HABILITATION SUMMARY

1. *Name:* Krzysztof Władysław Nalewajko
2. *Scientific titles:*
    - M.Sc. in astronomy, University of Warsaw, 2007
      Thesis title: *"Modeling of radiative processes in blazars"*
    - Ph.D. in astronomy, Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 2011
      Thesis title: *"Reconfinement shocks in jets of active galaxies"*
3. History of employment in research institutions:
    - University of Colorado Boulder (USA), Research Assistant, 2011-2013
    - University of Colorado Boulder (USA), Senior Research Assistant, 2013-2014
    - Stanford University (USA), postdoc, 2014-2015
    - Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, tenure-track, since 2015
4. Habilitation achievement:
    - Title:

      "Constraints on the gamma-ray emitting regions in relativistic jets of blazars"
    - Publications:

      [P1] K. Nalewajko, M. C. Begelman, B. Cerutti, D. A. Uzdensky, M. Sikora *"Energetic Constraints on a Rapid Gamma-Ray Flare in PKS 1222+216"*, 2012, MNRAS, 425, 2519 (80%)

      [P2] K. Nalewajko, M. Sikora, G. M. Madejski, K. Exter, A. Szostek, R. Szczerba, M. R. Kidger, R. Lorente *"Herschel PACS and SPIRE observations of blazar PKS 1510-089: a case for two blazar zones"*, 2012, ApJ, 760, 69 (61%)

      [P3] K. Nalewajko *"The brightest gamma-ray flares of blazars"*, 2013, MNRAS, 430, 1324 (100%)

      [P4] K. Nalewajko, M. C. Begelman, M. Sikora *"Constraining the Location of Gamma-Ray Flares in Luminous Blazars"*, 2014, ApJ, 789, 161 (90%)

1 Significance of gamma-ray emission of blazars in astrophysics

Blazars are a special class of active galaxies: their spectra are dominated by nonthermal radiation extending from the radio waves ($<$ GHz) up to the very-high-energy gamma rays ($>$ TeV) [2], they are also characterized by violent and chaotic flux variability over a very wide range of time scales (minutes to decades) [3]. The observed bolometric luminosities of blazars reach $10^{50}\ \mathrm{erg\,s^{-1}}$ [4], greatly exceeding the luminosities of their host galaxies, including the accretion component. Blazar images at the highest angular resolutions (milliseconds of arc), obtained in the radio and millimeter bands thanks to the very-large-baseline interferometry (VLBI), are characterized by the *core-jet* structure and apparently superluminal propagation speeds [32]. These observational facts are interpreted by the presence of a relativistic jet directed towards us, dissipating a significant fraction of energy in processes leading to efficient particle acceleration [12]. The luminosity amplification and superluminal velocities are effects of special relativity (Doppler effect, aberration and light-travel time) [56], the time variability of radiation is an effect of variable dissipation rate, and the spectral extent of photons is an effect of the energy extent of particles.

Blazars belong to the most important sources of cosmic gamma-ray radiation, they can account for at least 50% of the isotropic cosmic gamma-ray background at energies above 100 MeV [10]. In the early 1990s, thanks to the EGRET instrument onboard the Compton Gamma-Ray Observatory, it was discovered that gamma-ray radiation dominates the bolometric luminosity of the luminous blazars classified as flat-spectrum radio quasars (FSRQ) [26]. That discovery triggered a development of new theoretical models for production of gamma-ray emission in relativistic jets. I should emphasize here the role of prof. Marek Sikora (later my doctoral thesis advisor), who for FSRQs proposed Comptonization of radiation external to the jet in the form of broad emission lines [57]. Other basic models of gamma-ray emission include synchrotron self-Comptonization (SSC; especially in the case of less luminous BL Lac objects) [43], Comptonization of the accretion disk radiation [22], Comptonization of the thermal radiation of the dusty tori [15], as well as models involving hadronic interactions [42].

In recent years, blazars are intensely monitored by a new generation of gamma-ray observatories. The cosmic telescopes Fermi and AGILE observe the entire sky in the energy range 0.1-100 GeV with very few interruptions since 2007. Ground-based Cerenkov observatories, H.E.S.S., MAGIC and VERITAS, observe selected targets in the energy range 0.1-10 TeV. These observations are coordinated with various telescopes operating in lower energy bands: X-ray, UV, optical, infrared, millimeter and radio. A recent summary of multiwavelength observations of blazars can be found in the review [40].

Understanding the mechanism of gamma-ray emission in blazars is essential for understanding the physics of relativistic jets. Observations indicate that roughly 15% of active galaxies are radio galaxies [33]. Interferometric VLBI observations reveal jets as collimated plasma outflows reaching velocities very close to the speed of light (bulk Lorentz factors of order $\Gamma_\mathrm{j} \sim 10$) [37]. The opening angle of relativistic jets multiplied by their bulk Lorentz factor is typically $\Gamma_\mathrm{j}\Theta_\mathrm{j} \lesssim 1$ [54]. The acceleration and collimation of jets are gradual processes taking place over a distance scale of roughly $r_\mathrm{acc} \sim 10^3 R_\mathrm{g}$ of gravitational radii $R_\mathrm{g} = GM_\mathrm{bh}/c^2$ of the central black hole, and they are associated with the conversion of magnetic energy to kinetic energy and interaction of the jet with its environment [36]. Initially, the jet power is strongly dominated by magnetic power (Poynting flux), and after the acceleration phase is complete they are thought to be roughly in equipartition between the magnetic and kinetic powers [58]. The jet plasma is fully ionized and composed of both leptons (electrons and electron-positron pairs), as well as of hadrons (mostly

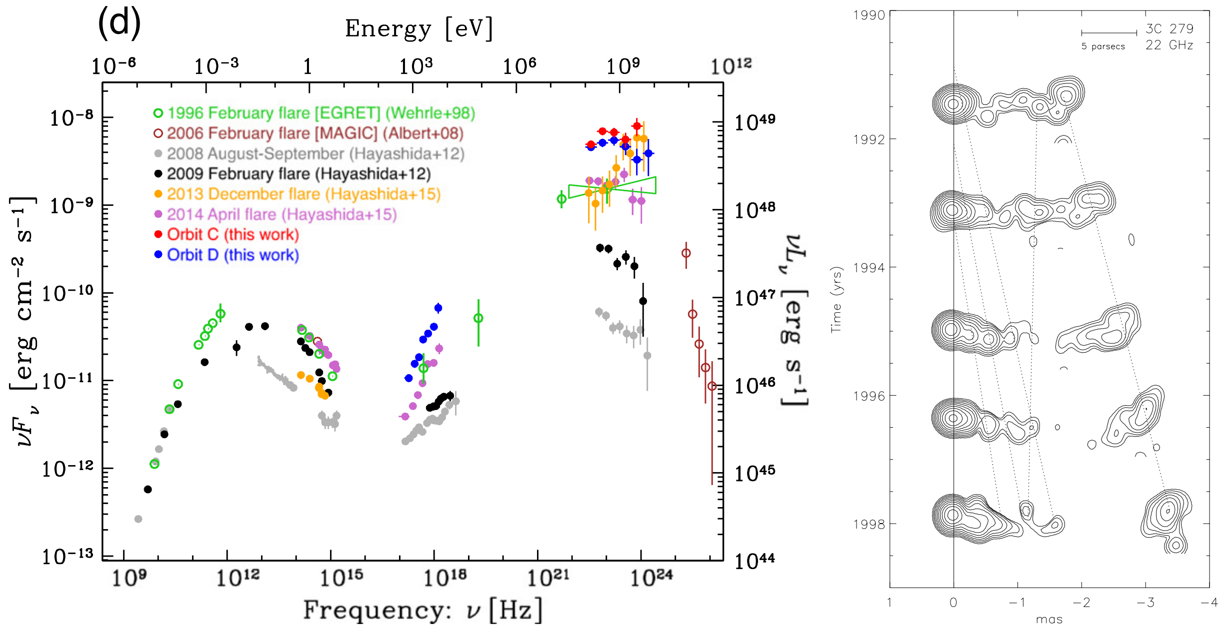

Figure 1: Observations of blazar 3C 279 belonging to the class of flat-spectrum radio quasars (FSRQ). *The left panel* shows spectral energy distributions (SED) for several epochs. The SED of a blazar consists of two main components, attributed to synchrotron ($\nu \in [10^9 : 10^{15}]$ Hz) and Comptonization ($\nu \in [10^{17} : 10^{26}]$ Hz) processes. The data are described in publications [1, 27, 28, 8]. *The right panel* shows radio images obtained with very-long-baseline interferometry (VLBI) at different epochs. They show a core-jet structure, as well as superluminal apparent propagation of radio knots. This figure is taken from publication [68].

protons) [17]. A mechanism of loading jets with matter components and their relative energy share are still subject of discussion. Production of nonthermal radiation is much more efficient in the case of leptons [60], nevertheless, relativistic jets may be responsible for acceleration of ultra-high-energy cosmic rays (UHECR; 10^{20} eV), as well as for the emission of very-high-energy neutrinos (10^{15} eV) [23].

Two basic dissipation mechanisms are considered in the context of relativistic jets. A viable dissipation mechanism should allow for efficient particle acceleration and production of strongly variable nonthermal radiation, in particular the energetic gamma rays.

- The first mechanism involves relativistic *shock waves* arising due to velocity field inhomogeneities in the jets (internal shock waves) [44] or due to interaction of the jets with their external environment (reconfinement shock waves) [20]. Shock waves are being connected with structures observed in relativistic jet images (radio, optical, X-ray): compact bright knots propagating with apparently superluminal motion are often interpreted as internal shock waves, while stationary knots are often interpreted as reconfinement shock nozzles. Relativistic shock waves can potentially accelerate particles in a first-order Fermi process [34]. The shock wave mechanism was popular for a long time, however, there are two problems that have not been resolved: low dissipation efficiency and neglecting the presence of magnetic fields. The dissipation efficiency for internal shock waves depends on the range of bulk Lorentz factor values for individual interacting jet shells. In order to achieve sufficient dissipation efficiency for blazars (∼ 10%), in the hydrodynamic limit the ratio of maximal to minimal bulk Lorentz factors should be at least $\Gamma_{\rm max}/\Gamma_{\rm min} \gtrsim 3$ [65]. That would mean a very strong modulation of the jet acceleration mechanism, which is still an outstanding issue. It appears that the required dissipation efficiency can be obtained more easily in the case of reconfinement shock waves — it is required that the jet collimation results in collimation parameter $\Gamma_{\rm j}\Theta_{\rm j} \gtrsim 1$ [46]. Unfortunately, the above results neglect the very likely presence of magnetic fields, for which we expect a significant reduction of dissipation efficiency. It turns out that the presence of uniform magnetic fields perpendicular to the shock normal substantially decreases the efficiency of particle acceleration in the Fermi process, which was demonstrated in kinetic simulations [62].

- The second mechanism is relativistic *magnetic reconnection*, in which interaction of regions with inverted magnetic field orientation leads to the release of magnetic energy and its transformation into thermal and nonthermal plasma energy [72]. Local inversions of magnetic fields in a relativistic jet can be realized in at least two ways: (1) by introducing into the jet base from outside a magnetic domain with globally inverted field orientation [38], or (2) as a result of nonlinear instabilities of the intrinsic jet structure, especially the current-driven kink modes [13]. Magnetic reconnection is expected to be particularly efficient in relativistically magnetized regions, in which magnetization $\sigma = B^2/(4\pi w) \gtrsim 1$ (where w is the relativistic enthalpy density). Magnetic reconnection is a nonlinear process and historically the analytic models (Sweet-Parker or Petschek) were not able to describe it realistically, especially in the case of collisionless plasma. Significant progress was made since it was discovered that reconnection can proceed efficiently (inducing electric fields of order $E \sim 0.1B_0$) in collisionless plasma as result of tearing-mode instability of the current layers leading to the formation of chains of plasmoids (or magnetic flux ropes) [31]. Kinetic simulations of large-scale relativistic magnetic reconnection have confirmed the high efficiency of particle acceleration, leading to power-law energy distributions $N(E) \propto E^{-p}$, where index $p \to 1$ in the limit of $\sigma \gg 1$ [63, 25, 69].

Besides determining the mechanism of energy dissipation and particle acceleration, the ultimate models of relativistic jets must also explain the stochastic nature of blazar variability. Variability statistics evaluated over a broad range of time scales (from minutes to decades) clearly indicate a turbulent nature of dissipation in jets. In order to realistically describe the development of magnetized turbulence in relativistic jets, global 3-dimensional simulations of jets of very high resolution will be required. Realistic jet simulations must also take into account physical process beyond the frame of relativistic ideal magnetohydrodynamics, e.g., kinetic effects or magnetic reconnection.

2 Identifying personal scientific priorities

My contribution to blazar studies involves interpretation and modeling of observational data, constraining the parameters of emitting regions, and theoretical inference. I have been introduced to this area by Prof. Marek Sikora, who assisted me in preparing my master thesis and later he was my doctoral thesis advisor at the Nicolaus Copernicus Astronomical Center. I would also like to acknowledge the support of Prof. Rafał Moderski and Prof. Grzegorz Madejski. Our main research tool was the numerical code `BLAZAR` created by Rafał Moderski [45], which calculates the spectral energy distributions of non-thermal radiation from an evolving population of electrons in a thin shell within a relativistic jet. The time of my doctorate coincided with a breakthrough in availability and quality of observational data on blazars. In 2008, the Fermi space telescope was launched and a continuous monitoring of all sky in the photon energy range of 0.1-10 GeV was initiated. In order to fully utilize the gamma-ray data, the Fermi Collaboration, including Grzegorz Madejski, initiated and coordinated a range of multiwavelength blazar monitoring projects, in particular in X-rays (Swift, RXTE), optical (WEBT, SMARTS) and radio (F-Gamma) bands. Anticipating this richness of observational data, I adopted as one of my priorities to utilize them as fully as possible when studying the actual problems in theory of relativistic jets.

My doctoral thesis concerns reconfinement shock waves and is mostly theoretical, including calculation of dissipation efficiency and polarization signatures. In the meantime, I began collaboration with Prof. Mitchell Begelman and Prof. Dmitri Uzdensky at the University of Colorado Boulder, who were particularly interested in the problem of relativistic magnetic reconnection in application to astrophysical sources of rapidly variable gamma-ray radiation. After defending my doctoral thesis, I went to Boulder for postdoctoral position, where I investigated the problem of current-driven instabilities in relativistic jets. I also invested a lot of time into continuing blazar studies. I formulated my individual program for blazar studies in my application for the Einstein Fellowship to provide support to the Fermi mission. Winning this fellowship in 2013 was a source of great satisfaction, especially because of my personal commitment to this program.

3 Publications constituting the habilitation achievement

The four publications selected for the habilitation achievement described here [P1, P2, P3, P4] reveal a broad approach to the problem of physical properties of gamma-ray emitting regions in blazar jets.

3.1 Analysis of rapid variability of 100 GeV emission of blazar PKS 1222+216

Publication [P1] presents an analysis of theoretical implications of detection of blazar PKS 1222+216, belonging to the class of flat-spectrum radio quasars (FSRQs), by the ground-based Cerenkov telescope MAGIC. Emission from blazar PKS 1222+216 (redshift $z = 0.432$) was detected in the photon energy range $70 - 400$ GeV during a single 30-minute observation with clear indication for gamma-ray flux variability on time scale of ~ 10 minutes (flux doubling) [11]. Such short variability time scale corresponds to the emitting region size of order $R \lesssim 10^{-4}$ pc. Previous publications, e.g. [67], proposed that such compact emitting regions could be obtained as result of jet recollimation due to its interaction with the external medium, in analogy to the problem of the HST-1 region in the jet of radio galaxy M87 [16]. An important point in the discussion is the requirement for the bulk Lorentz factor of the emitting region. Postulating a very compact emitting region producing energetic gamma-ray emission of very high luminosity leads to the potential problem of intrinsic gamma-ray absorption, and the easiest way to reduce the absorption optical depth is to adopt a higher than typical value for the bulk Lorentz factor (50-100 instead of 10-20) [14].

We began our analysis from a simple observation – in order to avoid absorption of gamma-ray emission by ultraviolet radiation produced in the broad emission line region (a typical problem for FSRQs), the emitting regions should be located at distance scale of order $r \gtrsim 0.5$ pc from the central black hole. This implies a jet collimation parameter of order $R/r \lesssim 10^{-4}$. In Section 5.1.3 we argue that this value is too small to be obtained realistically as result of jet recollimation, especially taking into account possible departures of the jet from axial symmetry.

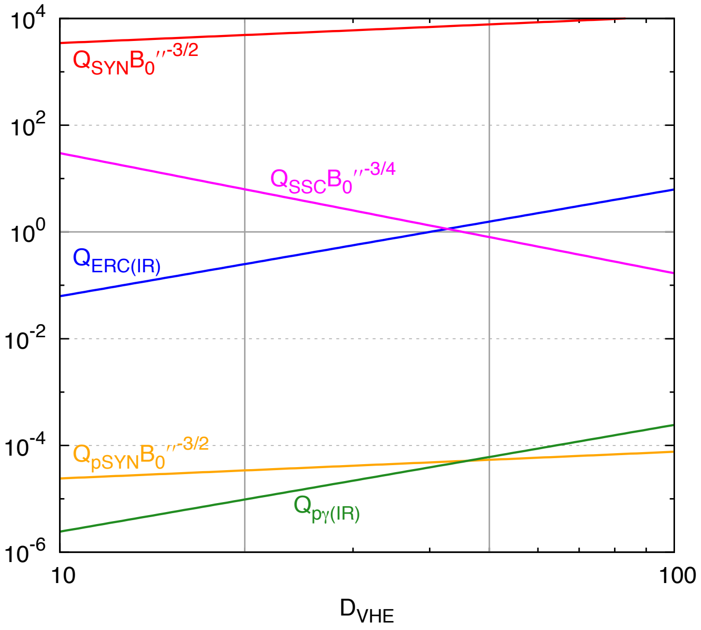

Figure 2: Figure 2 from publication [P1] showing a comparison of radiative efficiencies Q (defined in the main text) for several radiative processes as function of the Doppler factor in the context of gamma-ray emission in the photon energy range $\sim$ 100 GeV observed by the Cerenkov telescope MAGIC in blazar PKS 1222+216.

The main part of the publication is devoted to estimating the energetic requirements on the emitting regions producing radiation observed in two energy bands: $>$ 100 GeV (MAGIC) and $\sim$ GeV (Fermi/LAT). In Section 3, we introduce two types of energetic constraints: a local constraint on the energy density of the emitting region, and a global constraint on the total jet power. Under certain assumptions, the local constraint on the $>$ 100 GeV emission of 10 min variability time scale is more than three orders of magnitude stronger than the local constraint on the GeV emission of $\sim$ 1 d variability time scale. It seems to be extremely difficult to obtain such high energy density by dynamical interactions of jet layers, e.g. by internal shock waves. Therefore, we seek a solution that would allow to significantly reduce the local energetic constraint.

One of the key parameters determining the required energy density is the radiative cooling efficiency defined as $Q = t''_{\rm VHE}/t''_{\rm cool}$, where $t''_{\rm VHE}$ is the VHE gamma-ray variability time scale in the emitting region co-moving frame, and $t''_{\rm cool}$ is the radiative cooling time scale for the respective radiative process. In Section 4, we compare the radiative cooling efficiencies for five radiative processes: electron synchrotron (SYN), synchrotron self-Comptonization (SSC), Comptonization of external infrared radiation (ERCIR), proton synchrotron (pSYN) and photomeson process ($p\gamma$). Figure 2 shows that in the context of $>$ 100 GeV emission: (1) the hadronic processes (pSYN,$p\gamma$) are definitely inefficient ($Q \ll 1$), (2) the Comptonization processes (SSC, ERCIR) can be efficient depending on the Doppler factor value, and (3) the electron synchrotron process is definitely efficient. A proposition that electron synchrotron radiation could be the source of gamma-ray emission of blazars is treated as very preliminary. Such scenario was inspired by the hotly debated case of GeV gamma-ray flares from the Crab pulsar wind nebula [66, 5]. However, in order to break the 100 MeV limit on the energy of synchrotron photons in the co-moving frame of the emitting region, the electrons producing the emission observed by the MAGIC telescope in PKS 1222+216 would require an effective electric field of $E/B > 25(\mathcal{D}/20)^{-1}$. In our judgment, even in the case of highly relativistic magnetic reconnection such requirement would be very difficult to satisfy.

In the end, we propose that another interesting effect of relativistic reconnection – kinetic beaming – could be invoked to reduce the local energetic requirement. Kinetic simulations of particle acceleration in the process of relativistic magnetic reconnection revealed a strong anisotropy of the energetic particles, as well as of the synchrotron radiation produced by them [18]. Strong energy-dependent anisotropy of radiation enables a strong modulation of radiation sent in certain directions, allowing to shorten the effective variability time scale by 1-2 orders of magnitude. In such case, we can imagine a dissipation region being correspondingly larger than the gamma-ray emitting region, which allows to significantly decrease the required total energy density.

3.2 Observations of blazar PKS 1510-089 with the Herschel Space Telescope

Publication [P2] presents the results of an observational campaign on blazar PKS 1510-089 in the mid- and far-infrared bands using the PACS and SPIRE instruments of the Herschel Space Telescope. These results were analyzed in the context of simultaneous multiwavelength observations with the following telescopes: SMA (microwaves), SMARTS (optical and near-infrared), Swift (X-rays and ultraviolet) and Fermi (gamma rays).

Blazars are strong sources of nonthermal radiation in the range extending from the radio waves to the gamma rays. In practice, multiwavelength monitoring of blazars is limited to four main bands: (1) radio (up to $\sim$ mm wavelength), (2) optical (including near-infrared and ultraviolet), (3) X-ray (0.5-10 keV) and (4) high-energy gamma rays (100 MeV - 1 TeV). When modeling the broad-band spectral energy distributions of blazars, a significant source of uncertainty is the lack of data in three energy ranges: (1) mid- and far-infrared (2-500 μm), (2) extreme ultraviolet and soft X-rays, and (3) soft and medium gamma rays (0.1-100 MeV). Launching of the Herschel Space Telescope by the European Space Agency in 2009 provided a great opportunity to fill the infrared spectral gap.

A successful proposal for observations of two blazars, PKS 1510-089 and AO 0235+164, was prepared by Prof. Marek Sikora and Prof. Grzegorz Madejski. Executing the project required a well-coordinated international collaboration. Thanks to Prof. Ryszard Szczerba, we asked Dr Katrina Exter to reduce the observational results from Herschel. Dr Anna Szostek performed analysis of the observations made by Swift. My role in this project was to reduce gamma-ray data from the Fermi/LAT instrument, to collect and analyze the entire observational dataset, to perform modeling of the broad-band SEDs of blazar PKS 1510-089 with the `BLAZAR` code [45], to shape the theoretical discussion and to write up the publication.

In our proposal for Herschel, we expected to detect spectral breaks in the infrared synchrotron SED due to the process of synchrotron self-absorption. Spectral breaks observed in the mid- or far-infrared band would provide strong constraints on the physical size of the emitting region, and hence on its location along a conical jet [59]. However, the spectra determined from the PACS and SPIRE data did not show any breaks, instead they were consistent with power laws and did not evolve significantly. Variability in the infrared band appeared to be much weaker than variability in the gamma-ray band.

When modeling the SEDs obtained in two gamma-ray flux states, we found that a standard single-zone model cannot describe both the infrared and gamma-ray spectral bands. This is

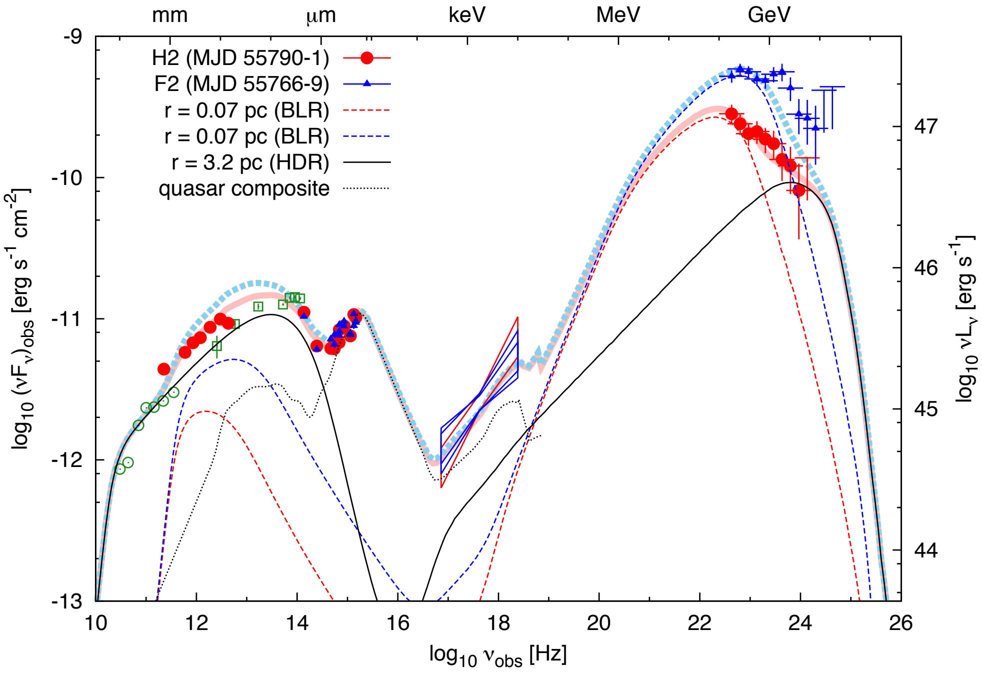

Figure 3: Figure 5 from publication [P2] showing the spectral energy distribution (SED) of blazar PKS 1510-089 based on observations with the following telescopes: Herschel (far infrared), SMARTS (near infrared and optical), Swift (ultraviolet and X-rays) and Fermi (gamma rays). Also shown are theoretical SED models obtained with the `BLAZAR` code illustrating the proposed scenario involving two distinct emitting regions.

because of a theoretical relation between the luminosity ratio $q = L_{\rm EC}/L_{\rm syn}$ (also known as the Compton dominance) and frequency ratio $w = \nu_{\rm EC}/\nu_{\rm syn}$ between the external Compton and synchrotron SED components produced by the same population of electrons, originally derived by Prof. Sikora [60]. As we show in Figure 8, the observationally estimated combination of q and w values would require unrealistically high energy density of external radiation fields.

Therefore, we proposed a two-zone model with the following components: (1) a strongly variable component dominating in the gamma rays, produced at the distance scale of 0.7 pc characteristic for the broad emission line region, and (2) a weakly variable component dominating in the infrared band, produced at the distance scale of 3.2 pc characteristic for the dusty torus. A similar model was discussed by our group in the context of blazar 3C 279, with mid-infrared observations obtained with the Spitzer Space Telescope, in which case a clear signature of synchrotron self-absorption was observed in one of the spectral states [27].

As we learned subsequently, few other blazars were observed by Herschel. Our results on blazar AO 0235+164 were not published due to poor quality of multiwavelength data from other telescopes, and hence we were not able to put significant constraints on the emitting region.

3.3 Analysis of the brightest gamma-ray flares in blazars

Publication [P3] is a result of my independent exploration of the publicly available data from the main instrument (LAT) of the Fermi Space Telescope. Since 2008, Fermi/LAT performs a uniform monitoring of all sky in the gamma-ray band, effectively between 100 MeV and 10 GeV.

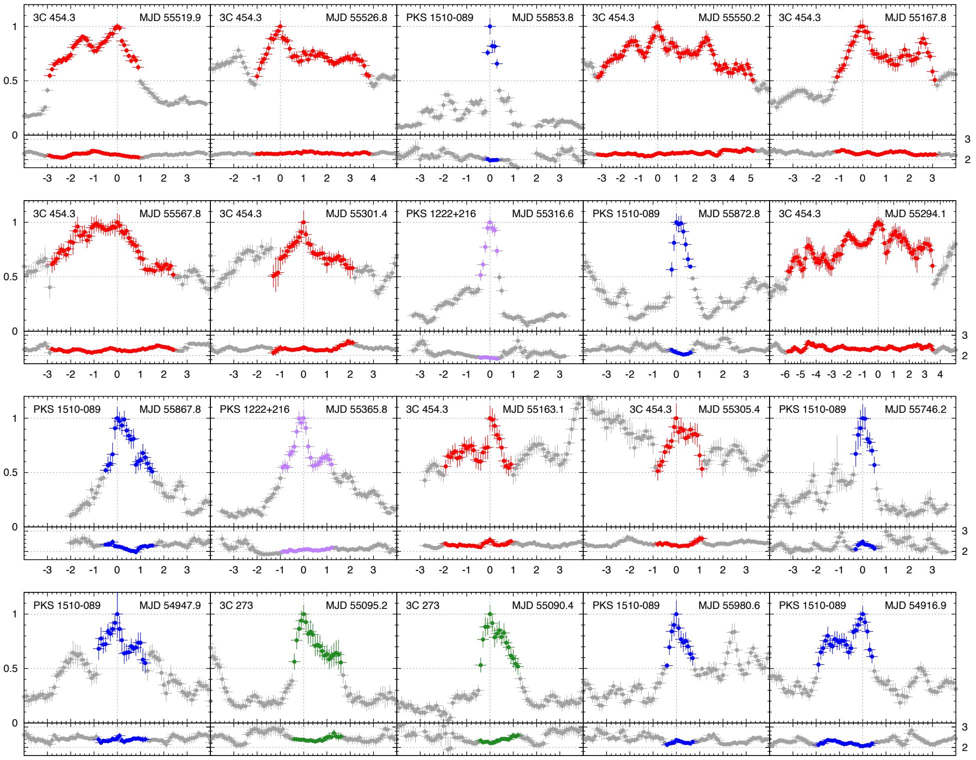

Figure 4: Figure 1 from publication [P3] showing light curves for the sample of the brightest gamma-ray flares in blazars based on the data from Fermi/LAT. Horizontal axes show observation time in days measured relative to the moment of flux maximum. Upper panels show the gamma-ray photon flux in the energy range 0.1-300 GeV normalized to its maximum value. Lower panels show the photon index. A flare is defined formally as the period of time during which the flux exceeds half of its maximum value.

Blazars are gamma-ray sources characterized by unceasing and unpredictable flux variability, and hence the observational strategy of Fermi/LAT allows for uniform measurements of the gamma-ray flux on time scales ranging between months and hours. Most detailed information about the gamma-ray emission can be obtained in the highest gamma-ray flux states that are referred to as flares. Therefore, I attempted one of the first uniform analyses of the brightest gamma-ray flares in blazars.

I began by selecting a list of all episodes from the period of the first four years of the Fermi mission (2008-2012) when the photon flux measured by LAT above 100 MeV exceeded the level of $3 \times 10^{-6}\ \mathrm{ph\,s^{-1}\,cm^{-2}}$. For each such episode, I calculated gamma-ray lightcurves using 12h time bins. A flare was formally defined as the period of time during which the photon flux exceeds half of its maximum value. By analyzing all episodes of high gamma-ray flux, I selected the final sample of 40 gamma-ray flares with the peak photon flux exceeding $7 \times 10^{-6}\ \mathrm{ph\,s^{-1}\,cm^{-2}}$. All these flares were produced by only 5 blazars, and most by 3C 454.3 and PKS 1510-089. Some flares appeared to be short (< 1.5 d) with simple light curves consisting of a single maximum; other were longer and their light curves included multiple peaks. The short flares show a tendency for time asymmetry with the flux raising phase shorter than the flux decaying phase. A curious finding is that the flares produced by blazar 3C 454.3 were usually long and complex, while those produced by blazar PKS 1510-089 were usually short and simple.

All identified flares were analyzed in the parameter space of gamma-ray flux vs. photon index. Such analysis could potentially introduce significant constraints on the acceleration mechanism behind the particles producing the gamma-ray emission. However, I did not identify any systematic dependence between flux and hardness. A number of hysteresis loops were identified without any preference for their direction.

This project was continued in collaboration with the graduate student Susanna Kohler, who analyzed the gamma-ray spectra calculated for each flare from the sample [35]. These spectra were analyzed by fitting three basic spectral models: power-law, broken power-law and log-parabolic. We identified a number of significant spectral breaks (the cases where a broken power-law model gave the best fit) and we did not find any preference for the break energy, in particular to the value of 4.8 GeV suggested by a model based on gamma-ray absorption by ionized Helium [53]. Instead, we noted another dependence – short flares with simple light curves showed more irregular spectra, some of them were characterized by strong spectral curvature. On the other hand, long flares with complex light curves show very regular spectra similar to those integrated over very long time periods. We suggested that the spectral irregularities of short gamma-ray flares reflect the physical fluctuations in the energy distribution of emitting electrons. In our view, the regular spectra of blazars integrated over long time periods are not necessarily a result of systematic particle acceleration processes (like the Fermi processes), but they could be due to averaging of statistical fluctuations associated with turbulent dissipation structures in relativistic jets.

3.4 Constraints on the location of gamma-ray emitting region in luminous blazars

I consider publication [P4] as the most important achievement in my studies of blazars. My goal was to resolve a major controversy in the theory of blazar emission, which is the distance scale for the location of the emitting region along a relativistic jet. At the same time, I attempted to compare various constraints on the parameters of blazar emitting regions by performing a uniform analysis of the available multiwavelength data.

The methodology adopted in this work is to constraint the space of two key parameters - the distance scale r and the Lorentz factor Γ (Section 2). Three types of constraints are sufficient to determine a closed region of allowed parameters indicated in yellow on Figures 1-8 – (1) a constraint from the collimation efficiency of relativistic jets; (2) a constraint from the luminosity of the synchrotron self-Compton (SSC) component; and (3) a constraint from the cooling time scale of the emitting electrons. Additional constraints (Section 3) – (4) a constraint from the characteristic frequency of the synchrotron self-absorption; and (5) a constraint from jet energetics – are treated as predictions of the adopted model.

Even before this work, I showed that the requirement for the SSC luminosity not to exceed the observed X-ray luminosity in FSRQs yields a stronger lower limit on the Lorentz factor than the more popular constraint from intrinsic absorption of the gamma-ray radiation [6]. Now, by analyzing seven bright gamma-ray flares of blazars for which high-quality multiwavelength observational data are available (Section 4), we showed that the aforementioned combination of three constraints (1-3) is very effective in selecting the parameter space of r and Γ. The seven cases were already discussed in detail by different groups using different methods. However, for the first time such cases were made subject of uniform analysis, the results of which can be easily compared looking at Figures 1-7 and Table 1.

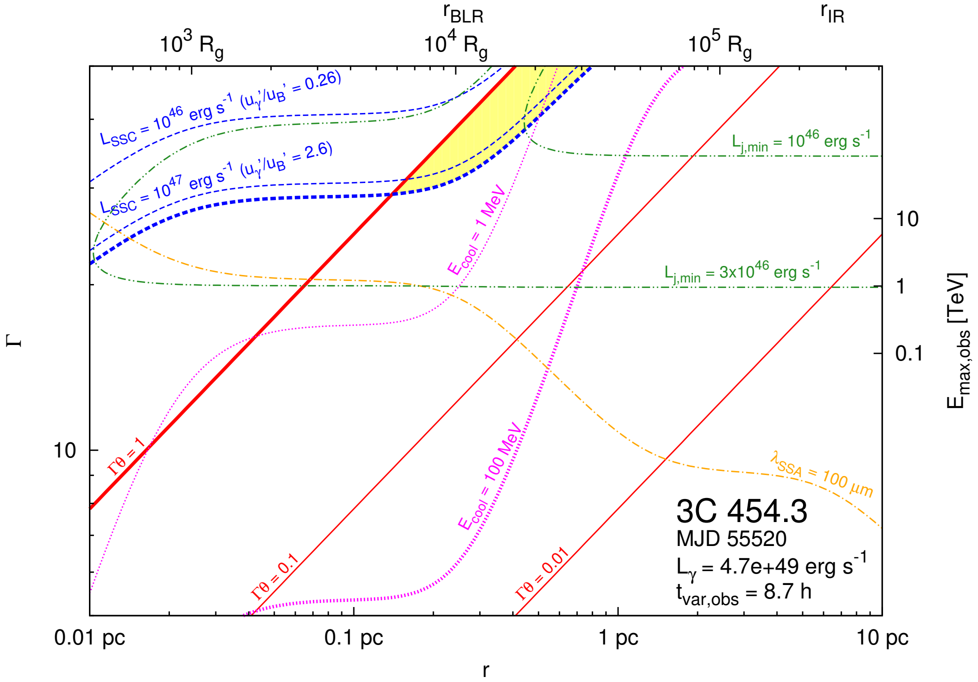

Figure 5: Figure 1 from publication [P4] showing various constraints on the parameter space of distance scale r and Lorentz factor Γ of the emitting region producing the historically brightest gamma-ray flare in blazar 3C 454.3. Given the observed gamma-ray luminosity L_γ and the variability time scale $t_{\rm var}$, we plot the following constraints: (1) from the jet collimation factor $\Gamma\theta$ (solid red lines); (2) from the SSC luminosity $L_{\rm SSC}$ (dashed blue lines); (3) from the characteristic photon energy $E_{\rm cool}$ corresponding to efficient radiative cooling (dotted magenta lines); (4) from the characteristic wavelength $\lambda_{\rm SSA}$ corresponding to synchrotron self-absorption (mixed orange line); and (5) from the minimal required jet power $L_{\rm j,min}$ (mixed green lines). A region of allowed parameters (yellow) is determined from the criteria $\Gamma\theta < 1$, $L_{\rm SSC} < L_{\rm X}$, and $E_{\rm cool} < 100$ MeV.

Our main conclusion is that the gamma-ray emission in luminous blazars is produced at the distance scales in the range $0.1 - 1$ pc. At these distances, production of gamma-ray radiation is dominated by Comptonization of broad emission lines, eventually with a contribution from the Comptonization of thermal infrared radiation from the dusty torus.

An important part of this publication are the Appendices, where detailed aspects of the blazar theory are discussed. Appendix A presents a universal and simply parametrized model of the distribution of external radiation in the vicinity of relativistic jets in luminous blazars associated with quasars. Appendix B presents a proposition to resolve a controversy arising from an apparent connection between gamma-ray flares and activity of blazars in the radio and millimeter bands. Based on such observation, it was concluded that the gamma-ray emission should be produced at large distance scales of order 10 pc [9]. Such far location of the blazar zone requires postulating additional sources of external radiation to be Comptonized to produce the observed gamma-ray emission. Two examples of such additional sources are discussed in Appendix C – a two-zone lateral jet structure ("spine-sheath") and "extended" broad emission line region.

4 Other projects accomplished after doctorate

4.1 Multiwavelength observations of blazars within Fermi/LAT Collaboration

Already during my doctorate studies, I began collaboration with Prof. Grzegorz Madejski from the Stanford University, who is one of the scientific coordinators for the Large Area Telescope (LAT) instrument of the Fermi Gamma-ray Space Telescope. As has been mentioned above, Fermi/LAT performs a practically contiguous monitoring of all sky in the effective gamma-ray photon energy range between 100 MeV and 10 GeV. This monitoring is particularly important in the investigations of blazars, which constitute the most numerous class of cosmic gamma-ray point sources.

In 2009, in collaboration with Dr Masaaki Hayashida, we began investigation of bright blazar 3C 279 (Figure 1). The first publication appeared in Nature [1] and showed a rotation of the optical polarization vector simultaneously with gamma-ray and optical flares. Additional analysis of these data was presented in publications [47, 30]. The project was continued and we performed a more detailed analysis of this very rich dataset including radio, millimeter, infrared, optical, ultraviolet, X-ray and gamma-ray data. The second publication in 2012 [27] presented detailed models of the broad-band spectra and new constraints on the physical parameters of the emitting regions. The third publication in 2015 [28] was focused on the case of very hard gamma-ray spectrum measured during a gamma ray flare observed without an optical counterpart. The fourth publication in 2016 [8] presented the results of the first successful pointed observation of a flaring blazar. Thanks to the unprecedented photon statistics, we discovered flux variability on suborbital time scales of a few minutes. This surprising and exciting observation challenges all theoretical models of blazar emission and of the structure of relativistic jets. In all of these publications, I had a significant or leading role in shaping the theoretical discussion.

Another interesting blazar investigated in collaboration with the Fermi/LAT team is AO 0235+164. In a 2012 publication [7] we presented a peculiar X-ray spectrum, which is probably the most convincing signature of Comptonization by cold electrons (bulk Compton), and we also proposed a modification of the model of extinction of ultraviolet radiation by an intervening foreground galaxy.

Prof. Grzegorz Madejski is also a member of the NuSTAR Collaboration. NuSTAR is a cosmic telescope sensitive in the hard X-ray band (3-80 keV). Observations of blazars in this range could provide strong constraints on the number of low-energy electrons, especially in the case of FSRQs, where the ERC component is characterized by hard spectral index in the X-ray band ($\alpha \sim 0.5$) [61]. Unfortunately, few FSRQs were observed with NuSTAR, even though we regularly submit proposals to this end. One project to which I had a major contribution concerned a BL Lac type source PKS 2155-304 [41], in which a hard X-ray excess over the typical high-energy end of the synchrotron component was found by NuSTAR, which was interpreted as a contribution from the middle-energy SSC component produced by electrons with Lorentz factor $\gamma \sim 100$. However, the number of low-energy electrons ($\gamma \sim 1$) is still unconstrained, end hence the overall matter composition of the jet of PKS 2155-304 cannot be precisely estimated.

4.2 Kinetic simulations of relativistic magnetic reconnection

During my postdoctoral period at the University of Colorado Boulder, I began a collaboration with Prof. Mitchell Begelman and Prof. Dmitri Uzdensky on kinetic simulations of the process of relativistic magnetic reconnection. I learned to work with the numerical particle-in-cell (PIC) code `Zeltron` created by Dr Benoît Cerutti.

My first publication based on numerical simulations [50] presents a detailed analysis of the spatial distribution of the particle acceleration processes during magnetic reconnection initiated from standard Harris-type current layers in a doubly periodic numerical domain. Thin current layers evolve by tearing mode instability, which results in chains of plasmoids (magnetic islands, O-points or flux ropes) separated by magnetic X-points. Plasmoids in a closed domain evolve by hierarchical inelastic collisions. We demonstrated that particle acceleration proceeds in three distinct circumstances: (1) in the vicinity of an X-point, (2) between merging plasmoids, and (3) within a single accelerating plasmoid. We also showed that a model of particle acceleration within contracting elongated plasmoids [24], that is popular in studies of non-relativistic reconnection, is not so important in the relativistic case.

During my postdoctoral period at the Stanford University, I began a collaboration with Prof. Roger Blandford, his doctorate student Yajie Yuan, and postdocs Dr Jonathan Zrake and Dr William East. Dr Zrake proposed to investigate a class of magnetostatic structures called “ABC fields”, in which the magnetic fields are described by simple trigonometric functions. Such structures are in general unstable to coalescence, and this instability leads to magnetic reconnection despite the initial absence of thin current layers. Simulating these structures allows for a self-consistent study of the formation and dynamical evolution of thin current layers. In publication [51], we presented the results of one of the first kinetic simulations of ABC fields performed with the `Zeltron` code (independently from the project led by Prof. Maxim Lyutikov in collaboration with Dr Lorenzo Sironi [39]). In particular, we analyzed the dynamics of energy conversion by reconnection, particle acceleration and evolution of the current layers. In the second publication [70], which was also included in the doctoral thesis of Ms. Yuan, we studied the synchrotron radiative signatures produced by the high-energy particles, addressing such issues as the mechanism of rapid flux variability and linear polarization.

4.3 Instabilities in magnetized jets

One of the fundamental questions in the physics of relativistic jets is the stability of their structure. Highly magnetized jets are prone to current-driven instabilities, in particular when they are dominated by the toroidal magnetic field component [13]. Usually, the fastest growing modes are $m = 0$ (*pinch*) and $m = 1$ (*kink*). Local current-driven instabilities can potentially enable efficient energy dissipation, while global instabilities should be avoided, as they could destroy the jet structure. Observations of radio galaxies indicate the presence of globally stable jets up to extremely large distance scales ($\gtrsim 100$ kpc).

In the publication [48], we presented a local stability analysis of the current-driven modes in a magnetized jet, taking into account for the first time the effect of a local poloidal velocity shear. Following the approach of Prof. Mitchell Begelman [13], for the local stability analysis we adopted an assumption of short wavelength of the radial modes ($kr \gg 1$; WKB-type approximation). The main result of this calculation is the dispersion relation (Equation 25), which is then solved numerically. We identified two classes of unstable modes: the purely imaginary (exponential) modes and the mixed (overstable) modes. It is inferred that the overstable modes result from the nonzero radial gradient of the poloidal velocity component, and as such they could be a qualitatively new physical effect in relativistic jets.

As a continuation of this project, we performed numerical simulations of magnetized axisymmetric columns (cylindrical periodic approximations of jets in their co-moving frame) using the magnetohydrodynamical code `Athena` in collaboration with Dr Sean O’Neill (who was the main author of publication [52]). Unfortunately, despite spending a substantial effort and time, we were not able to confirm numerically the existence of overstable modes. The simulations results clearly indicated that introducing a radial gradient of the poloidal velocity component resulted in decreased instability growth rate, instead of the expected increase. The results of our numerical studies were not published, since we could not reconcile them with theoretical predictions.

4.4 Selected other publications

In the publication Danforth, Nalewajko, France & Keeney (2013) [21] we present observations of blazars S5 0716+714 using the ultraviolet spectrograph COS (Cosmic Origins Spectrograph) at the Hubble Space Telescope (HST). I was invited to this project by the COS team at the University of Colorado Boulder since they measured strong time variability of the blazar continuum flux on time scales of a few hours. Detection of strong variability in this source is not surprising, as it is known for very high variability duty cycle ($> 90\%$) and is a subject of intense ground-based optical monitoring campaigns. The main goal of HST/COS observations of this blazar was to look for weak emission or absorption lines in order to constrain the unknown redshift value, and also to probe the intergalactic medium along the line of sight.

Given the HST/COS light curve, I performed modeling of the variability, the results of which are presented in Figure 2 and Table 1. The light curve has regular gaps for every HST orbit, and it indicates a strong flare with asymmetric time profile. Modeling the observational data with a single-component profile (Model A), I estimated the flux raising time scale (e-folding) at $T_{\rm r} \sim 0.13$ h, and the flux decaying time scale at $T_{\rm d} \sim 1.9$ h. In Section 5, I discuss the theoretical implications of the these time scales. The flux raising time scale is connected to the physical size of the emitting region, while the flux decaying time scale is connected to the radiative cooling time scale. Equation (12) shows that the ratio of the two time scales $T_{\rm d}/T_{\rm r}$ allows to constrain the energy density ratio of electrons to synchrotron radiation $u'_{\rm e}/u'_{\rm syn}$, while Equation (9) shows a strong relation between the Doppler factor $\mathcal{D}$ and the Compton dominance parameter $q = u'_{\rm rad}/u'_{\rm B}$. We discuss two sample scenarios: (1) assuming equipartition between electrons and magnetic field, we obtain the Doppler factor of $\mathcal{D} \simeq 62$ and very weak Comptonization ($q \simeq 0.03$); (2) assuming $q = 1$, we obtain the Doppler factor of $\mathcal{D} \simeq 38$ and very strong matter domination ($u'_{\rm e}/u'_{\rm B} \simeq 60$). Hence, regardless of the composition of the emitting region, very high value of the Doppler factor is required.

In the publication Chatterjee, Nalewajko & Myers (2013) [19] we present an analysis of the blazar PKS 0208-512. Dr. Ritaban Chatterjee, analyzing the optical and near-infrared (OIR) data on blazars from the SMARTS telescope, identified an anomaly during one of the optical flares in PKS 0208-512, as it was not accompanied by any gamma-ray flare. Dr. Chatterjee invited me to the project in order to explain the weak gamma-ray emission by modeling of the broad-band SED of PKS 0208-512. I promptly identified this as a problem of reduced Compton dominance parameter $q = L_{\rm ERC}/L_{\rm syn}$, where $L_{\rm ERC}$ is the bolometric luminosity of the external radiation Comptonization (ERC) component dominating the gamma-ray emission, and $L_{\rm syn}$ is the bolometric luminosity of the synchrotron component dominating the OIR emission. Since $q \simeq u'_{\rm ext}/u'_{\rm B}$, where $u'_{\rm ext}$ is the energy density of external radiation and $u'_{\rm B} = B'^2/8\pi$ is the magnetic energy density, I suggested that a change in the q value could result from the change in the magnetic field strength B'. Parameters of the models listed in Table 1 show that increasing B' by factor 2 (hence increasing $u'_{\rm B}$ by factor 4) between the two flares would be sufficient to explain the observed spectral variations. In Section 4, I also propose an alternative solution, in which the location of the emitting region varies across the characteristic radius of the broad emission line region, assuming that $u'_{\rm ext}(r)$ is a steeper function than $u'_{\rm B}(r)$.

In the publication Sobolewska, Siemiginowska, Kelly & Nalewajko (2014) [64] we present a stochastic modeling of the long-term variability of the gamma-ray flux of blazars. My role in this project was to reduce the gamma-ray data from the *Fermi*/LAT instrument for 13 bright blazars and to calculate the gamma-ray light curves. In order to account for very high amplitudes of gamma-ray fluxes of individual blazars, I adopted a technique of adaptive time bins. Given an initial time bin in which the blazar is detected, this time bin is halved, and if the blazar is detected in both halves, they substitute the initial time bin. Starting from very long time bins (200 days), in the case of the brightest blazar flares the final time bins could be reduced to suborbital scales (1.6h). Calculating such adaptive gamma-ray light curves is very time consuming, in the case of the brightest gamma-ray blazar 3C 454.3 the calculation took several months. Besides providing the light curves, I participated in discussing the results of statistical modeling.

In the publication Nalewajko, Sikora & Begelman (2014) [49] we discuss the consequences of estimating the magnetic field strengths in the jets of luminous blazars obtained with the technique of radio core shifts [55]. We point out that the magnetic field strength determines the luminosity of the synchrotron component, and hence we show in Equation (1) that the magnetic jet power $L_{\rm B}$ is related to the Compton dominance parameter $q = u'_{\rm ext}/u'_{\rm B}$, where $u'_{\rm ext}$ is the energy density of external radiation and $u'_{\rm B} = B'^2/8\pi$ is the magnetic energy density. Since the magnetic jet powers are comparable with the accretion disk luminosities $L_{\rm d}$, we should expect moderate values of the Compton dominance ($q \sim 1$), while the observed broad-band spectra of luminous blazars (in particular the FSRQs) show clearly higher values ($q \sim 10 - 100$). We propose that the magnetic field strengths in regions responsible for the gamma-ray emission are systematically lower than those measured with the radio core shifts. We briefly discuss two scenarios that allow for a local reduction of magnetic fields: (1) magnetic reconnection, (2) radial jet structure with a weakly magnetized spine.

I should stress that the main author of this analysis is Prof. Marek Sikora, who was very kind to grant me the first place on the author list for assistance in writing up the paper. My contribution also included making Figures 1 and 2 based on the data from publication [71], as well as describing the distribution and anisotropy of the external radiation in the Appendix and Figure 3.

In the publication Itoh, Nalewajko et al. (2016) [29] I proposed a theoretical interpretation of a very interesting observational result obtained by the Japanese team KANATA who monitor blazars using an optical polarimeter. They found a systematic correlation between the maximal optical linear polarization degree measured for a given blazar and its average gamma-ray luminosity derived from the Fermi/LAT data. I suggested that this must be due to a systematic difference in magnetic field configurations in blazar jets of different powers. The maximum linear polarization degree could be a function of parameter $\gamma_{\rm opt}/\gamma_{\rm max}$, where $\gamma_{\rm opt}$ is the characteristic Lorentz factor of electrons producing optical emission via synchrotron radiation and $\gamma_{\rm max}$ is the maximum Lorentz factor in the distribution of electrons. The latter possibility can be tested by observations of weak blazars (BL Lac objects) in X-ray linear polarization.

4.5 Summary of the habilitation achievement

The habilitation achievement presented here is to introduce novel constraints on the parameters of gamma-ray emitting regions in the relativistic jets of blazars. Systematic investigation of the parameter space for seven gamma-ray flares in luminous blazars presented in the key publication [P4] was made possible by collecting several-year experience in blazar studies by participating in the Fermi/LAT projects [1, 6, 27, 7]. Particularly significant from the theoretical point of view are the cases of very rapid variability (time scales of a few minutes) of the gamma-ray flux, such as PKS 1222+216 [P1] or 3C 279 [8]. I also demonstrated leadership in executing an international team project [P2], as well as independent exploration of the Fermi/LAT data [P3]. I conclude that the presented scientific results reflect a broad approach to the mystery of blazars, an ability to connect theoretical expertise with careful analysis of complex observational data sets, and also a substantial scientific independence. Moreover, it is not the only area of my scientific interests, which also include numerical investigations of relativistic magnetic reconnection [50, 51].

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