Magnetic Fields in Blazar Jets

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Blazars are defined as a AGN class with following features:

- *featureless spectra;*
- *violent variability through the entire electromagnetic spectrum at different timescales (from years down to TeV flares of ~5 min duration).*
- *strong and variable linear polarization from radio to UV wavelengths (up to 40%, Jostad et al. 2006);*
- Blazars are found to be active galactic nuclei of bright elliptical galaxies (e.g. Scarpa et al. 2000) with supermassive BH+accretion disc+opositely directed jets structure. It's generally accepted that one of blazar jet should be pointed towards to the observer, so, in fact, we are able to observe only its nonthermal emission. Hot, magnetized plasma should flow outward with relativistic speeds.
- AGN jets are believed to be launched by accreting BHs and powered via Blandford & Znajek (1977) mechanism, incorporating the collimation of disc matter along the twisted magnetic field lines threading the ergosphere of rotating central BH. This field should be generated by the currents flowing in the AD and it can extract the spin energy of rotating BH. Levinson (2008) gives the following expression for maximum extracted energy:

$$L_{BZ} = 10^{45} \varepsilon B_4^2 M_8^2 \text{ ergs cm}^{-1}$$

where M_8 is the central BH mass expressed in the units of 10^8 solar masses; B_4 is the strength of magnetic field threading the horizon, expressed in units of 10^4 Gauss; ε is an efficiency factor of order 0.1.

- Alternative scenario: jets are powered by the gravitational energy of accreting matter that moves toward the black hole (see e. g. Begelman et al.1984). They can be launched from the inner regions of the accretion disk as centrifugally driven outflow of disc matter if the poloidal component of disc magnetic field makes an angle of 30°- 60^0 with respect to the disc surface. The toroidal component becomes dominant from Alfven surface and drives the outflow into jets via pinching force (Marscher 2009, hereafter M09)

$$F_{\text{pinch}} = B_{\text{tor}}^2/(4\pi R),$$

- Magnetic pressure is expected to drop with distance from BH creating thus a strong negative pressure gradient along the axis and accelerates the flow (M09).
- In both scenario, large scale jet magnetic field is expected to have a helical structure.

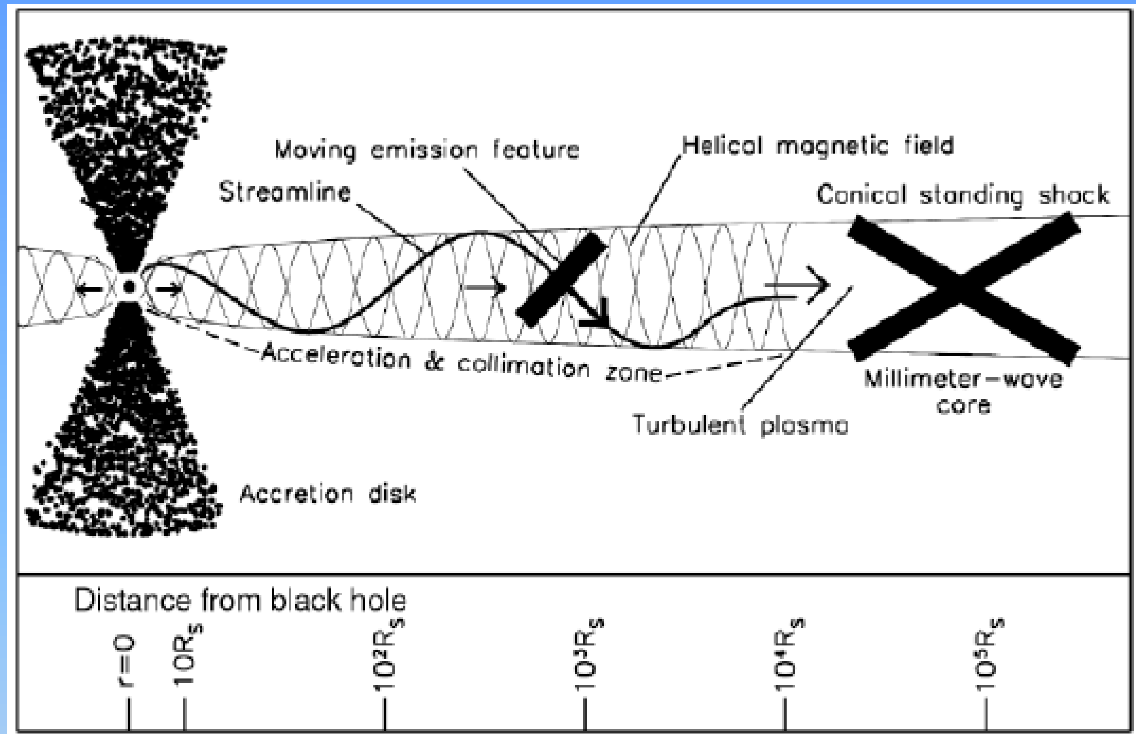

Figure 1. Sketch of hellical magnetic field in blazars (from Marscher 2008)

- Curved radio structures and bent trajectories of moving features are frequently found in radio jets on parsec and kpc scales. In some cases, the bends are quasi-periodical, suggesting a helical nature of the underlying structure (Marscher 1996). Quasi-periodical X-ray flares found in AO 0235+164 and 1ES 2321+419 (Rani et al. 2009) were explained by movement of the feature with enhanced emission along the helical field lines thus changing periodically its orientation with respect to the Observer. Due to the extreme sensitivity of Doppler boosting to viewing angle, One should expect periodical changes in the observed flux.

VLBI observations of nearby blazars (PKS 0745+241, PKS 0820+225, Mark 501, 3C 371) revealed the presence of Faraday rotation gradients which are transverse to the local jet directions (Gabuzda et al. 2004). This detection provided a new evidence that the jet magnetic fields should be either toroidal or helical.

From the end acceleration and collimation zone (~100 r_g), current driven instabilities can generate the fields of more chaotic configuration. According to M09, velocity shear can either align the magnetic field parallel to jet axis or generate turbulence that disorders the field.

- Long-term blazar flares are attributed to the propagation of relativistic shock waves through blazar jets. They can arise a s a result of major increase of flow velocity or internal energy of the matter deposited into jet base (Marscher & Gear 1985).
- It is currently widely accepted that particles can be accelerated at shock front via the first order Fermi mechanism up to TeV-EeV energies (one of the possible way of comic ray production! See e.g. Ellison 2003).

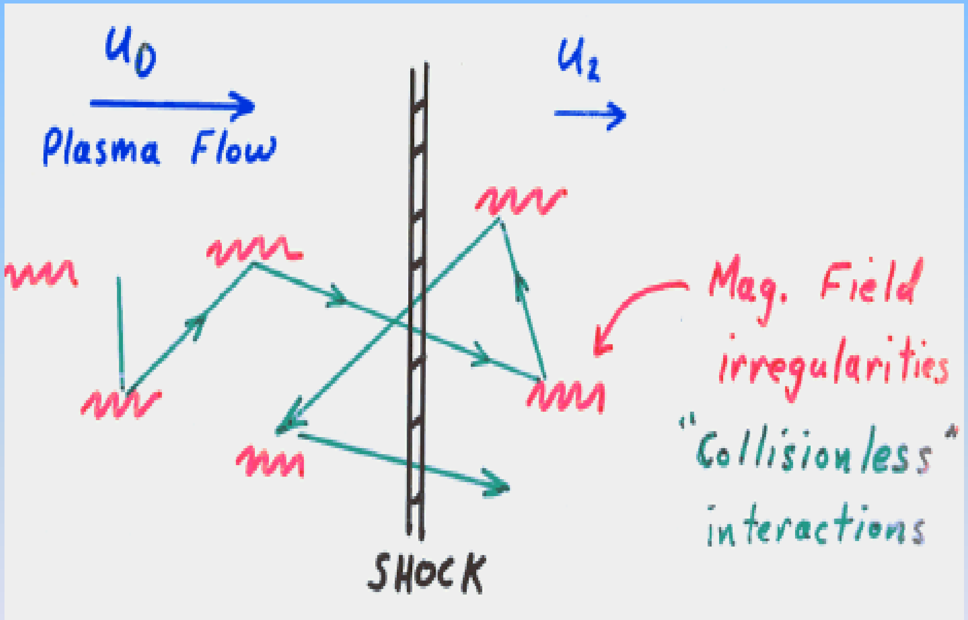

Figure 2. Sketch of first order Fermi acceleration (Ellison , Cracow Symposium 2003).

According to the diffusive shock acceleration (DSA) scenario, charged particles scattered elastically by magnetic irregularities (Alfven waves or random fields) confine them near the shock front for some time (Achterberg et al. 2001). They gain energy in each shock crossing due to converging flows (in the shock rest frame). The resulted particle energy spectum is given by following power-law

$$N_s(E) \propto E^{-s} dE$$

where *s is* a slope of the distribution:

$$s = 1 + \frac{ln(1/P_{ret})}{ln\langle E_f/E_i \rangle}$$

with P_{ret} - mean probability per cycle that a particle returns to the shock and re-crosses into the upstream medium, and E_f/E_i - ratio of final to initial energy in a cycle, and the angular brackets indicate the average value. Typically, ***s****~2.3 (Ellison 2004)*

Particle acceleration near relativistic shocks is not DSA. The bulk velocity is comparable to the particle velocity caussing the great anisotropy in angular distribution of accelerated particles . In the ultrarelativistic limit, the average energy gain per crossing (Achtenberg et al.)

$$\langle E_f/E_i \rangle \sim 2$$

Eventually, electrons escape from the shock front and lose energy radiatively downstream to the shock front via synchrotron or inverse Compton (*IC*) mechanisms with the following rates (Graff et al. 2008):

$$\dot{\gamma} = \dot{\gamma}_s + \dot{\gamma}_{IC}, \quad \dot{\gamma}_s = \frac{4\sigma_T}{3mc}\gamma^2 U_B, \quad \dot{\gamma}_{IC} = \frac{4\sigma_T}{3mc}\gamma^2 \int_{\epsilon_{min}}^{min[\epsilon_{max}, 3/(4\gamma)]} U(\epsilon, t) d\epsilon$$

- It is firmly established that the low-frequency component (radio to X-rays) of blazar SED is of synchrotron nature while MeV-TeV emission is thought to originate via inverse Compton scattering Of low-energy photons On ultra-relativistic particles (see e.g. Böttcher 2007).
- Here, we deal with magnetic fields from ***B***~1 mG (used for modelling of parsec-scale radio jets,) up to ***B***~1 G at the distances ~0.1 pc from the central source (in the case of hadronic models, Spada et al. 2001, Mucke et al. 2003).

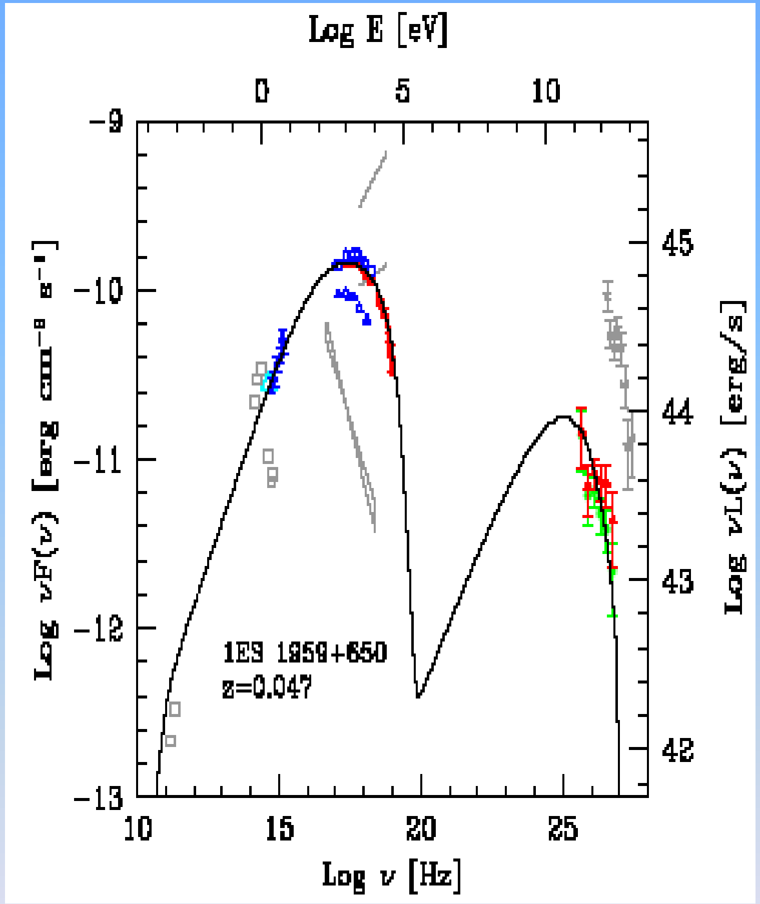

Figure 3. SED oF 1ES 1959+650 (Tagliaferri et al. 2008)

- Lower amplitude flares and flickerings can be explained as the consequence of a shock interacions with jet inhomogeneities linked to turbulent magnetic fields (Marscher, Gear & Travis 1992; Rani et al. 2009). (No suitable simulations have been performed yet!).

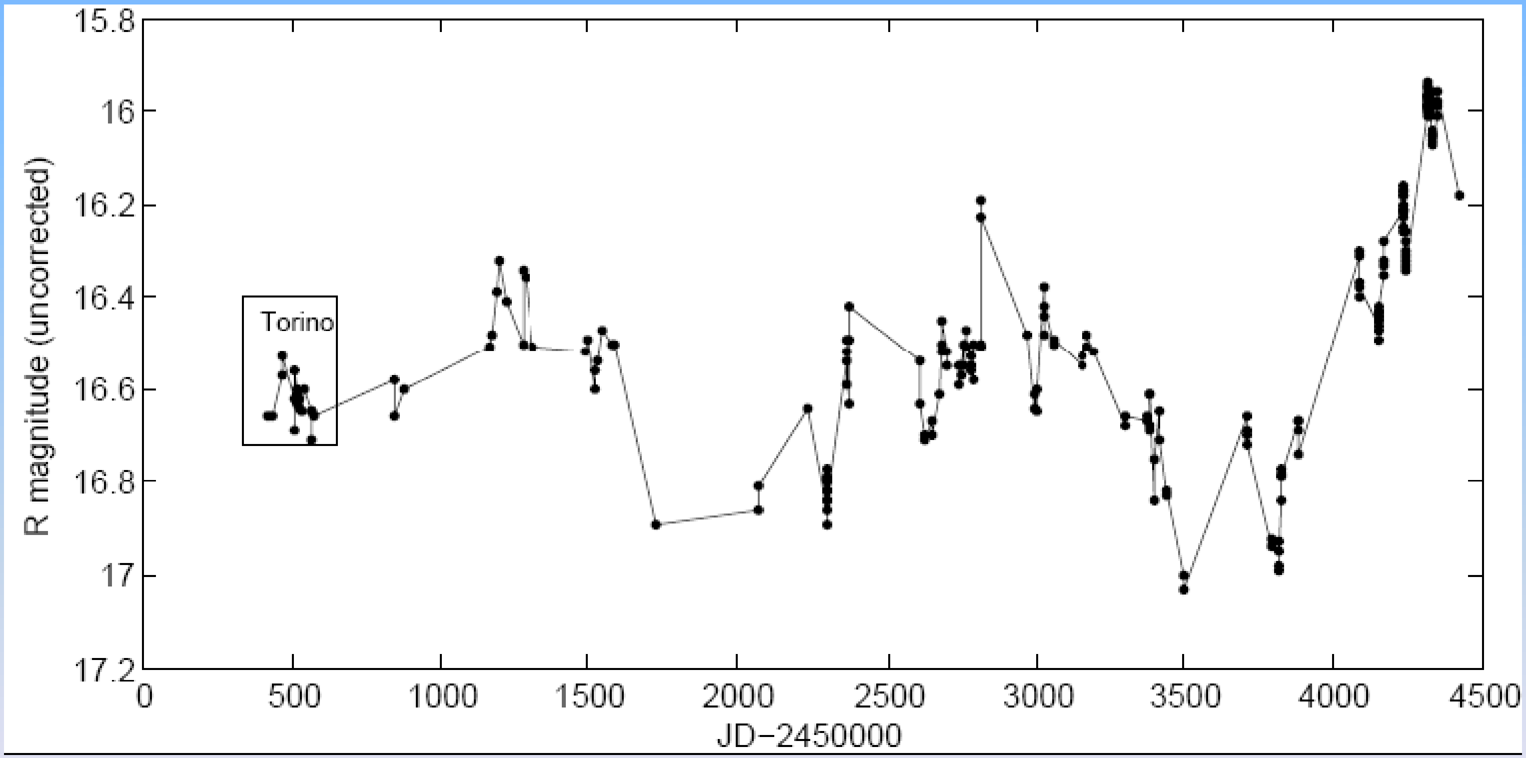

Fig. 4. Optical R-band historical light curve of 1ES 1028+511 (from Kapanadze, 2009, MNRAS, 398, 832)

- Tabe 1 gives the statistics of short-term burst of 10 X-ray selected blazars (XBLs) Monitored at Abastumani Observatory, Georgia. The fact that 73 out of 102 bursts belong to epochs of long-term flares gives rise to the suggestion that interaction between jet inhomogeneities and shock waves, propagating through blazar jets, can serve as a primary mechanism responsible for short-term bursts.

Table 1. Statistics of short-term flares of selected XBLs observed at Abastumani Observatory.

Object (1)	N_t (2)	N_f (3)	N_q (4)	N_u (5)	N_{sct} (6)	DC (7)	Slope (ascending) (8)	Slope (desc.) (9)	Amp (mag) (10)	Amp (%) (11)
1ES 0323+022	9	7	1	1	32	40	-0.08—0.30	0.08-0.40	0.11-0.45	14-51
1ES 0414+009	6	4	2	0	15	22	-0.13—0.25	0.09-0.85	0.18-0.32	19-36
1ES 0502+675	15	10	5	0	38	31	-0.13—0.73	0.13-1.00	0.15-0.45	16-52
1ES 0647+250	0	-	-	-	-	0	-	-	-	-
1ES 0806+524	10	7	2	1	35	32	-0.10—0.53	0.09-0.54	0.16-0.45	18-52
1ES 1028+511	9	8	1	0	19	20	-0.20—1.50	0.08-0.20	0.14-0.33	16-36
1ES 1426+428	2	2	0	0	4	5	-0.51—0.55	0.23-0.40	0.24-0.33	27-38
1ES 1517+656	9	7	2	0	15	21	-0.24—0.98	0.10-0.71	0.13-0.30	14-33
1ES 1959+650	27	24	2	1	114	32	-0.04—1.50	0.11-2.02	0.11-0.32	11-34
1ES 2344+514	8	4	2	2	22	14	-	-	0.23-0.43	25-49

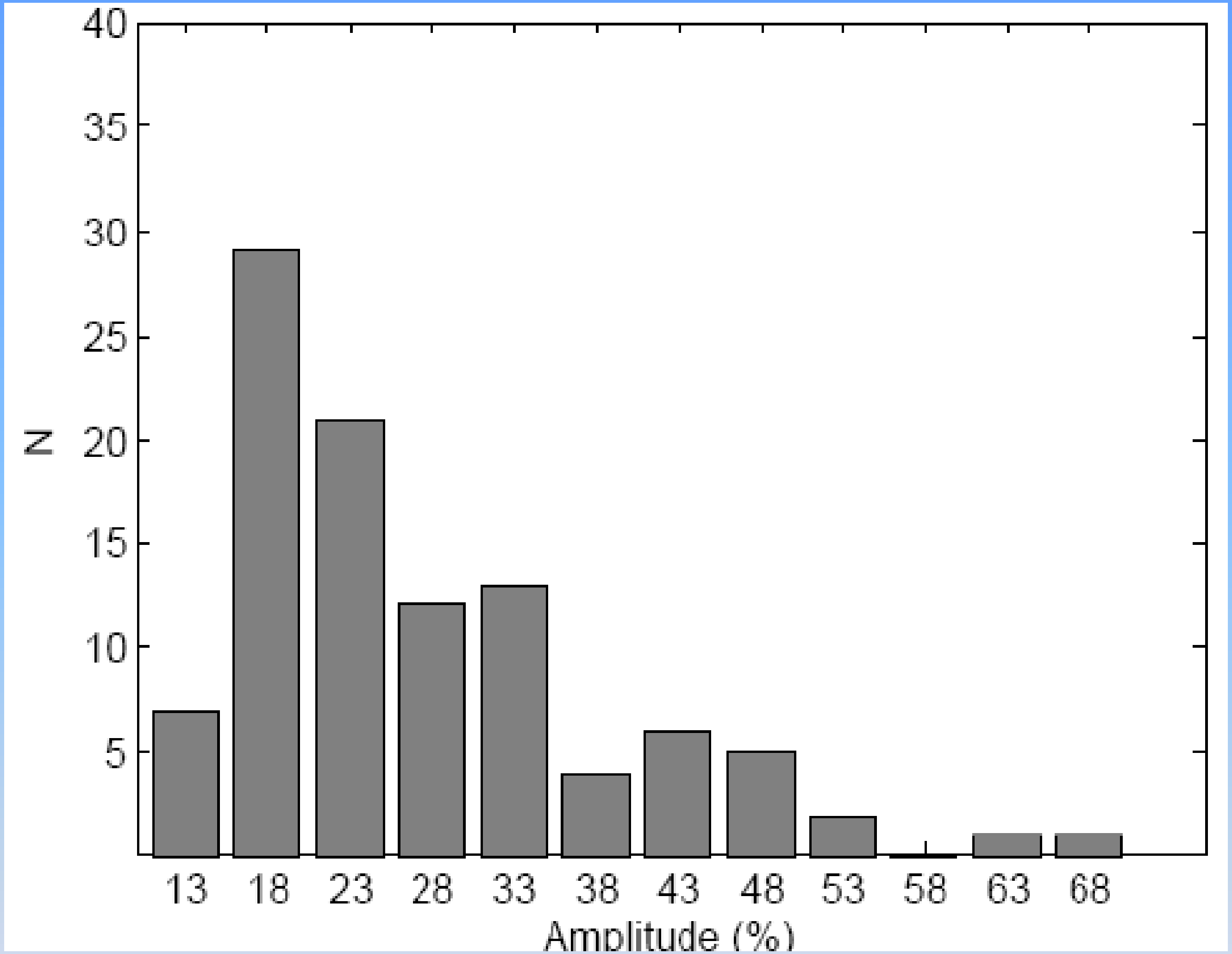

Figure 5. Statistics of the amplitudes of Short-term bursts (Kapanadze, 2010, in preparation)

- according to different duty cycles of sampled objects, the jet turbulence should vary from object to object. For example, the jets of 1ES 0647+250 (DC=0) and 1ES 1426+428 (DC=5%) seem to be relatively homogenous while the jet of 1ES 0323+022 should be the most turbulent among the targets (*DC*=40%). Thus, we probably deal with the variety of physical conditions within the jets of sampled objects.
- Nevertheless, other hypothetic mechanism can be at work while about 24% of the bursts belong to minimum epochs (There should be no more shocks in the optical jet!). For instance, fast spine+slow sheath geometry proposed by Ghisellini et al. (2005) for blazar jets can give rise to Kelvin-Helmholz instability leading to the development of the turbulence. No simulations have been done yet to prove the validity of this hypothesis.

- Blazars show clear variability in polarized flux, polarization degree and angle at all timescales. No simple correlation have been found between total and polarized fluxes or polarization degree. For 6 blazars from Jannuzi et al. (1993) sample, maximum polarized flux is correlated with total one; for nine objects – we have a correlation between maximum polarized flux and maximum polarization degree. In the case of H 0323+022, P(%)=0.86÷10.37. Polarization degree increases towards greater frequencies but this is not always the case (see Jorstad et al. 2006; Jannuzi et al. 1994). It can reach 40% at optical frequencies for FSRQs (Flat Spectrum Radio Quasars – a blazar subclass).

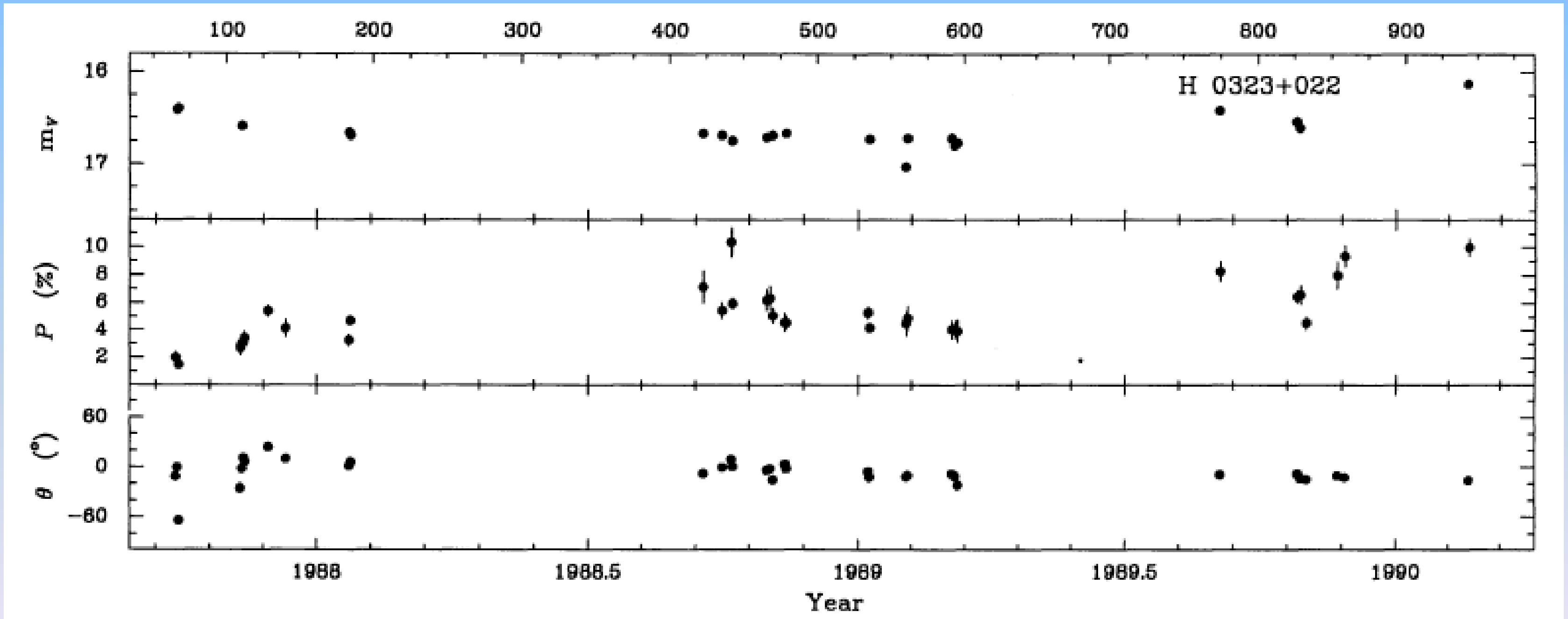

Figure 5. Long-term optical V-band polarization observations of H 0323+022 (Jannuzi et al. 1993)

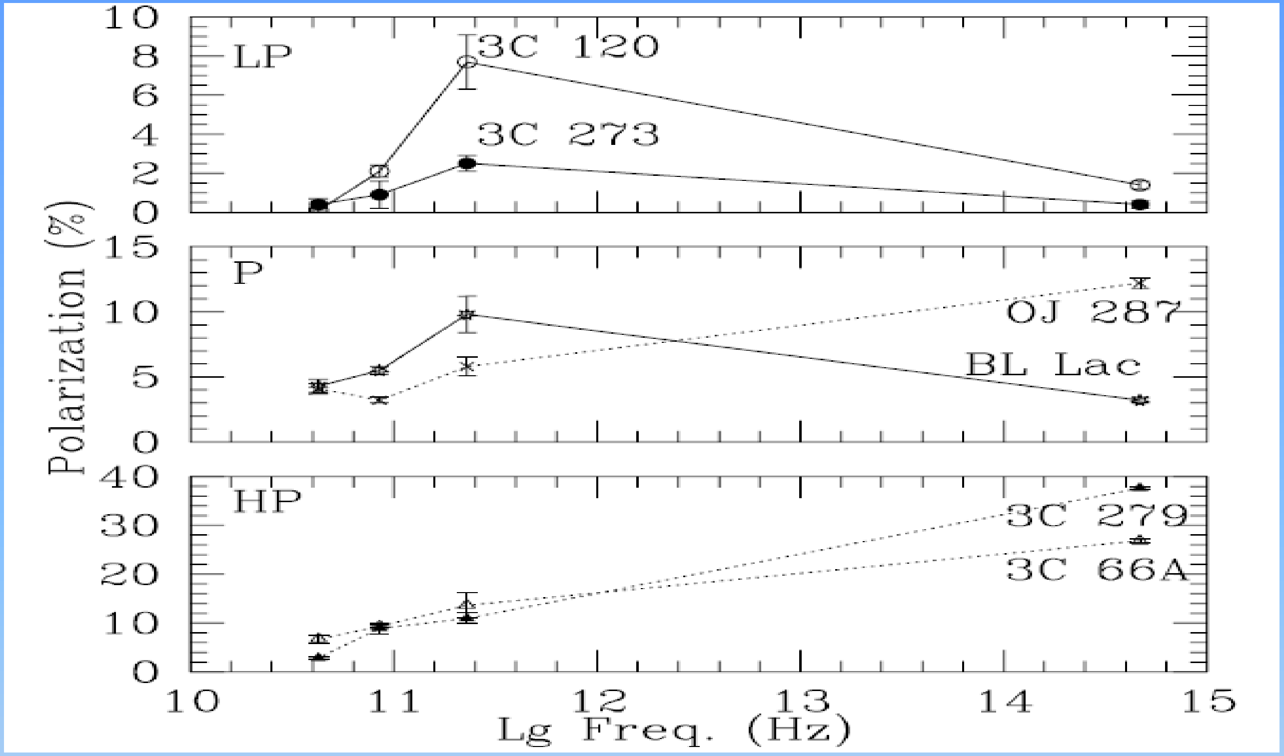

Figure 6. Polarization degree at different wavelengths (Jostad et al. 2006).

- The relationship between the polarization degree and total flux can serve as a diagnostic of physical process occurring in blazar jets. In the case of the shock-in-jet model, one can expect an increase of polarization with an increase of brightness due to ordering of the magnetic field in the shocked region. A reverse connection is possible if newly ejected plasma responsible for shock production has a chaotic magnetic field or one that is misaligned with the large-scale field (Jorstad et al. 2006).

Summary

- Whichever model used, magnetic fields should play major role in launching and collimation of blazar jets.
- Large-scale magnetic fields are considered to have helical structure. Nevertheless, turbulent fields should be also prominent.
- Magnetic irregularities can serve as major jet ingredients in particle acceleration up to ultra-relativistic velocities through first-order Fermi mechanism.
- Short-term blazar burst can be the result of interaction between moving shocks and jet inhomogeneities of turbulent origin.
- Polarization properties of blazars are very complex indicating that the configuration of magnetic field is not the same in newly injected material for different epochs.

Thank You!