Jets and Disks

Final Report on KITP Program, April—July 2005

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1 Introduction

This program was devoted to the study of the physics of energetic astrophysical outflows and accretion disks. The first half of the program was focused on outflows (pulsar magnetospheres and winds, black hole magnetospheres, relativistic jets from galactic black-hole binaries and active galactic nuclei, and winds from disks), while the second half was focused on accretion disks and related phenomena (state transitions in black hole binary systems, dynamos in disks, photon bubbles, transport of vertical field in disks, modeling of disk spectra, quasi-periodic oscillations from disks).

The spirit of the program was to emphasize physical processes rather than phenomenology. Indeed, since jets and disks are found in so many different astrophysical environments— pulsars, young stellar objects, x-ray binaries, active galactic nuclei, gamma-ray bursts, quasars, the proto-Jovian nebula, and planetary rings— this was the only possible way to straddle the range of topics and interests of all the participants.

The program had broad participation, with 64 participants over the 4 months of the program. The participants were diverse, from Europe, Australia, Asia, and every corner of the United States. Ten of the participants were women, including four who were key, long-term participants (Done, Szuszkiewicz, Celotti, and Rossi). The broad participation reflects the underlying strength of the field and the physically rich set of problems that touch almost every area of astrophysics. The program also involved a number of junior people whose active participation enabled them to become acquainted and socialized with the community in this field.

2 Organization

The core of the program was a morning discussion session held 5 days a week, for a total of 90 discussions. The format and content of the discussion sessions included presentations of new results by participants, followed by a vigorously critical discussion, and roundtable discussions of topics suggested by organizers or participants.

We also held two formal seminars a week, for a total of 30 talks. Normally these were hour-long talks, but some ran for as long as 3 hours. Weekly dinners and many informal lunches and outings facilitated interaction among the participants.

In the middle of the program we held a conference with about 80 participants. The organizers valiantly resisted pressure to pack the schedule with talks, and according to feedback we received the conference was quite successful. Our most important piece of advice to future coordinators is to minimize the number of talks and maximize the time for discussion.

3 Accomplishments

A number of papers were completed during the course of the program, and are listed below. However, much of the research work that was accomplished is still in the process of being written up, and we expect many papers to be submitted over the coming year. The program clearly initiated many new collaborations between participants, and also helped set the intellectual agenda for the field over the next few years. Here are some of the key issues raised during the course of the program:

Many aspects of jet and wind propagation are now fairly well understood. Given boundary conditions on the parent body (black hole, neutron star, disk, etc.) and the structure of the external medium, numerical methods exist that can efficiently calculate the structure of the jet (with some symmetry restrictions). In special cases analytic solutions are available. This sort of work is now being actively pursued in the context of gamma-ray bursts (MacFadyen, Begelman, Uzdensky, Spruit), and specialized numerical methods have been developed for relativistic flows (MacFadyen, Komissarov, Spitkovsky, Gammie, Hawley, Del Zanna, Amato, Fragile, Zhang). Some of the key remaining questions relate to the stability of the jet or wind, and dissipation within the jet (there was considerable discussion of dissipation in the context of "striped winds" from pulsars and gamma-ray bursts). But the most important question of all: what are the boundary conditions, i.e. what conditions lead to the launching of jets and winds?—is still unanswered. But global numerical models of accreting black holes offer tantalizing clues, suggesting that gas pressure (!) plays a key role.

In the context of winds from disks, this question is intimately connected with the large scale structure of the magnetic field. The widely held, although untested, assumption is that a large-scale, dipole-like field is required to efficiently launch a magnetic wind (much progress has been made in studying radiatively driven winds, as well). What generates this field in a disk, and why shouldn't it be expelled by the disk according to the turbulent resistivity and viscosity model described some years ago by Van Ballegoijen? Put differently, how does a dynamo work in an accretion disk? Or: what is the magnetic power spectrum of disk turbulence? Or: how are vertical fields transported within a disk? Suggestions were made for numerical experiments that might clarify some of these questions, and speculative ideas (e.g. Spruit, Uzdensky) related to magnetic field transport in disks were put forward.

A closely connected problem is the structure of magnetohydrodynamic turbulence in the

context of disks and in the sort of stirred-box thought experiments that are a focus of numerical and analytic attacks. One issue that has emerged out of the work of Cowley and others over the last few years is the question of the dependence of the magnetic power spectrum on the ratio of viscosity to resistivity (the magnetic Prandtl number, well-defined only in the event that both viscosity and resistivity are scalars). There is numerical evidence that the magnetic power spectrum is sensitive to the magnetic Prandtl number; this connected to the larger issue of how small-scale closure models influence, or possibly compromise, the outcome of the numerical experiments that are informing much of the progress in the field.

Numerical experiments and numerical methods played a starring role in our discussions. This is inevitable as jet and disk structure depends on complicated dynamical and radiative processes that cannot be reliably studied using analytic techniques (the situation is analogous in some ways to the problems of stellar structure and evolution). **Many of our numerical participants expressed frustration at the state of computing at the KITP, and felt strongly that better numerical facilities would be useful — for example, a small cluster.**

One of the triggers for the program was the emergence of a physical theory of angular momentum transport in disks. Turbulent transport of angular momentum was widely discussed in view of a slew of new numerical results from global disk models and models including new physical processes. But an obvious lacuna in the development of this theory is the absence of firm predictions for astronomical observations; this remains profoundly difficult, in part because most astrophysical disks are not spatially resolved. One way of making progress on this may be to ask: what is wrong with the α model? The classical model of disk structure at least makes some predictions for disk structure and evolution; which of these survive into the MHD turbulence era?

One way of attacking this last issue is through modeling of spectra, and considerable progress was made during the course of this program on this. Done and Davis succeeded in making direct comparisons between α disk models and black hole X-ray binary spectra in the thermally dominant state. These comparisons suggest that a number of the new physical effects expected from MHD turbulence are not in fact present to a large degree in this particular state. In addition, progress was made on building accretion disk spectral models more directly on the MHD simulations. For example, vertical dissipation and magnetic pressure profiles from simulations by Turner and Hirose et al. have now been incorporated into spectral models. Distributions of electric current density in the global general relativistic MHD simulations of Hawley have been computed and scaled so as to mock up global patterns of dissipation in radiatively inefficient flows in X-ray binaries, and these can now be used to make predictions for both timing and spectra.

Another key development is that thermodynamics is now being incorporated directly into the MHD turbulence simulations. New codes such as ATHENA rigorously conserve total energy, and are now being employed to study MHD turbulence. Radiation MHD simulations by Turner and Hirose et al. incorporate both heating and cooling directly.

Optically thin cooling has also been incorporated directly in global MHD simulations by Machida and Matsumoto, and Fragile and Meier are pursuing similar simulations. The coupling of magnetic forces and torques to thermodynamics is likely to lead to a deeper theoretical understanding of the bewildering variety of behaviors exhibited by astrophysical disks.

One of the most mysterious of these behaviors is the nature of well-defined spectral/timing states and state transitions in black hole X-ray binaries. A particularly fruitful portion of the program was the visit by observer Ron Remillard for a week where we really focused on educating ourselves on the complex phenomenology of these states. Some new ideas were generated (and critiqued!) about the nature of the flow in these states, and a number of program participants are now pursuing these.

Another example of the coupling between thermodynamics and magnetic forces lies in the problem of the ionization state of disks around young stellar objects. These disks are the site of planet formation, and are widely believed to be so cold and dense that they are effectively decoupled from magnetic forces. But work by Inutsuka and Sano– arguing that microscopic electric fields in these disks are strong enough to produce nonthermal electrons that generate additional ionizations, leading to runaway self-ionization– excited considerable controversy. A collaboration (Gammie, Ostriker, Zweibel, Gardiner) was formed to investigate the matter, along with the related problem of localized heating in protoplanetary disks, and it was shown that the self-ionization mechanism is marginal at best.

4 Conclusion

We feel that the jets and disks program was a tremendous success, a view which is supported by the comments in the activity reports of most of the participants. Program participants were forced to face some of the key hard questions, and new ideas and new collaborations were formed to tackle some of these. Virtually everyone left feeling educated and stimulated about a whole host of issues, and a key factor in this was having the participation of plasma physicists, observers, analytically-minded astrophysical theorists, and numericists all together at the same time.

We wish to thank everyone at the KITP (the director, deputy director, permanent members, advisory board, and the staff) for approving the program, providing such excellent advice on how to make it a success, and then making it so *easy* to actually do so. This was such a fun and productive experience that we all look forward to the next time we have an opportunity to participate in a KITP program!

5 List of participants

Abramowicz, Marek (Goteborg)
Akiyama, Shizuka (Texas)
Amato, Elena (Arcetri)
Armitage, Philip (Colorado)
Arons, Jon (Berkeley)
Balbus, Steve (Ecole Normale, Paris)
Begelman, Mitch (Colorado)
Bellan, Paul (Caltech)
Beloborodov, Andrei (Columbia)
Bisnovatyi-Kogan, Gennady (IKI, Moscow)
Blackman, Eric (Rochester)
Blaes, Omer (UCSB)
Bogovalov, Sergei (Moscow State)
Bucciantini, Niccolo (Berkeley)
Celotti, Anna Lisa (Trieste)
Cowley, Steve (UCLA)
Davis, Shane (UCSB)
Del Zanna, Luca (Arcetri)
Done, Christine (Durham)
Dorland, William (Maryland)
Dubus, Guillaume (CNRS)
Eichler, David (Ben-Gurion)
Fragile, Chris (UCSB)
Fromang, Sebastien (Queen Mary)
Gammie, Charles (UIUC)
Gardiner, Thomas (Princeton)
Granot, Jonathan (Stanford)
Hammett, Greg (Princeton)
Hawley, John (Virginia)
Howes, Gregory (Berkeley)
Kato, Yoshiaki (Kyoto)
Königl, Arieh (Chicago)
Komissarov, Serguei (Leeds)
Krolik, Julian (Johns Hopkins)
Lai, Dong (Cornell)
Levinson, Amir (Tel Aviv)
Lyubarsky, Yuri (Ben-Gurion)
MacFadyen, Andrew (IAS)
Machida, Mami (NAO Japan)
Malzac, Julien (CESR/CNRS)
Marti, Jose (Valencia)

Matsumoto, Ryoji (Chiba)
Meier, David (JPL)
Menou, Kristen (Columbia)
Nayakshin, Sergei (Leicester)
Nordlund, Åake (Niels Bohr Institute)
Ogilvie, Gordon (Cambridge)
Ostriker, Eve (Maryland)
Quataert, Eliot (Berkeley)
Remillard, Ron (MIT)
Reynolds, Chris (Maryland)
Rossi, Elena Maria (MPA-Garching)
Sano, Takayoshi (Tsukuba)
Sharma, Prateek (Princeton)
Spitkovsky, Anatoly (Stanford)
Spruit, Hendrik (MPA Garching)
Sramkova, Eva (Opava)
Stone, Jim (Princeton)
Szuszkiewicz, Ewa (Szczecin)
Terquem, Caroline (Institut d'Astrophysique)
Turner, Neal (JPL)
Usov, Vladimir (Weizmann Institute)
Uzdensky, Dmitri (Princeton)
Zhang, Weiqun (UCSC)

6 List of Talks and Seminars

Date	Speaker	Title
4/11, 12:15 p.m.	Henk Spruit	Introduction of the Jets and Disks Program (KITP Blackboard Lunch)
4/12, 11:00 a.m.	Julien Malzac	Interaction Between Disks and Jets in Black Hole Binaries: The Case of KV UMa
4/19, 2:00 p.m.	Jonathan Arons	Relativistic Shock Waves and Flow Structure in Relativistic Winds
4/21, 11:00 a.m.	Anatoly Spitkovsky	Physics of Magnetized Rotators: Force Free Electrodynamic Simulations
4/26, 2:00 p.m.	Steven Cowley	Magnetohydrodynamic Turbulence: Collisional Effects
4/28, 11:00 a.m.	Luca del Zanna	Relativistic MHD Simulations of Pulsar Wind Nebulae
5/03, 2:00 p.m.	Weiqun Zhang	Generation and Propagation of Jets in a Collapsars
5/05, 11:00 a.m.	Henk Spruit	Magnetohydrodynamics at the Interface Between a Disk and a Jet
5/09, 3:30 p.m.	Amir Levinson	High-Energy Aspects of Astrophysical Jets
5/12, 2:00 p.m.	Jonathan Granot	Jets in Gamma-Ray Bursts
5/16, 3:30 p.m.	Eli Waxman	Neutrinos Produced in Gamma-Ray Burst Jets
5/19, 2:00 p.m.	Greg Hammett	Current Status of Fusion Energy Research and Related Plasma Physics Studies
5/20, 11:00 a.m.	G. Bisnovatyi-Kogan	Magnetorotational Supernovae
5/31, 2:00 p.m.	Elena Rossi	Gamma-Ray Bursts as Neutron-Loaded Explosions
6/02, 11:00 a.m.	Takayoshi Sano	Local Behavior of the MRI
6/07, 2:00 p.m.	Chris Reynolds	Relativistic X-Ray Iron Lines: A Window on the Horizon Scale Astrophysics in Accreting Black Hole Systems
6/09, 11:00 a.m.	Ake Nordlund	Collisionless Shocks: Dynamics and Synthetic Spectra
6/13, 12:15 p.m.	Omer Blaes	How Astrophysical Disks Work (KITP Blackboard Lunch)
6/14, 2:00 p.m.	Paul Bellan	Simulating Astrophysical Jets in the Laboratory
6/16, 11:00 a.m.	Shane Davis	Continuum Spectral Constraints on the Near Horizon Physics of Black Hole Accretion Disks
6/21, 2:00 p.m.	Eliot Quataert	MRI in Collisionless Plasmas
6/23, 2:00 p.m.	Arieh Konigl	Hydromagnetic Driving of Astrophysical Jets
6/28, 2:00 p.m.	Ron Remillard	Spectral/Variability States of Black Hole X-Ray Binaries
6/30, 2:00 p.m.	Phil Armitage	Disks and Massive Planet Formation
7/05, 2:00 p.m.	David Meier	Magnetically Dominated Accretion Flows
7/07, 2:00 p.m.	Kristen Menou	Hot Accretion with Saturated Conduction
7/12, 2:00 p.m.	Sergei Nayakshin	Sgr A* Young Massive Stars: The First Evidence for Star Formation in AGN Disks
7/14, 2:00 p.m.	Caroline Terquem	Magnetic Effects on Planet Migration
7/19, 2:00 p.m.	David Eichler	The Brightest Astronomical Flash Ever Recorded
7/21, 2:00 p.m.	Eve Ostriker	Turbulence and Structure in Galactic Gas Disks
7/26, 2:00 p.m.	Sebastien Fromang	Dust Dynamics in Turbulent Protoplanetary Disks

Conference Schedule

	Monday, May 23, 2005	
	Morning Session	
	Session Chair - C. Gammie	
8:45am	David Gross	Welcome
9:00am	Mitch Begelman	Issues and Challenges in Jets, Outflows and Disks
10:00am	MORNING BREAK	
11:00am	Anatoly Spitkovsky	Pulsar Winds
12:00pm	Niccolo Bucciantini	MHD Models of Pulsar Winds
12:30pm	LUNCH BREAK	
	Afternoon Session	
	Session Chair - M. Begelman	
2:00pm	Serguei Komissarov	Simulations of Black Hole Magnetospheres
3:00pm	Marina Romanova	Accretion and Outflows from the Vicinity of Magnetized Stars
3:30pm	AFTERNOON BREAK	
4:15pm	Davide Lazzati	Jets in AGN, GRB's and Microquasars
5:00pm	Andrei Beloborodov	GRB Accretion Disks, Outflows, and External Blast Waves
	Tuesday, May 24, 2005	
	Morning Session	
	Session Chair - J. Hawley	
9:00am	Andrew Wilson	Observational Overview of Extragalactic Jets
9:45am	Denise Gabuzda	Polarization in Jets
10:30am	MORNING BREAK	
11:30am	Ryoji Matsumoto	Simulations of Jets
12:30pm	LUNCH BREAK	
	Afternoon Session	
	Session Chair - O. Blaes	
2:00pm	Richard Lovelace	Explosive Formation of Poynting Jets
2:30pm	Mark Wardle	Finite Conductivity Effects in Protostellar Disks and Jets
3:00pm	Sergei Bogovalov	Collimation of relativistic Jets
3:30pm	AFTERNOON BREAK	
4:15pm	Arieh Konigl	Hydromagnetic Driving of Jets
4:45pm	Peggy Varnire	Accretion-ejection Instability

	Wednesday, May 25, 2005	
	Morning Session	
	Session Chair - C. Done	
9:00am	Hui Li	Jets as Expanding Spheromaks
9:15am	David Ballantyne	Accretion Geometry in Radio-Loud Active Galaxies
9:30am	Ron Remillard	Observations of QPO's in X-ray Binaries
10:30am	MORNING BREAK	
11:30am	Chris Fragile	Tilted Thick-Disk Accretion onto a Kerr Black Hole
11:45am	Jeremy Schnittman	Imaging Black Hole QPO Models
12:00pm	Smita Mathur	Absorbing Outflows in AGNs: X-ray and UV Signatures
	Thursday, May 26, 2005	
	Morning Session	
	Session Chair - R. Remillard	
9:00am	Danny Steeghs	Structure of Accretion Disks from Tomographic Imaging
10:00am	Mike Eracleous	Emission Lines from the Outer Disk
10:30am	MORNING BREAK	
11:00am	Jon Miller	Observations of Relativistically Broadened Iron K-alpha Lines
11:45am	Chris Done	Testing Accretion Disk Theory Using X-ray Spectra
12:30pm	LUNCH BREAK	
	Afternoon Session	
	Session Chair - J. Arons	
2:00pm	John Hawley	Global Relativistic MRI Simulations
3:00pm	Daniel Proga	Dynamics of Winds from Luminous Accretion Disks
3:30pm	AFTERNOON BREAK	
4:00pm	Neal Turner	Radiation MHD Simulations of Accretion Disks
5:00pm	Julian Krolik	MRI Thermodynamics in Optically Thick, Gas Pressured Dominated Disks
	Friday, May 27, 2005	
	Morning Session	
	Session Chair - H. Spruit	
9:00am	Bill Dorland	Experimental Observations of the MRI
9:45am	Jeremy Goodman	The Princeton MRI Experiment
10:30am	MORNING BREAK	
11:30am	Eliot Quataert	Radiation Pressure Supported Disks on 100 pc Scales
12:30pm	LUNCH BREAK	
	Afternoon Session	
	Session Chair - J. Goodman	
2:00pm	Pierre-Yves Longaretti	Hydrodynamic (in)stability of Accretion Disks
2:20pm	Joe Barranco	Vortices in Disks
2:40pm	Bryan Johnson	Stability of Stratified Disks
3:00pm	CONFERENCE END	

7 Partial List of Publications

Abramowicz, M. A., Blaes, O. M., Horak, J., Kluzniak, W., & Rebusco, P. 2005. "Epicyclic oscillations of fluid bodies. Paper II: Strong gravity", Classical and Quantum Gravity, submitted.

Armitage, P. J. 2005, "Planetary Migration", to appear in proceedings, A Decade of Extrasolar Planets Around Normal Stars, 2005 STScI May Symposium.

Armitage, P. J., & Natarajan, P. 2005, "Eccentricity of supermassive black hole binaries coalescing from gas rich mergers", ApJ, submitted.

Bromberg, O., Levinson, A., & van Putten, M. 2005, "The gravitational-wave spectrum of a non-axisymmetric torus around a rapidly spinning black hole", astro-ph/0507078.

Levinson, A., Melrose, D., Judge, A., & Luo, Q. 2005, "Large Amplitude, Pair Creation Oscillations in Pulsar and Black Hole Magnetospheres", ApJ, submitted.

Machida, M., Nakamura, F., & Matsumoto, R. 2005, "Formation of Magnetically Supported Disks during State Transition in Black Hole Accretion Flows", ApJL, submitted.

Noble, S. C., Gammie, C. F., McKinney, J. C., Del Zanna, L. 2005, "Primitive Variable Solvers for Conservative General Relativistic Magnetohydrodynamics", ApJ, submitted.

Paesold, G., Blackman, E. G., & Messmer, P. 2005, "On Particle Acceleration from Poynting Flux Dominated Flows", Plasma Physics and Controlled Fusion, submitted.

Varniere, P., & Blackman, E. G. 2005, "Flux modulation from non-axisymmetric structures in accretion disks", New Astronomy, in press.