Final progress report on project

Nonlinear Weibel Instability and Turbulence in Strong Collisionless Shocks

supported by DOE grant DE-FG02-04ER54790 (PI: Medvedev, M.V.)

This research project was devoted to studies of collisionless shocks, their properties, microphysics and plasma physics of underlying phenomena, such as Weibel instability and generation of small-scale fields at shocks, particle acceleration and transport in the generated random fields, radiation mechanisms from these fields in application to astrophysical phenomena and laboratory experiments (e.g., laser-plasma and beam-plasma interactions, the fast ignition and inertial confinement, etc.). Thus, this study is highly relevant to astrophysical sciences, the inertial confinement program and, in particular, the Fast Ignition concept, etc. It makes valuable contributions to the shock physics, nonlinear plasma theory, as well as to the basic plasma science, in general.

Scientific results

During the project, we with collaborators performed PIC simulations of the non-relativistic Weibel instability in the electron-ion plasmas in full 3D for the first time. This was a highly computationally challenging task. The simulations confirmed that the Weibel instability is a

Figure 1. - Snapshots representing the evolution of B-fields in the nonlinear Weibel turbulence.

dominant mechanism of the shock formation in collisionless unmagnetized relativistic and non-relativistic shocks. We had studied the long-term evolution of the magnetic fields and discovered the inverse-cascade of the magnetic energy from the skin-depth scales toward larger scales (see Figure 1). Theory of this process had been developed which explains the self-similar nature of the process. This study establishes a relation between the physics of highly-energetic astrophysical phenomena and high-energy density plasma experiments. A structure of non-relativistic Weibel magnetic fields at saturation is shown in Figure 2(a). The results were described in several papers and conference talks/presentations.

We also demonstrated that the radiation produced by energetic electrons in Weibel magnetic fields is anisotropic and its spectrum depends on the viewing angle, see Figure 2(b). The 3D jitter radiation theory has been developed and the results are described in several papers and conference presentations and seminars.

The anisotropic 3D jitter theory together with relativistic aberration and the angle-dependent Lorentz boost readily explain why the spectrum parameters of gamma-ray bursts (GRBs) change

during each emission episode. Such a spectral variability is a long-standing (over 15 years!) puzzle in the theory of gamma-ray bursts (GRBs), and is often referred to as the hardness

Figure 2. (a) -- Non-relativistic Weibel fields; (b) -- Jitter spectra for three viewing angles.

-intensity correlation, hard-to-soft evolution and the tracking behavior.

We proposed that 3D jitter radiation is a unique diagnostic tool in studies of laser-produced Weibel instability and filament structure in high-energy-density experiments. This diagnostic is particularly useful in the regime when the secondary (probe) beam electron random deflections in Weibel fields are small compared to the beam angular dispersion. These ideas raised strong interest in the Plasma Astrophysics and High-Energy-Density physics communities.

We re-analyzed particle transport in highly turbulent plasmas with strong magnetic field fluctuations. We considered the effects of particle trapping/mirroring in the presence of the mean field gradient. We demonstrated that the transport is described by the generalized asymmetric diffusion, which is missing in the standard Fokker-Planck approach. The result forces a paradigm shift in cosmic ray production at shocks and their propagation through magnetized media (e.g., our Milky Way galaxy). This work was partially supported from other sources.

We analyzed X-ray emission produced by charge-exchange collisions in the plasma of the outer heliosphere and the termination shock region. The unique spectral characteristics make these X-rays a powerful diagnostics of plasma parameters, e.g., the ion composition of plasma. This work was done in collaboration with the KU Space group and was partially supported from other sources.

Publications, conference talks, etc.

For the duration of the project, our group had been demonstrating strong and active research. We published **18** scientific papers in *refereed journals* and have **11** *non-refereed* publications. Here is the list of papers produced by our group, which are fully or partially funded by the DOE grant.

Refereed publications:

- 1) J.C. Workman, B.C. Morsony, D. Lazzati, M.V. Medvedev, **Jitter radiation in gamma-ray bursts and their afterglows: emission and self-absorption**, *Mon. Not. R. Astron. Soc.*, **386**, 199 (2008)
- 2) M.V. Medvedev, **Extragalactic Shocks as Cosmic Accelerators**, *Highlights in Astronomy* (eds. M. Karlicky, J. Brown), **14**, 95 (2007)
- 3) M.V. Medvedev, L.O. Silva, M. Kamionkowski, **Cluster magnetic fields from large-scale structure shocks**, in *Proceedings of the 6th IGPP Annual International Astrophysics conference* (ed. Dastgeer Shaikh), 117 (2007)
- 4) M.V. Medvedev, D. Lazzati, B.C. Morsony, J.C. Workman, **Jitter radiation as a possible mechanism for Gamma-Ray Burst afterglows. Spectra and lightcurves**, *Astrophys. J.*,

- 666, 339 (2007)
- 5) M.V. Medvedev, **Can cluster evaporation explain the missing thermal energy in galaxy clusters?**, *Astrophys. J. Lett.*, **622**, L11 (2007)
 - 6) M.V. Medvedev, A.L. Melott, **Do extragalactic cosmic rays induce cycles in fossil diversity?**, *Astrophys. J.*, **664**, 879 (2007)
 - 7) M.V. Medvedev, **Electron acceleration in relativistic GRB shocks**, *Philosophical Transactions of the Royal Society A*, **365**, 1177 (2007)
 - 8) L.M. Ejzak, A.L. Melott, M.V. Medvedev, B.C. Thomas, **Terrestrial Consequences of Spectral and Temporal Variability in Ionizing Photon Events**, *Astrophys. J.*, **654**, 373 (2007)
 - 9) M.V. Medvedev, **Weibel Turbulence in Laboratory Experiments and GRB/SN Shocks**, *Astrophysics and Space Science*, **307**, 245 (2007)
 - 10) M.V. Medvedev, **Electron Acceleration in Relativistic Gamma-Ray Burst Shocks**, *Astrophys. J.*, **651**, L9 (2006)
 - 11) M.V. Medvedev, I.P. Robertson, T.E. Cravens, G.P. Zank, V. Florinski, **Charge exchange X-rays from the heliosheath**, *AIP Physics of the Inner Heliosheath*, **858**, 348 (2006)
 - 12) M.V. Medvedev, L.O. Silva, and M. Kamionkowski, **Cluster magnetic fields from large-scale-structure and galaxy shocks**, *Astrophys. J. Lett.*, **642**, L1 (2006)
 - 13) M.V. Medvedev, **The theory of spectral evolution of the GRB prompt emission**, *Astrophys. J.*, **637**, 869 (2006)
 - 14) B.C. Thomas, A.L. Melott, C.H. Jackman, C.M. Laird, M.V. Medvedev, R.S. Stolarski, N. Gehrels, J.K. Cannizzo, D.P. Hogan, L.M. Ejzak, **Gamma-Ray Bursts and the Earth: Exploration of Atmospheric, Biological, Climatic and Biogeochemical Effects**, *Astrophys. J.*, **634**, 509 (2005)
 - 15) M.V. Medvedev, L.O. Silva, R.A. Fonseca, J.W. Tonge, W.B. Mori, **Particle Kinetics in Relativistic Collisionless Shocks**, *Chapter in the monograph "Astrophysical Particle Acceleration in Geospace and Beyond"* (2005)
 - 16) M.V. Medvedev, M. Fiore, R.A. Fonseca, L.O. Silva, and W. B. Mori, **Long-time evolution of magnetic fields in relativistic GRB shocks**, *Astrophys. J. Lett.*, **618**, L75 (2005)
 - 17) M.V. Medvedev, **Magnetic field generation and evolution in cosmological shocks**, *Journal of the Korean Astronomical Society*, **37**, 533 (2004)
 - 18) M.V. Medvedev, **Boundary Layer Self-Similar Solution for the Hot Radiative Accretion onto a rapidly Spinning Neutron Star**, *Astrophys. J.*, **613**, 506 (2004)

Non-refereed publications:

- 1) M. Medvedev, **GRB Physics with Fermi**, *6th Huntsville Symposium*, Huntsville (2008), arXiv:0901.0051
- 2) K.-I. Nishikawa, M. Medvedev, B. Zhang, P. Hardee, J. Niemec, A. Nordlund, J. Frederiksen, Y. Mizuno, H. Sol, G.J. Fishman, **Radiation from relativistic jets in turbulent magnetic fields**, *6th Huntsville Symposium*, Huntsville (2008); arXiv:0901.4058
- 3) K.-I. Nishikawa, J. Niemec, H. Sol, M. Medvedev, B. Zhang, A. Nordlund, J. Frederiksen, Y. Mizuno, D. Hartman, G.J. Fishman, **New Relativistic Particle-In-Cell Simulation Studies of Prompt and Early Afterglows from GRBs**, *in proc Proceedings of The 4th Heidelberg International Symposium on High Energy Gamma-Ray Astronomy*, Heidelberg (2008), arXiv:0809.5067
- 4) M.V. Medvedev, **Relativistic Shocks in GRBs**, *in Proc of 2008 Nanjing Gamma-Ray Burst Conference*, eds Y-F Huang, Z.-G. Dai, B. Zhang, 314 (2008)
- 5) K.-I. Nishikawa, M.V. Medvedev, B. Zhang, P. Hardee, Y. Mizuno, H. Sol, D.H. Hartmann,

- G.J. Fishman, R. Preece, **Particle-In-Cell Simulation of GRB Shocks**, in *Proc of 2008 Nanjing Gamma-Ray Burst Conference*, eds Y-F Huang, Z.-G.Dai, B. Zhang (2008)
- 6) K.-I. Nishikawa, P. Hardee, Y. Mizuno, M.V. Medvedev, B. Zhang, D.H. Hartmann, G.J. Fishman, **Relativistic Particle-In-Cell Simulation Studies of Prompt and Early Afterglows from GRBs**, proc. of the Seventh European Workshop on Collisionless Shocks, Paris (2008), arXiv:0802.2558
 - 7) M.V. Medvedev, A. Spitkovsky, **Whence particle acceleration**, in *Proceedings of conference 070228: The next decade of GRB afterglow* (ed. R. Wijers) (2007)
 - 8) M.V. Medvedev, **A key to the spectral variability of prompt GRBs**, *AIP Conf. Proc. Gamma-Ray Bursts in the Swift Era*, 836, 169 (2006)
 - 9) M.V. Medvedev, **Comment on "Nonextensive theory of dark matter and gas density profiles"** e-print archive: *arXiv astro-ph/0510031* (2005)
 - 10) P. Robertson, T.E. Cravens, M.V. Medvedev, M.R. Collier, G.P. Zank, V. Florinski, **X-ray emission from charge exchange in the heliosphere**, *Proceedings of the Solar Wind 11/SOHO 16 conference, Connecting Sun and Heliosphere*, 16, 41 (2005)
 - 11) M.V. Medvedev, **Comment on the paper "Diffusive Synchrotron Radiation from Relativistic Shocks of Gamma-Ray Burst Sources" by G. D. Fleishman**, e-print archive: *arXiv astro-ph/0503463*(2005)

Our scientific results had been broadly disseminated in the astrophysical, plasma physical and fusion communities via seminars and colloquia, conference talks, poster presentations and discussions. Our results already received broad resonance in these communities. The PI presented **13 invited talks** at international conferences, **23 invited colloquia and seminars**. He and his group also presented **39 oral conference talks** and *poster presentations*. The list of colloquia/seminars, conference talks and presentations is given below.

Invited Talks:

- 1) M.V. Medvedev, **Jitter radiation mechanism --- a diagnostic tool of Weibel turbulence and Gamma-Ray Bursts**, annual *American Physical Society meeting DPP-07*, Orlando (2007)
- 2) M.V. Medvedev, **Cosmic Ray Variability and Galactic Dynamics**, annual *American Astronomical Society Spring meeting* (Hawaii), Abstract 054.01 (2007)
- 3) M.V. Medvedev, **GRB + Lab. Weibel (shocks). Jitter radiation**, workshop on *Laboratory Plasma Astrophysics*, Rice University, Houston, TX (2007)
- 4) M.V. Medvedev, **Whence the Magnetic Fields**, Debate-opening talk at the GRB conference *070228: The Next Decade of Gamma-Ray Burst Afterglows*, Amsterdam, Netherlands (2007)
- 5) M.V. Medvedev, **Cluster Magnetic Fields from Large-Scale Structure Shocks**, annual *International IGPP-6 space and astrophysics conference*, Honolulu, Hawaii (2007)
- 6) M.V. Medvedev, **Collisionless dissipative dynamics of nonlinear Alfvén waves**, *conference on Nonlinear Waves and Turbulence in Space Plasmas (NLW-06; held every four years)*, Fukuoka, Japan (2006)
- 7) M.V. Medvedev, **Extragalactic Shocks as Cosmic Accelerators**, annual conference: *XXVII General Assembly of the IAU, Joint Discussion 1 on Cosmic Particle Acceleration*, Prague, Czech Republic (2006)
- 8) M.V. Medvedev, **Do Extragalactic Cosmic Rays induce cycles in fossil diversity?**, annual *Mid-American Regional Astrophysics Conference (MARAC-06)*, Missouri (2006)
- 9) M.V. Medvedev, **Weibel Turbulence in Laboratory Experiments and GRB/SN Shocks**, *High-Energy Density physics and Laboratory Astrophysics conference (HEDLA-06; held every two years)*, Houston (2006)

- 10) M. Medvedev, **Physics of Collisionless Shocks in SN and GRBs: Weibel Instability**, *KITP Conference: Supernova and Gamma-Ray Burst Remnants*, Santa Barbara (2006)
- 11) M. Medvedev, **Collisionless Shocks in GRBs: from Speculations to Physics**, *Annual American Physical Society DPP Meeting, Miniconference on Plasma Astrophysics*, Denver (2005)
- 12) M.V. Medvedev, **A plasma physicist's view of gamma-ray burst shocks**, annual *American Physical Society meeting*, Session M3, Plasma Astrophysics, Tampa, FL (2005).
- 13) M.V. Medvedev, L.O. Silva, **Towards the theory of nonlinear Weibel turbulence**, annual *American Physical Society meeting, Division of Plasma Physics*, Savannah, GA (2004)

Invited colloquia and seminars:

2007

- 1) KU Graduate seminar, *Astrophysics at KU*
- 2) KU, Space seminar, *Astro Shocks in a lab; cooling issues*
- 3) Russian Research Center "Kurchatov Institute", Plasma Physics seminar, *Astrophysics News*
- 4) KU, Space seminar, *Extra-Galactic CR propagation and their possible observational effects*
- 5) Princeton Plasma Physics Lab seminar, *Plasma Physicist View of Astrophysical Shocks*

2006

- 6) "Quasi-public" Evolutionists talk, Lawrence, Kansas, *Do Cosmic Rays Induce Diversity Cycles?*
- 7) U. Missouri at Kansas City, Astrophysics Colloquium, *Do Cosmic Rays Induce Diversity Cycles?*
- 8) U. Wisconsin, Madison, Plasma seminar, *Physics of Astrophysical Collisionless Shocks*
- 9) Chicago U., KICP Colloquium, *Do Extragalactic Cosmic Rays induce cycles in fossil diversity?*
- 10) IAS, Biology seminar, *Do Extragalactic Cosmic Rays induce cycles in fossil diversity?*
- 11) IAS, Astrophysics seminar, *Astrophysical shocks: from Gamma-Ray Bursts to Large-Scale Structure*
- 12) KU, Physics Colloquium, *Do Extragalactic Cosmic Rays induce cycles in fossil diversity?*
- 13) UCSD, Plasma seminar, *Astrophysical collisionless shocks*
- 14) KU, Astrobiology seminar, *Extragalactic Cosmic Rays and biodiversity cycle*
- 15) KU, Space and Plasma Physics seminar, *Physics of GRB shocks*
- 16) Russian Research Center "Kurchatov Institute", Plasma Physics seminar, *Do extragalactic Cosmic Rays induce cycles in fossil diversity?*

2005

- 17) KU, Space and Plasma Physics seminar, *More details on radiation from shocks*
- 18) KU, Physics Colloquium, *A plasma physicist's view of gamma-ray burst shocks*
- 19) KU, Astrophysics seminar, *Sudden ionospheric disturbances due to cosmological gamma-ray bursts*
- 20) Kansas Center for Advanced Scientific Computing seminar, Kansas University, *Long-term evolution of magnetic fields in collisionless shocks*

2004

- 21) KU, Astrophysics/Space physics seminar, *A short overview of accretion physics, Part 2*
- 22) KU, Astrophysics/Space physics seminar, *A short overview of accretion physics, Part 1*
- 23) KU, Astrophysics seminar, *Current status of GRBs*

Conference Oral Talks and Presentations:

- 1) M.V. Medvedev, **Can cluster evaporation explain the missing thermal energy in clusters?** High-Energy Astrophysics (HEA-07) conference, Moscow Russia, 2007 [oral]
- 2) K.-I. Nishikawa, P. Hardee, Y. Muzino, M.V. Medvedev, B. Zhang, D.H. Hartmann, G.J. Fishman, **Relativistic Particle-In-Cell Simulation Studies of Prompt and Early Afterglows from GRBs**, Seventh European Workshop on Collisionless Shocks, Paris (2007) [oral]
- 3) M.V. Medvedev, **Shock models of GRBs: physics, predictions, observational tests**, GRB-07 meeting, Santa Fe (2007) [oral]
- 4) J.C. Workman, B.C. Morsony, D. Lazzati, M.V. Medvedev, **Jitter Radiation in the prompt and afterglow GRB emission**, GRB-07 meeting, Santa Fe (2007)
- 5) K.-I. Nishikawa, E. Ramirez-Ruiz, P. Hardee, C. Hededal, Y. Muzino, G.J. Fishman, D.H. Hartmann, M.V. Medvedev, **Simulations of relativistic, collisionless shocks: The X-ray hot spot in the M87 jet**, GRB-07 meeting, Santa Fe (2007)
- 6) M.V. Medvedev, A. Spitkovsky, **Radiative cooling in relativistic collisionless shocks. Can simulations and experiments probe relevant GRB physics?**, APS DPP-07 meeting, Orlando (2007) [oral]
- 7) S. Reynolds, S. Pothapragada, S. Graham, M.V. Medvedev, **Jitter radiation produced by electrons with anisotropic distribution in Weibel turbulence of GRBs and lab experiments**, APS DPP-07 meeting, Orlando (2007)
- 8) S. Graham, S. Reynolds, S. Pothapragada, M.V. Medvedev, **Phase-space distribution of accelerated electrons in Weibel-mediated relativistic GRB shocks**, APS DPP-07 meeting, Orlando (2007)
- 9) S. Pothapragada, S. Reynolds, S. Graham, **Modeling the spectral evolution of prompt GRBs and X-ray flares**, APS DPP-07 meeting, Orlando (2007)
- 10) K.-I. Nishikawa, E. Ramirez-Ruiz, P. Hardee, C. Hededal, Y. Muzino, G.J. Fishman, D.H. Hartmann, M.V. Medvedev, **Simulations of relativistic, collisionless shocks: The X-ray hot spot in the M87 jet**, Chandra meeting, Huntsville (2007)
- 11) K.-I. Nishikawa, E. Ramirez-Ruiz, P. Hardee, Y. Muzino, M.V. Medvedev, C. Hededal, G.J. Fishman, **Particle acceleration, magnetic field generation and emission in collisionless shocks**, 7th European workshop on collisionless shocks, Paris, France (2007) [oral]
- 12) M.V. Medvedev, **On Fermi vs. Non-Fermi Electron Acceleration at Relativistic Shocks of GRBs**, *AAS Spring meeting* (Hawaii), Abstract 041.03 (2007) [oral]
- 13) S. Pothapragada, S. Reynolds, S. Graham, M.V. Medvedev, **Modeling the spectral evolution of prompt GRBs and X-ray flares**, *APS April meeting*, Abstract S1.00007, Jacksonville, FL (2007)
- 14) S. Reynolds, S. Pothapragada, S. Graham, M.V. Medvedev, **Theoretical aspects of jitter radiation from Weibel turbulence laboratory experiments**, *APS April meeting*, Abstract S1.00021, Jacksonville, FL (2007)
- 15) S. Graham, S. Pothapragada, S. Reynolds, M.V. Medvedev, **Phase-space distribution of accelerated electrons in relativistic GRB shocks**, *APS April meeting*, Abstract S1.00008, Jacksonville, FL (2007)
- 16) M.V. Medvedev, **Distribution of Cosmic Rays in the Galaxy -- a Link to Biodiversity Cycles**, *APS April meeting*, Abstract E11.00008, Jacksonville, FL (2007) [talk]
- 17) A. Melott, L. Ejzak, B. Thomas, M.V. Medvedev, **Terrestrial Effects of Astrophysical Ionizing Photon Events: Spectrum and Variability**, *APS April meeting*, Abstract E11.00006, Jacksonville, FL (2007) [talk]
- 18) M.V. Medvedev, **Local Electron Acceleration in GRB Shocks**, *American Astronomical Society January Meeting*, Abstracts 209, #223.06 (2007) [talk]
- 19) M.V. Medvedev, **Modeling prompt GRBs and afterglows**, *High-Energy Astrophysics conference (HEA-06)*, IKI, Moscow, Russia (2006) [talk]
- 20) M.V. Medvedev, **Electron Acceleration in relativistic GRB Shocks**, *American Astronomical Society (HEAD) Meeting*, San Francisco (2006)

- 21) M. V. Medvedev, **Electron acceleration in relativistic GRB shocks**, *APS DPP Meeting Abstracts* 1004 (2006) [talk]
- 22) S. Pothapragada, S. Reynolds, M.V. Medvedev, **Modeling the spectral evolution of prompt GRBs and X-ray flares**, *APS DPP Meeting Abstracts* 1081P (2006)
- 23) S. Reynolds, S. Pothapragada, M.V. Medvedev, **Theoretical aspects of jitter radiation from Weibel turbulence in Hercules experiment**, *APS DPP Meeting Abstracts* 1080P (2006)
- 24) M.V. Medvedev, **Electron Acceleration In Relativistic GRB Shocks**, *Royal Society Meeting on GRBs*, London, UK (2006) [talk & poster]
- 25) M.V. Medvedev, **Fermi vs non-Fermi acceleration in GRBs**, *INTEGRAL-06 meeting*, IKI, Moscow, Russia (2006)
- 26) M.V. Medvedev, T.E. Cravens, I. P. Robertson, G.P. Zank, V. Florinski, **X-ray tomography of the Heliosheath**, *Spring AGU meeting*, Baltimore (2006)
- 27) M. Medvedev, A. Melott, **The Cosmogenic Origin of the 62 Myr Biodiversity Oscillation**, *APS April Meeting Abstracts* 7003 (2006) [talk]
- 28) S. Reynolds, M. Medvedev, **Diagnostics of Weibel Turbulence by Anisotropic Radiation Spectra**, *APS April Meeting Abstracts* 1043 (2006)
- 29) M. Medvedev, **Rapid Spectral Variability of GRBs. A Puzzle Solved?**, *APS April Meeting Abstracts* 7002 (2006) [talk]
- 30) M. Medvedev, A. Melott, **The Cosmogenic Origin of the 62 Myr Biodiversity Oscillation**, *Astrobiology Science conference, AbSciCon-06*, Washington, DC (2006) [talk]
- 31) M.V. Medvedev, **Short-time variability of Gamma-Ray Bursts**, *High-Energy Astrophysics conference (HEA-05)*, IKI, Moscow, Russia (2005) [talk]
- 32) M.V. Medvedev, **Jitter radiation from highly relativistic shocks**, *conference on Relativistic Jets: AGNs, micro-Quasars, GRBs*, Ann Arbor, Michigan (2005) [talk]
- 33) L.M., Ejzak, A.L. Melott, B.C. Thomas, M.V. Medvedev, **Effects of Spectral and Temporal Variations in Gamma Ray Burst Parameters**, *Bulletin of the American Astronomical Society* 37, 1188 (2005)
- 34) M. Medvedev, **Anisotropic Radiation Spectra from Strong Weibel Turbulence**, *APS DPP Meeting Abstracts* 1092P (2005)
- 35) I.P. Robertson, T.E. Cravens, M.V. Medvedev, M.R. Collier, G.P. Zank, V. Florinski, **X-ray emission from charge exchange in the heliosphere**, *Solar Wind 11/SOHO 16 conference*, Whistler, Canada (2005) [talk]
- 36) M.V. Medvedev, I. P. Robertson, T.E. Cravens, G.P. Zank, V. Florinski, **Charge-exchange x-rays from the heliospheric termination shock. An outside view**, *Spring AGU meeting*, New Orleans (2005)
- 37) M.V. Medvedev, **A key to the spectral variability of prompt GRBs**, *Swift-05 meeting* (2005)
- 38) M.V. Medvedev, **Towards the understanding of spectral variability of the prompt GRB emission**, *AAS HEAD Meeting, Bulletin of the American Astronomical Society* 36, 941 (2004)
- 39) M.V. Medvedev, **Spectral Evolution in Prompt GRBs and the Magnetic Turbulence in Relativistic Shocks**, *American Astronomical Society meeting*, 204, (2004)

Personnel, advising, etc.

The grant had also been supporting a postdoctoral researcher Dr. Oleg Bakunin (PhD in 1998) and four graduate students: Juthika Khargaria (MS program), Sarah Reynolds (MS/PhD program), Sriharsha Pothapragada (MS/PhD program), Scott Graham (PhD program).