MAGNETIC RECONNECTION IN RELATIVISTIC JETS*

Krzysztof Nalewajko

Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences
Bartycka 18, 00-716 Warsaw, Poland
knalew@camk.edu.pl

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Relativistic jets are produced by accreting black holes around which accumulation of magnetic fields leads to relativistic magnetizations; they are the dominant feature of blazars, a class of active galactic nuclei. Blazars are defined by very broad and luminous spectral energy distributions (SEDs) that are both strongly (stochastically) variable and spectrally stable. The maximum energy of electrons (and positrons) producing these SEDs must be robustly regulated. The prevalent view is that the regulating factor is radiative cooling, however, this implies extremely weak electric fields relative to magnetic fields, $E/B \sim 10^{-9}$ (this is equivalent to the separation of Larmor and cooling time scales; this is also why the synchrotron SEDs of blazars extend to much lower energies than that of the Crab pulsar wind nebula). The alternative regulating factor could be local (highly inhomogeneous) magnetization. Relativistic magnetic reconnection has been proposed to explain rapid (a few minutes) gamma-ray flares of blazars. Two particular scenarios have been developed: minijets (Alfvénic outflows) and plasmoids (magnetic flux ropes). It was recently demonstrated that plasmoids are better suited to produce rapid flares (by tail-on mergers), because their higher density is a decisive advantage over the higher Lorentz factors of minijets. Magnetic reconnection can be triggered in relativistic jets by instabilities of toroidal magnetic fields, driven either by electric currents or by gas pressure, which were recently shown to lead to efficient particle acceleration.

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1. Observational evidence

The electromagnetic spectrum of radiation detected from the Universe extends to the broad gamma-ray range (MeV to PeV photon energies). Both

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space-based (Fermi, AGILE) and ground-based (H.E.S.S., MAGIC, VERITAS, HAWC, LHAASO) gamma-ray telescopes detect individual bright sources of gamma rays. The most numerous classes of sources, particularly in the GeV photon energy range, are blazars and pulsars [1].

Blazars are a class of active galactic nuclei (AGN; phenomena produced by accreting supermassive black holes — SMBH, with $M_{\rm BH} \gtrsim 10^7 M_\odot$, where $M_\odot$ is the mass of the Sun), the emission of which is dominated by broad-band non-thermal components produced in a relativistic jet pointed closely (at small viewing angle $\theta_{\rm obs}$) towards the observer, for review, see [2]. The relativistic jet is a collimated (with small half-opening angle $\theta_{\rm j}$) outflow with relativistic bulk speeds: $v_{\rm j} \lesssim c$, where c is the speed of light in vacuum; with the corresponding bulk Lorentz factors $\Gamma_{\rm j} = [1-(v_{\rm j}/c)^2]^{-1/2} \sim \mathcal{O}(10)$. The smallness of half-opening angles means that $\theta_{\rm j} \sim 1/\Gamma_{\rm j}$, and the smallness of viewing angles in blazars means that $\theta_{\rm obs} \lesssim 1/\Gamma_{\rm j}$. Small viewing angles imply relativistic Doppler factors $\mathcal{D}_{\rm j} = [\Gamma_{\rm j}(1-(v_{\rm j}/c)\cos\theta_{\rm obs})]^{-1} \sim \Gamma_{\rm j}$. Radiation from an emitting jet region of intrinsic luminosity L' will be boosted to an apparent luminosity of $L \simeq \mathcal{D}_{\rm j}^4 L'$. This relativistic boost by factor $\sim 10^4$ makes blazars the brightest class of AGN and the most luminous persistent cosmic sources with total luminosities up to $\sim 10^{49}\ {\rm erg\,s^{-1}}$ [3] (only the gamma-ray bursts are more luminous, but they are transient). The fact that blazars are sources of non-thermal emission extending to the gamma-ray band requires in addition an efficient conversion of the jet energy to non-thermal high-energy particles. These energetic particles may include both leptons (electrons and positrons) and hadrons (protons). The broad-band spectral energy distribution (SED) $E({\rm d}L/{\rm d}E)$ consists of two main components. The low-energy component extends from the radio band to the optical/UV band (~ 10 eV; in high-luminosity blazars known as the flat spectrum radio quarars, FSRQs), or even to the X-ray band (~ 10 keV; in low-luminosity blazars known as the BL Lac objects), it is attributed to the synchrotron radiation of leptons. The high-energy component, which peaks in the gamma-ray band, and in certain blazars may extend down to the X-ray band, can be attributed either to leptonic mechanisms (inverse Compton scattering) and/or to hadronic mechanisms (photo-hadronic cascades, synchrotron radiation of protons) [4, 5].

Blazars are strongly variable sources, their variations are observed in many bands, but particularly in the gamma-ray band, they are stochastic and occur on a broad range of time scales, down to minutes [3, 6], which is less than the light crossing time scale $R_{\rm g}/c$ for a $\sim 10^9 M_\odot$ SMBH, where $R_{\rm g} = GM_{\rm BH}/c^2$ is the gravitational radius (G is the gravitational constant). The most rapid gamma-ray flares require very compact emitting regions, utilizing a significant fraction of the total jet power. Rapid flares observed in the BL Lac blazars could be produced at very short distances from the

SMBH ($\sim 10^{1-2} R_{\rm g}$). On the other hand, rapid flares observed in the FSRQ blazars would be absorbed (in the photon–photon pair production process) if produced too close ($\lesssim 10^4 R_{\rm g}$) to the SMBH. This creates an *energy density challenge* — how to focus a large fraction of the jet power into a tiny cross section [7].

The statistical analysis of multiwavelength variability of blazars shows that fractional variability is maximized at photon energies corresponding to the most energetic particles ($\gamma_{\rm max}$). In the case of BL Lacs this means that variability is the strongest in hard X-rays (synchrotron emission of $\gamma_{\rm max}$ leptons) and in TeV gamma-rays (synchrotron self-Compton (SSC) emission of $\gamma_{\rm max}$ leptons), *e.g.*, [8]. In the case of FSRQs variability, it is the strongest in the UV band (synchrotron emission of $\gamma_{\rm max}$ leptons) and in GeV gamma-rays (external radiation Comptonization (ERC) emission of $\gamma_{\rm max}$ leptons). That these variations are produced by the same particle populations by different mechanisms is underlined by their strong correlation. Polarimetric observations of blazars in the optical band provide another piece of evidence of the importance of $\gamma_{\rm max}$ leptons. The results of KANATA [9] and RoboPol [10] surveys show that FSRQs have systematically higher optical linear polarization degrees ($\Pi \sim 30$–40%) than the BL Lacs ($\Pi \sim 10\%$). A possible explanation of this trend is that the mean polarization degree, like the fractional variability, scales with $\gamma/\gamma_{\rm max}$, which in the optical band is maximized for the FSRQs. This makes a specific prediction for the polarization of blazars in the X-ray band, which should be $\Pi \sim 30$–40% for the high-energy peaked BL Lacs (HBLs), and much lower for the FSRQs (depending on the exact emission mechanism). This prediction will be tested very soon by new X-ray polarimeters like IXPE. The reason why fractional variability and polarization degree should scale with $\gamma/\gamma_{\rm max}$ may be related to the turbulent state of the blazar zones in relativistic jets. If the blazar zones consist of a large number of turbulent eddies, each with random orientation of the magnetic field and producing lepton energy distribution with different $\gamma_{\rm max}$, the volume filling factor of these leptons will be a decreasing function of their energy [11]. The existence of multiple independent emitting regions is also indicated by a tentative relation between the structure of light curves of bright gamma-ray flares of blazars with their gamma-ray spectra detected by Fermi [12].

Despite such relentless variability, the overall SED shapes remain very stable. This is an important indication that the particle acceleration processes are robust and, in particular, that the maximum particle energies are well regulated. The high-luminosity FSRQs require leptons with random Lorentz factors up to $\gamma_{\rm max} \sim 10^3$, and the low-luminosity BL Lacs require leptons with $\gamma_{\rm max} \sim 10^6$. These well-determined $\gamma_{\rm max}$ values constitute a theoretical basis for the blazar sequence, the observational anticorrelation between the synchrotron peak photon energy, and synchrotron luminosity in the radio band [13].

Pulsars are rapidly rotating magnetized neutron stars, their co-rotating magnetospheres extend to relativistic striped winds that terminate at stationary shock waves and inflate pulsar wind nebulae (PWNe). The pulsed gamma-ray emission is produced by energetic particles accelerated in the magnetosphere (or just outside). Between the pulses, a steady emission component is observed, which is produced along the striped wind and further in the nebula [14]. A primary example of a multiwavelength PWN is the Crab, its steady emission is dominated by a very broad synchrotron component, extending from the radio band to the gamma-rays, with a high-energy cut-off at ~ 100 MeV [15], beyond which is an SSC component, which extends at least to PeV energies. The energy of ~ 100 MeV is consistent with the theoretical limit for the energy of synchrotron photons produced by electrons accelerated by parallel electric fields of strength not exceeding the perpendicular magnetic field strength that determines the synchrotron cooling rate, $E_{\|} \le B_{\perp}$, as required by magnetohydrodynamics (MHD) [16].

2. Maximum electron energy in blazar jets

Why are the synchrotron SEDs of FSRQ blazars extending only to the observed photon energy of ~ 10 eV and not to the MHD limit of $\sim 100\mathcal{D}_{\rm j}$ MeV (to account for the Doppler boost of the photon energy)? *Why are blazar SEDs not Crab-like?* This question is fundamentally related to the problem of what mechanism determines $\gamma_{\rm max}$ in blazars.

2.1. Limited by radiative cooling

A popular hypothesis is that particle acceleration in blazar jets is limited by radiative cooling [17]. However, the energy densities $u'_{\rm cool}$ (the prime indicates the jet co-moving frame) of magnetic and radiation fields in the jets of FSRQs are well constrained by various observations and models of blazar emission [5]. An electron of energy $\gamma m_e c^2$ (where m_e is the electron mass) is accelerated at the rate $\mathrm{d}\gamma/\mathrm{d}t' = eE'_{\|}/(m_e c) \equiv \beta\gamma/\tau'_{\rm L}(\gamma)$, where e is the electron charge, $\beta \equiv E'_{\|}/B'_{\perp}$ is the strength ratio of electric and magnetic fields, and $\tau'_{\rm L}(\gamma) \equiv \gamma m_e c/(eB'_{\perp})$ is the Larmor time scale. On the other hand, the radiative cooling rate for this electron is $\mathrm{d}\gamma/\mathrm{d}t' = -4\sigma_{\rm T} u'_{\rm cool}\gamma^2/(3m_e c) \equiv -\gamma/\tau'_{\rm cool}(\gamma)$, where $\sigma_{\rm T}$ is the Thomson cross section, and $\tau'_{\rm cool}(\gamma) \equiv 3m_e c/(4\sigma_{\rm T} u'_{\rm cool}\gamma)$ is the cooling time scale. Taking $\gamma_{\rm max}$ to be the electron Lorentz factor at which acceleration is balanced with radiative cooling allows to estimate the relative electric field strength as $\beta = \tau'_\mathrm{L}(\gamma_\mathrm{max})/\tau'_\mathrm{cool}(\gamma_\mathrm{max})$. For parameters typical for the FSRQ jets at distances $r \sim (0.1\text{–}01)$ pc, where blazar emission is thought to be produced [18], *i.e.*, $B'_\perp \sim 1$ G, $u'_\mathrm{cool} \sim 10u'_{\mathrm{B},\perp}$, where $u'_{\mathrm{B},\perp} = B'^2_\perp/8\pi$, the Larmor time scale is $\tau'_\mathrm{L}(\gamma_\mathrm{max}) = 60(\gamma_\mathrm{max}/10^3)(B'_\perp/1\ \mathrm{G})^{-1}$ μs, and the cooling time scale is $\tau'_\mathrm{cool}(\gamma_\mathrm{max}) = 80(\gamma_\mathrm{max}/10^3)^{-1}(B'_\perp/1\ \mathrm{G})^{-2}$ ks. These time scales are separated by 9 orders of magnitude, *i.e.*, $\beta \sim 10^{-9}$. This suggests that *particle acceleration in relativistic jets should be extremely slow*, if γ_max is indeed limited by radiative cooling [19]. In the case of magnetic reconnection, β can be identified as the reconnection rate. A similar result has been obtained in the context of shock waves in terms of the electron mean free path relative to the Larmor radius $\lambda_\mathrm{mfp} \sim 10^7 R_\mathrm{L}$ [20].

The effect of radiative cooling on magnetization-dependent turbulent particle acceleration in blazars has been recently investigated by [21] in terms of diffusion and advection in the energy space (using coefficients measured by [22] from the results of radiative kinetic numerical simulations of relativistically magnetized turbulence). For magnetization $\sigma = 1$, their acceleration rate is roughly $\mathrm{d}\gamma/\mathrm{d}t' \simeq (2.9\gamma_0 + 17.9\gamma + 4.3\gamma_0^2/\gamma)/\tau'_\mathrm{cool} \simeq 25\gamma_0/\tau'_\mathrm{cool}$ for $\gamma \simeq \gamma_0$, where $\gamma_0 \simeq 200$ is the mean electron Lorentz factor and $\tau'_\mathrm{cool} = 9m_e c/(16\sigma_\mathrm{T} u'_\mathrm{cool}\gamma_0)$ is the adopted by them radiative cooling time scale. For $B'_\perp = 1$ G and $u'_\mathrm{cool} = 10u'_{\mathrm{B},\perp}$, the cooling time scale is $\tau'_\mathrm{cool} \simeq 300$ ks, but the Larmor time scale is $\tau'_\mathrm{L}(\gamma_0) \simeq 10$ μs, hence $\beta \simeq 25\tau'_\mathrm{L}/\tau'_\mathrm{cool} \simeq 10^{-9}$.

The argument is thus independent of the details of the particle acceleration mechanism, since the effective co-moving acceleration electric field $E'_\parallel$ is robustly constrained by the radiative cooling rate.

2.2. Limited by magnetization

An alternative constraint on the value of γ_max in relativistic jets of blazars can be placed in the scenario of particle acceleration in highly relativistic magnetic reconnection. In the limit of relativistic magnetization $\sigma = B^2/(4\pi w) \gg 1$, where $w = \rho c^2 + u_\mathrm{int} + P$ is the relativistic enthalpy density (with ρ the mass density, u_int the internal energy density, and P the pressure), accelerated particles were predicted to form a hard power-law energy distribution $\mathrm{d}N/\mathrm{d}\gamma \propto \gamma^{-p}$ with index $p \simeq 1$ [23]. This result has been confirmed by numerous kinetic numerical simulations [24–27]. In such hard particle distributions ($p < 2$), most energy is contained at their high-energy end, around $\gamma_\mathrm{max} \sim \sigma$, since σ is roughly the measure of mean magnetic energy per particle. Considering a plasma consisting of protons with number density n_p and electrons+positrons with number density $n_e \geq n_p$, one can distinguish electron magnetization $\sigma_e = B^2/(4\pi w_e) \simeq (w_p/w_e)\sigma \gg \sigma$, then with $\gamma_{e,\mathrm{max}} \sim \sigma_e$, it is even easier to achieve high electron energies.

Blazar jets are relativistic because they are accelerated in the process of converting relativistic magnetization $\sigma_{\rm base}$ at the base of the jet (a magnetosphere of a supermassive spinning black hole) to the relativistic bulk Lorentz factor. If this process is highly efficient, the terminal jet Lorentz factor would be $\Gamma_{\rm j} \sim \sigma_{\rm base}$, *e.g.*, [28]. However, $\sigma_{\rm base}$ can also be used to accelerate particles in the process of magnetic reconnection, if the magnetic fields of the jet are locally reversed. In such a case, it would be possible that $\sigma_{\rm base} \gg \Gamma_{\rm j}$. Physical conditions at the bases of relativistic jets are poorly understood, one particular problem is the mass loading. Electron–positron pairs may be seeded uniformly across the jet base by soft gamma-ray radiation from the accretion disk corona [29]. Protons need to find their way across the magnetic fields, most likely by means of instabilities like the interchange of Kelvin–Helmholtz. It is quite likely that the loading of protons is filamentary and thus highly inhomogeneous. The inhomogeneity of mass density would imply a strong inhomogeneity of σ with 'bubbles' of $\sigma_{\rm max} \gg \sigma_{\rm base}$. In the case of BL Lacs, $\gamma_{\rm max} \sim 10^6$ could be explained with $\sigma_{\rm max} \sim 10^3$. In the case of FSRQs, the uniform seeding of electron–positron pairs would reduce $\sigma_{\rm max}$ and also $\gamma_{\rm max}$, providing an alternative explanation of the blazar sequence [19]. Similar results have been presented recently in the context of particle acceleration in relativistically magnetized turbulence [30].

3. Minijets versus plasmoids

The discovery of rapid (a few minutes) gamma-ray flares of blazars required to consider a highly localized (of size $R < R_{\rm g}$) dissipation mechanism in relativistic jets. One concern was to avoid the TeV gamma-rays being absorbed within the emitting region. This led to the requirement of very high bulk Lorentz factors for the flaring regions $\Gamma_{\rm fl} \gtrsim 50$ [31]. It was then proposed that high $\Gamma_{\rm fl}$ could be a combination of the standard jet Lorentz factor $\Gamma_{\rm j} \sim 10$ and an additional Lorentz factor of a local *minijet* $\Gamma_{\rm mj} \sim 10$, so that $\Gamma_{\rm fl} \sim \Gamma_{\rm j}\Gamma_{\rm mj} \sim 100$ [32]. The minijet was associated with an Alfvénic outflow driven by relativistic magnetic reconnection, requiring a local jet magnetization of $\sigma_{\rm j} \sim \Gamma_{\rm mj}^2 \sim 100$. A detailed model for the radiative signatures of the minijets has been presented in [33].

Subsequent developments in the understanding of relativistic magnetic reconnection emphasized the role of *plasmoids*, regions of closed magnetic field lines in 2D (magnetic flux ropes in 3D) arising due to the tearing mode instability of thin reconnection layers that trap a large fraction of particles passing through the magnetic diffusion regions (X-points) and the minijets [34]. Since plasmoids are tied to a reconnection layer, they can be accelerated along it and interact with other plasmoids by mergers. The acceleration rate of a plasmoid is anti-correlated with its size [35], which means that plasmoids of different sizes can merge tail-on (a small/fast plasmoid capturing a large/slow plasmoid) even in a globally diverging reconnection outflow. Plasmoid mergers are quick and efficient magnetic dissipation events that can instantly accelerate particles and produce rapid flares of radiation [36]. A detailed model for the production of blazar flares by reconnection plasmoids has been presented in [37].

What is the relative importance of minijets and plasmoids for particle acceleration and radiative signatures in relativistic magnetic reconnection? This question has been recently addressed using kinetic numerical simulations of relativistic reconnection in open boundaries including synchrotron cooling [38]. These simulations show that minijets and plasmoids co-exist in the same reconnection layer. Every gap between plasmoids is filled with an Alfvénically fast low-density outflow. The plasmoids are characterized by much higher particle density and stronger magnetic fields, they are thus much significantly slower. Individual particles can be accelerated in a different scenario, either in a minijet region on a free Speiser orbit, or trapped into a plasmoid. Higher particle energies can be achieved in the minijet regions, especially under efficient synchrotron cooling. The net effect for the radiative signatures is that: minijets produce synchrotron radiation extending to higher energies, but less luminous and relatively steady; plasmoids produce radiation extending to lower energies, but more luminous and highly variable. *High particle densities of the plasmoids appear to be more important than high Lorentz factors of the minijets.* Overall, plasmoid mergers are most promising for the production of rapid gamma-ray flares of blazars.

4. Instabilities of magnetized jets

Magnetic reconnection can operate in relativistic jets in the presence of local reversals of magnetic field lines. Magnetic field reversals may happen due to global reversals of fields inherited from the accretion flow [39] or due to plasma instabilities. Ordered magnetic fields in jets may include two main components — poloidal and toroidal. Lateral expansion of the jet decreases the strength of both components, but the toroidal component decays more slowly and eventually may become dominant. In the presence of a strong toroidal field, jets are susceptible to instabilities driven either by poloidal electric current, *e.g.*, [40] or by the gas pressure [41], depending on the radial force balance. These instabilities can arise on the time scale comparable to the Alfvén crossing time scale of the jet, hence rapidly for relativistic magnetizations. The fastest-growing azimuthal modes are the axisymmetric $m = 0$ pinch and an asymmetric $m = 1$ kink.

Recently, the first 3D kinetic simulations of cylindrical jets with strong toroidal fields providing relativistic magnetization have investigated non-thermal particle acceleration in the alternative limits of the pressure-driven modes [42] and the current-driven modes [43]. Both of these studies found non-thermal particle acceleration, but with different detailed mechanisms. In the case of gas-pressure-balanced toroidal fields (Z-pinch), the fastest-growing modes are characterized by short-wavelength (internal modes) and mixed azimuthal modes, generating a turbulence with electric fields largely perpendicular to the local magnetic fields. The particle energies are limited by a Hillas-type confinement $R_{\rm L} \lesssim R_0$, where $R_{\rm L}$ is the Larmor radius for peak toroidal field strength B_0 attained at a jet radius R_0 [42]. In the case of toroidal fields balanced by poloidal fields (force-free screw-pinch), the fastest-growing modes are long-wavelength (external modes) and dominated by the kink mode, generating helical perturbations that locally may create conditions for magnetic reconnection. The particle energies also scale with the confinement energy, but they are somewhat lower than in the gas pressure balanced case [43].

A new study is currently ongoing that attempts to bridge those two limits by considering a mixed radial force balance including different combinations of gas pressure and poloidal field for the same toroidal field profile.

5. Conclusions

Magnetic reconnection is a very efficient mechanism of dissipation and particle acceleration that can operate in the relativistic AGN jets, if the structure of jet magnetic fields is not too orderly.

Observational evidence from multiband monitoring of blazars suggests that their emitting regions are turbulent and highly intermittent, occasionally releasing large amounts of radiation from very compact regions. The stability of spectral energy distributions (SED) of particular blazar classes (the blazar sequence) is a strong indication that the maximum energy $\gamma_{\rm max}$ of electrons (and positrons) producing the observed radiation is robustly regulated. It is often presumed that lepton acceleration (regardless of the mechanism) is limited by radiative cooling, however, that implies extremely weak mean electric fields relative to the typical magnetic field strengths, $E'_{\parallel}/B'_{\perp} \sim 10^9$. Alternatively, $\gamma_{\rm max}$ could be determined by magnetization, if the acceleration mechanism is relativistic magnetic reconnection.

Magnetic reconnection has been proposed to explain the production of rapid gamma-ray flares of blazars. Two particular scenarios have been developed: minijets (low-density Alfvénic outflows from magnetic diffusion regions) and plasmoids (high-density magnetic flux ropes). Recent kinetic numerical simulations showed that:

(1) these structures co-exist in the same reconnection layer;

(2) minijets can accelerate particles to higher energies;

(3) the high density of plasmoids is a decisive advantage for their luminosity, as they can produce rapid flares during tail-on mergers.

Magnetic reconnection can be triggered in relativistic jets by instabilities developing from strong toroidal magnetic fields. These instabilities have been demonstrated to lead to efficient particle acceleration, which is particularly fast when the toroidal fields are balanced by the gas pressure.

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