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**Final Project Summary Report**

NASA Grant NAG5-3839

Project Title: Frequency Stratification of the Nonthermal Emission in Blazars

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Research supported by this grant involved theoretical investigations of the multifrequency nonthermal emission from the relativistic jets in blazars, which are quasars and related objects with highly variable brightness. Graduate students Markos Georganopoulos (PhD in 1999), Matthew Lister (PhD in 1999), and Andrei Sokolov (now a 2nd-year graduate student), worked on the project along with me. Dr. Lister is now a Jansky postdoctoral research fellow at the National Radio Astronomy Observatory, following a two-year postdoctoral research appointment at the Jet Propulsion Laboratory. Dr. Georganopoulos will soon finish a two-year postdoctoral research position at the Max-Plank-Institut für Kernphysik in Heidelberg, Germany, after which he will become a NAS/NRC Resident Research Associate at NASA Goddard Space Flight Center.

In the initial stage of the project, one-dimensional, conical (i.e., spherical symmetry between the jet axis and surface is assumed) jet models were used to explain the multiwaveband spectra and variability of blazars. The results were applied to two flares observed in the object PKS 2155−304, leading to the conclusion that the distinct differences in the observed characteristics of the two flares can be explained with the same jet model if two different physical parameters (the magnetic field in the first flare and the efficiency of acceleration of electrons to high energies in the second) varied.

The range of multiwaveband spectra of BL Lac objects was explained as a manifestation of relativistic beaming combined with a Gaussian distribution of values of key physical parameters (e.g., magnetic field), self-similar scaling laws of jets, and radiative energy losses of the electrons. This unification of BL Lac objects explains also the previously puzzling observation that the equivalent widths of emission lines decreases as one considers sources with lower bolometric luminosities.

A new significant result from the funded research is that there is a time delay between a synchrotron and synchrotron self-Compton(SSC) flare. This results from the extra time it takes for the synchrotron photons to reach the scattering electrons, whereas the synchrotron photons travel directly to the observer. The effect only occurs for regions of the jet that are pointing within about 2° of the line of sight, as is the case for the most active blazars. Another finding is that light curves whose profiles are determined by light-travel time delays do not produce symmetric exponential rises and decays characteristic of the majority of observed X-ray flares. This suggests that either the emission regions have exponential magnetic field and/or density distributions or, more likely, that there is an important effect that has not yet been included in existing models for blazar emission. We think that the best explanation is that X-ray flares are caused mainly by the passage of a propagating shock wave through a standing shock.

Another significant result, obtained in collaboration with Dr. Ian McHardy (U. of Southampton, England), relates directly to the correlation of X-ray variations with changes in the brightness of the radio, infrared, and optical synchrotron emission. We found that synchrotron "seed" photons from each decade of frequency in the range of (very roughly) $10^{10}$–$10^{15}$ Hz contribute equally to the scattered X-ray flux.

However, the synchrotron photons are not exactly co-spatial (the higher frequency emission comes from smaller regions), hence the X-ray variations correlate with brightness changes across only a fraction of the above frequency range. This explains the otherwise puzzling on and off nature of multifrequency light-curve correlations.

In comparing our theoretical results with multifrequency light curves and times of appearance of new superluminal knots in the radio-emitting portions of the jets (observed by the PI and collaborators with the VLBA), we find that the X-ray and $\gamma$-ray emission in blazars arises in the radio-emitting portion of the jet, not closer to the "central engine," as had been supposed previously based on short variability timescales. The rapid variability is then explained as a dual consequence of extreme relativistic beaming in the most active blazars and the concentration of high-frequency emission in localized regions where the particle acceleration is most efficient.

There were no inventions under this grant.

The following publications resulted from this project (reprints/preprints are enclosed):


Georganopoulos, M., and Marscher, A.P. "Variability in the Accelerating Inner Jet Model of PKS 2155−304," 1997, in *Relativistic Jets in AGNs*, ed. M. Ostrowski, M. Sikora, G. Madejski, and M. Begelman (Cracow, Poland), 313–317.

Marscher, A.P. "The Blazar Paradigm: Synchro-Compton Emission from Relativistic Jets," 1998, in IAU Colloquium 164, *Radio Emission from Galactic and Extragalactic Compact Sources,* ed. J.A. Zensus, J.M. Wrobel, and G.B. Taylor, Astronomical Soc. Pacific Conf. Proc. **144**, 25.

Gómez, J.L., Martí, J.M., Marscher, A.P., Ibáñez, J.M., and Alberdi, A. "Relativistic Numerical Simulations of Superluminal Sources," 1997, in IAU Colloquium 164, *Radio Emission from Galactic and Extragalactic Compact Sources,* ed. J.A. Zensus, J.M. Wrobel, and G.B. Taylor, Astronomical Soc. Pacific Conf. Proc. **144**, 49–50.

Marscher, A.P. "Some Theoretical Thoughts about OJ 287," 1998, in *Multifrequency Monitoring of Blazars,*, ed. G. Tosti and L. Takalo, *Perugia Univ. Observatory Publ.*, **3**, 68–73.

Georganopoulos, M., and Marscher, A.P. "Modeling the Variability of the BL Lacertae Object PKS 2155−304," 1998, *Astrophysical Journal Letters*, **506**, L11–L14.

Georganopoulos, M., and Marscher, A.P. "A Viewing Angle – Kinetic Luminosity Unification Scheme for BL Lacertae Objects," 1998, *Astrophysical Journal*, **506**, 621–636.

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Lister, M., and Marscher, A.P. "Predictions of ECS and SSC Models for Flux-Limited Samples of $\gamma$-Ray Blazars," 1999, *Astroparticle Physics*, **11**, 65–67.

Lawson, A.J., McHardy, I.M., and Marscher, A.P. "*RXTE* Observations of 3C 279 during a High Energy Flare," 1999, *Monthly Not. Royal Astron. Soc.*, **306**, 247–252.

McHardy, I., Lawson, A., Newsam, A., Marscher, A., Robson, E.I., and Stevens, J. "Simultaneous X-Ray and Infrared Variability in the Quasar 3C273," 1999, *Monthly Not. Royal Astron. Soc.* **310**, 571–576.

Agudo, I., Gómez, J.L., Martí, J.M., Ibáñez, J.M., Marscher, A.P., Alberdi, A., and Hardee, P.E. "Jet Stability and the Generation of Superluminal and Stationary Components," 2001, *Astrophysical Journal Letters*, **549**, L183–L186.

Marscher, A.P. "Time Delays of Blazar Flares Observed at Different Wavebands," 2001, in *Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring*, ed. B.M. Peterson, R.S. Polidan, and R.W. Pogge, *Astronomical Soc. Pacific Conf. Ser.*, **224**, 23–34.