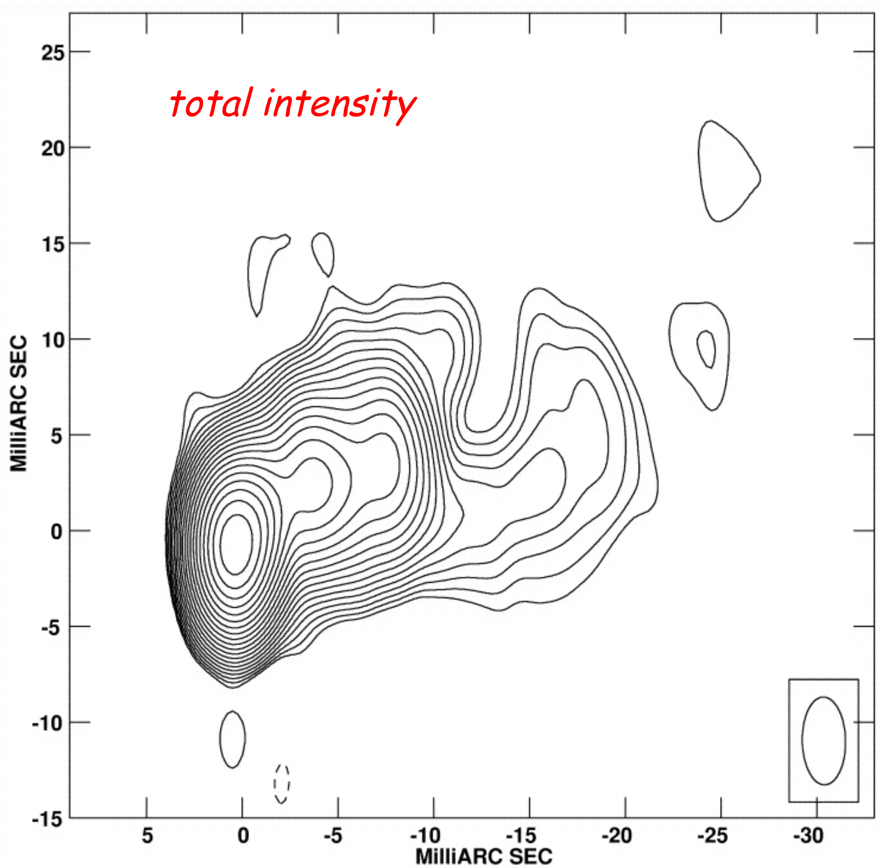
Shear cosmic ray (CR) acceleration within turbulent boundaries of relativistic jets:

- it operates preferentially on hadronic CRs rather than e^+e^- pairs, due to the fact that in the case of e^+e^- pairs a regular turbulent acceleration is more efficient for the typical parameters of AGN jets (only higher-energy hadronic CRs have mean free paths large enough to experience a sufficient bulk velocity gradient between subsequent scatterings, since maximum energies of leptonic CRs are limited by radiative losses; see Ostrowski 2000, Stawarz & Ostrowski 2002);

- the leptons follow therefore the bulk flow rigorously, but the higher energy protons sample a range of velocities (since they "know" about the transverse velocity gradient), so inside the jet, where the electron current is the largest, they lag behind on average, giving **a net negative current outward**, $I_{\rm bl}$;

- there will be a toroidal magnetic field $B_{\rm bl}$ associated with this net current, which can be responsible for the RM gradients with CW orientation across pc-scale jets.

Shear Boundary Layers



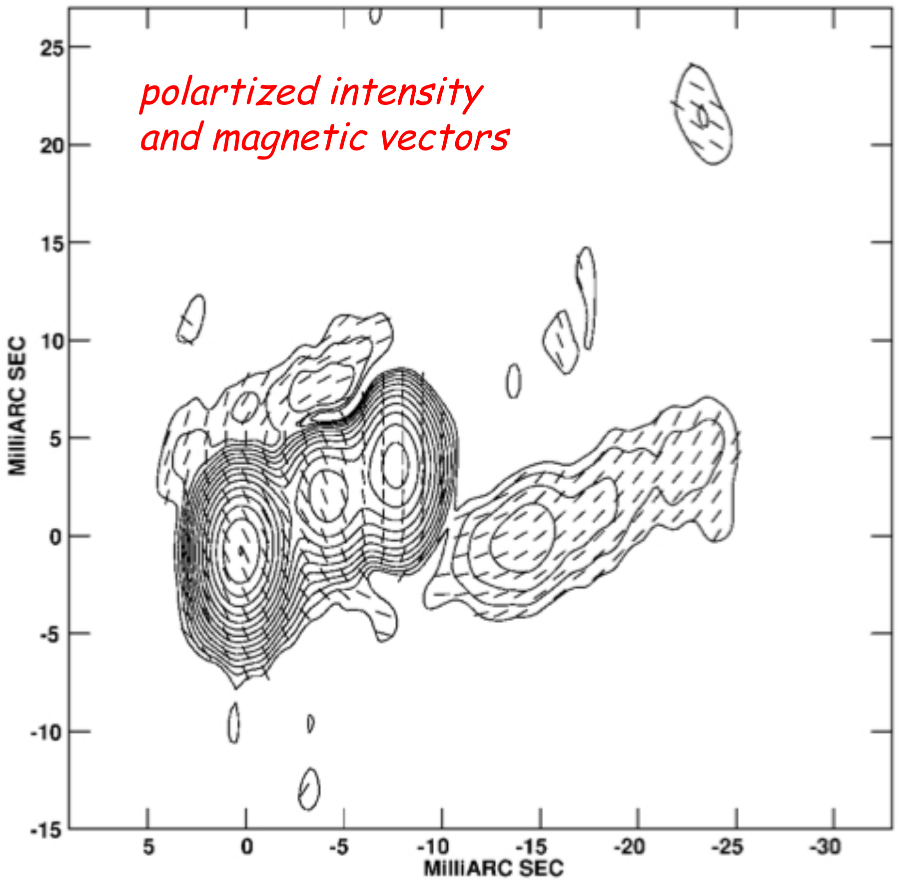
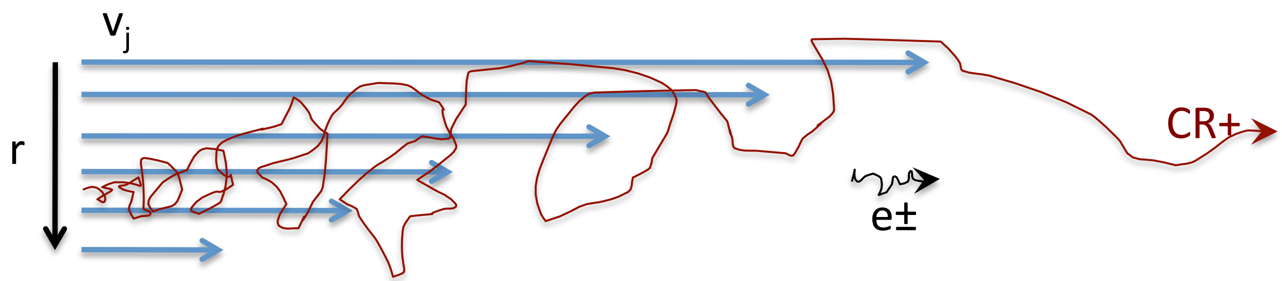


FIG. 1b

Atridge et al. 1999

Shear Acceleration



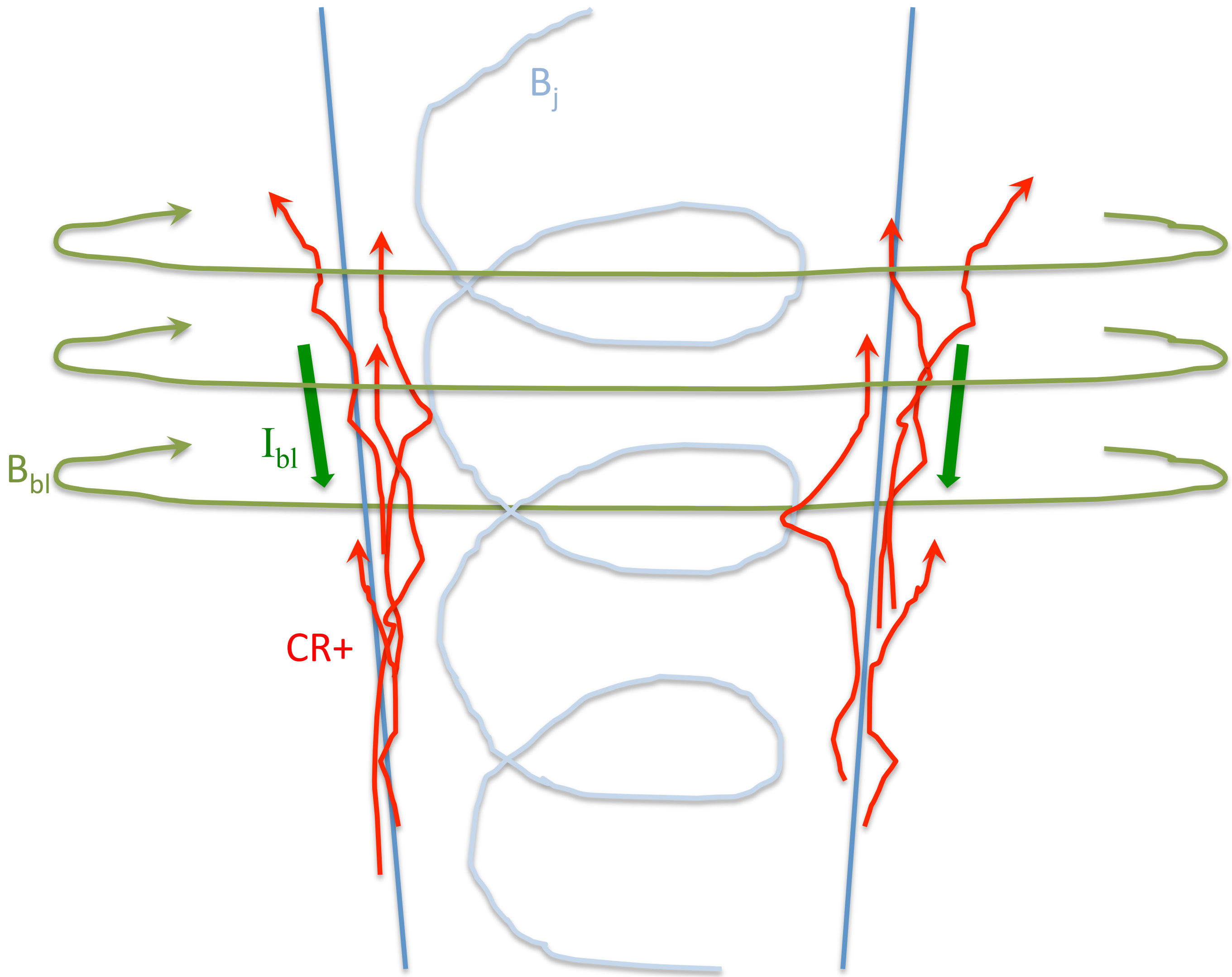
Note that the shear acceleration timescale is inversely proportional to the particle energy,

$$\tau_{\rm shear}(r) \simeq 3\ \frac{c}{\lambda(\gamma)}\ \frac{1}{\left(\Gamma_j^2(r)\,\frac{\partial v_j(r)}{\partial r}\right)^2}\,, \tag{17}$$

unlike in the case of a turbulent Fermi process,

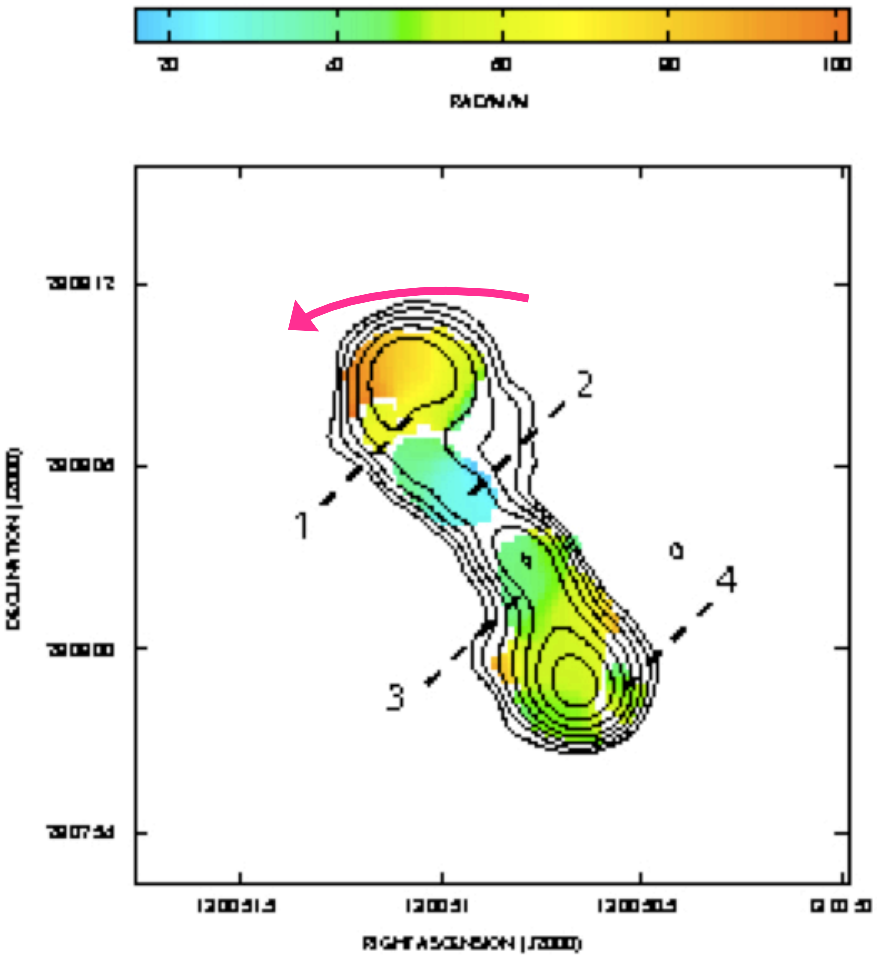
$$\tau_{\rm turb}(r) \simeq 3\ \frac{\lambda(\gamma)}{c}\ \frac{c^2}{v_A^2(r)}\,, \tag{18}$$

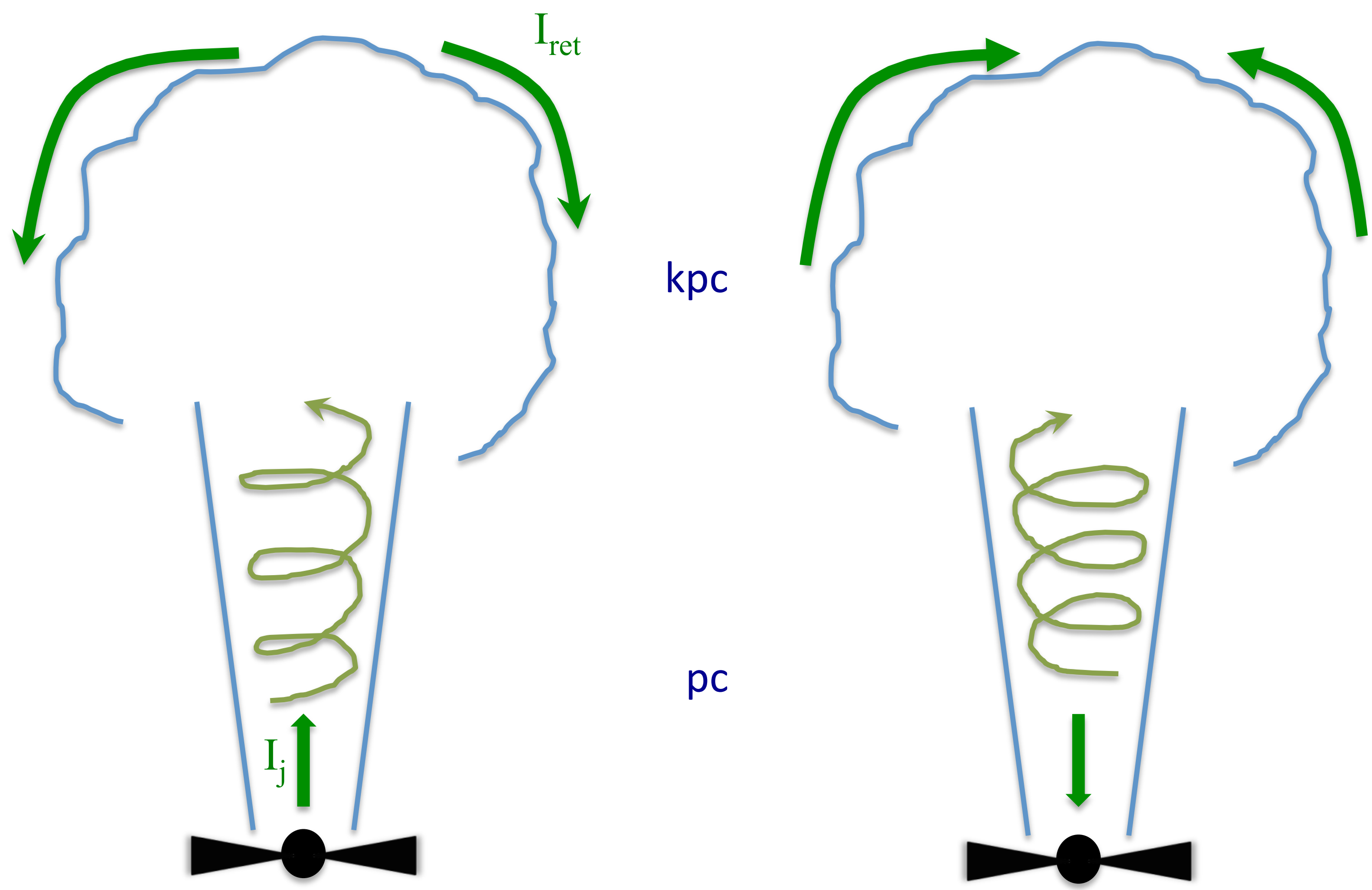
where $\lambda(\gamma)$ is the energy-dependent particle mean free path, and v_A is the scattering turbulence (Alfven) velocity.



B_j
I_{bl}
B_{bl}
CR+

Large (kpc) Scales

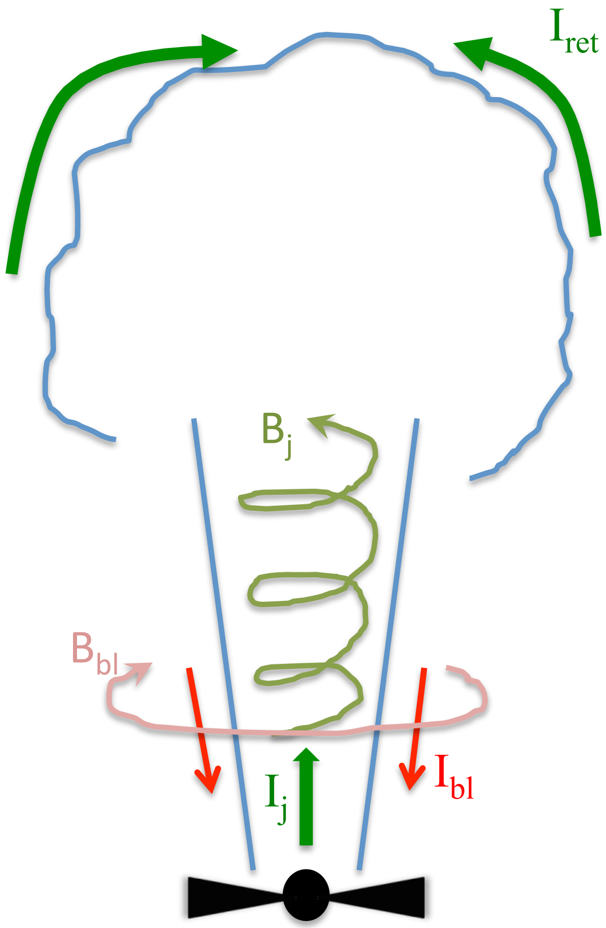


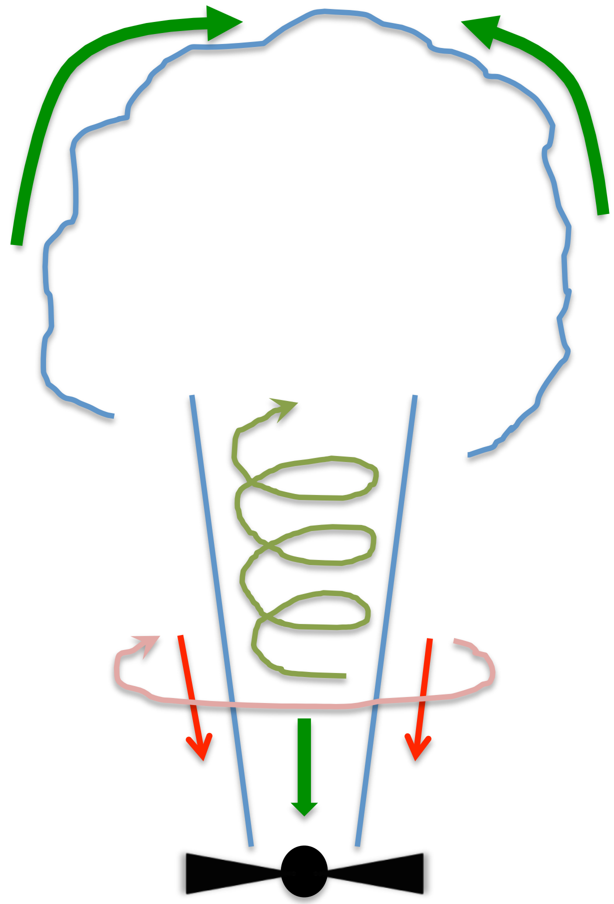


pc-scale: CCW
kpc-scale: CW

pc-scale: CW
kpc-scale: CCW

(assuming that the RM gradients on kpc scales are due to returning currents)





pc-scale: CW
kpc-scale: CW

pc-scale: CW
kpc-scale: CCW

(assuming that the RM gradients on kpc scales are due to returning currents)

Attractive Features of the Model

- Model consistent with the Faraday screen being external to the emission region (as required by the $\Delta\chi \sim \lambda^2$ dependence, or high fractional polarization indicating a strong poloidal MF component from the RM gradient regions), but yet being strictly related to the outflow;
- several observational findings – such that RM gradients are often seen around the jet/ISM interaction regions, or that a decrease of RM along the jets is observed in some cases – can be naturally reconciled with the boundary layer acceleration scenario (since the efficiency of the acceleration process depends in this case on the velocity shear, which is controlled by the jet interaction with the ambient medium, and which may decrease along the outflow);
- variability of RM gradients on the timescales of years may be accounted for as well, since KH instabilities or CR pressure back-reaction may lead to a temporal decrease of the acceleration efficiency;
- since the acceleration efficiency is not a universal parameter, in the framework of the model considered the RM values are expected to be characterized by a relatively wide range, in agreement with observations;
- and of course, **mostly** CW orientations are expected on pc scales!

Model Predictions

- <u>“Standard” Model:</u>
  - **equal** number of CW and CCW on both pc and kpc scales
  - **universal** RM gradient reversals between pc and kpc scales
  - jet/c-jet RM gradient asymmetries on both pc and kpc scales may be present **depending** on the “dipol/quadrupol” MF configuration in the jet launching region

- <u>PR Cosmic Battery:</u>
  - **universal** CW on pc scales and CCW on kpc scales
  - **universal** RM gradient reversals between pc and kpc scales
  - **no** jet/c-jet RM gradient asymmetries on either pc and kpc scales

- <u>Boundary Layer Current:</u>
  - **mostly** CW on pc scales, but **equal** number of CW and CCW on kpc scales
  - RM gradient reversals between pc and kpc scales **expected but not universal**
  - **expected** jet/c-jet RM gradient asymmetries on pc scales; on kpc scales such asymmetries may be present **depending** on the “dipol/quadrupol” MF configuration in the jet launching region