ANNUAL REPORT 2000–2001

Canadian Institute for Theoretical Astrophysics
Institut d'Astrophysique Théorique Canadien

The following is an abbreviated version of the 2001 CITA Annual Report, which covers scientific activities from September 2000 to August 2001. The full report is available on the web at
`http://www.cita.utoronto.ca/~fiege/AnnRep`.

1 FOREWORD

The Canadian Institute for Theoretical Astrophysics is a nationally supported research center for studies in theoretical astronomy and related subjects, hosted by the University of Toronto, and receiving research support from an NSERC collaborative special project grant, as well as the Canadian Institute for Advanced Research. CITA's primary missions are to foster interaction within the Canadian theoretical astrophysics community and to serve as an international center of excellence for theoretical studies in astrophysics. This report has been prepared by Jason Fiege, Andrei Frolov, Christopher Matzner, and Christopher Thompson.

Research at CITA covers a broad range of fields in astrophysical theory. During the 2000/2001 academic year the areas of study included:

- cosmology: microwave background anisotropies, large-scale structure, reionization, gravitational lensing, galaxy formation, Lyman alpha clouds;
- early universe: inflation, big bang nucleosynthesis, extra dimensions;
- dynamics: extra-solar planets, chaos, planet migration, galaxy clustering, warps, bars, and mergers;
- interstellar medium: Galactic HI distribution, molecular clouds, star-forming regions, dust physics;
- high energy astrophysics and stellar physics: accretion flows, AGN winds, supernovae, stellar pulsations, gamma-ray bursts, magnetars, stellar winds, AGB stars;
- general relativity: black holes, relativistic MHD, modifications of general relativity;
- computational physics: cosmological n-body simulations and hydrodynamics, particle-mesh and tree-code algorithms, internal modes of rotating stars;

2 PERSONNEL

The research staff of CITA for the 2000/2001 academic year (July 2000 to July 2001) is listed below.

Faculty:
- J. Richard Bond, Professor and Director (Ph.D. Caltech 1979)
- Norman Murray, Professor and Associate Director (Ph.D. Berkeley 1986)
- Lev Kofman, Professor (Ph.D. Tartu 1985)
- Peter Martin, Professor (Ph.D. Cambridge 1972)
- Ue-Li Pen, Assistant Professor (Ph.D. Princeton 1995)
- Christopher Thompson, Associate Professor (Ph.D. Princeton 1988)

Senior Research Associates:
- Dmitri Pogosyan, Ph.D. Tartu (1990)
- Istvan Szapudi, Ph.D. Johns Hopkins (1995)
- Ludovic Van Waerbeke, Ph.D. Toulouse (1997)

Research Associates:
- Phillip Arras, Ph.D. Cornell (2000)
- Rennan Barkana, Ph.D. MIT (1997)
- Carlo Contaldi, Ph.D. Imperial College (2000)
- John Dubinski, Ph.D. Toronto (1991)
- Jason Fiege, Ph.D. McMaster (1999)
- Andrei Frolov, Ph.D. Alberta (2000)
- Henk Hoekstra, Ph.D. Groningen (2000)
- Robin Humble, Ph.D. Monash (1999)
- Christopher Matzner, Ph.D. UC Berkeley (1999)
- Mikhail Medvedev, Ph.D. UC San Diego (1997)
- Simon Prunet, Ph.D. IAS Orsay (1998)
- Nir Shaviv, Ph.D. Israel Inst. Technology (1996)
- Peter Van Hoof, Ph.D. Groningen (1997)
- Joseph Weingartner, Ph.D. Princeton (1999)
- Yanqin Wu, Ph.D. Caltech (1997)

Staff:
- Margaret Fukunaga, Administrator
- Chris Loken, CITA Computing Manager
- Laura Waters, Administrative Assistant

Students: Masters students working with CITA faculty were K. Blagrave (Astronomy, completed Sept 2000; advisor Martin), L. Chamandy (Astronomy; advisor Thompson), and T. Rothwell (Astronomy; advisor Martin). Students working on Ph.D. theses were K. Balgrave (Astronony; advisor Martin), A. Dirks (Astronomy; advisor Bond), G. Felder (Ph.D. 2001, Physics, Standford University; advisor Kofman), J. Karr (Astronomy; advisor Martin), R. McNaughton (Astronomy; advisor Murray), M. Ruetalo (Astronomy; advisor Bond); H. Trac (Astronomy; advisor Pen), P. Troischt (Physics and Astronomy, UNC; advisor Thompson), and P. Zhang (Astronomy; advisor Pen). CITA also hosted several predoctoral fellows from outside institutions, who included Y. Dolivet (Ecole Normale Superieur; advisor Kofman), K. Kadota (Berkeley; advisor Kofman), A. Karakas (Monash; advisor Humble), J. Kim (Seoul; advisor Dubinski), J. Martin (Jena University; advisor Kofman), and T. Montroy (UCSB; advisor Bond). Last but not least, CITA maintains a vigorous summer research program for Canadian undergraduate student students. The students are supported both by NSERC awards and by faculty grants. The students working at CITA in the summer of 2001 were C. Armitage (UBC; advisor Bond), M. Bichan (Toronto; advisor Pen), L. Chamandy (Queens; advisor Thompson); L. Leung (Toronto; advisor Thompson), A. Mariampillai (Queens; advisor C. Matzner and C. Murray), M. Pritchard (Toronto; advisor Dubinski), S. Tonnesen (Swathmore, working with Bond, Contaldi, Pogosyan and Prunet); and B. Wang (UBC; advisor Pen).

Changes in 2000/2001: This was a bumper year for CITA post-docs, as five people moved on to faculty positions. Dmitri Pogosyan was hired by the University of Alberta as an associate professor. Istvan Szapudi began an assistant professorship at the University of Hawaii in January 2001. Ludo van Waerbeke began a permanent research position at the Institut d'Astrophysique (Paris) in October 2000, and was soon followed by Simon Prunet, who was hired by the IAP later in the year. (Van Waerbeke continued to divide his time between Paris and Toronto during the 2000-2001 academic year.) Nir Shaviv and Rennan Barkana both accepted tenure track faculty positions in Israel, at Hebrew University and the University of Tel Aviv, respectively, beginning in fall 2001. To add icing to the cake, we received news that former CITA postdocs accepted permanent positions: Brad Hansen is joining the faculty of UCLA, James Murray is a Lecturer at Leicester, Roman Scoccimarro joined New York University, Phil Armitage is joining the faculty at the University of Colorado from St. Andrew's University, Brett Gladman joined the faculty at UBC, Andrew Jaffe became a Lecturer at Imperial College, Lloyd Knox joined UC Davis Jan 2001, and Derek Richardson joined the faculty at the University of Maryland.

Chris Thompson returned to CITA as an associate professor, having spent the last four years at the University of North Carolina at Chapel Hill. Chris Matzner was promoted to a five-year Senior Research Associateship. New CITA post-docs in the fall of 2000 were Rennan Barkana (who arrived from the Institute for Advanced Study, Princeton); Carlo Contaldi (who had just received his Ph.D. at Imperial College London); Andrei Frolov (a new graduate of the University of Alberta); Henk Hoekstra (from the University of Groningen); and Mikhail Medvedev (who had completed a post-doctoral position at Harvard University). New additions to CITA in the fall of 2001 will include Andrei Beloborodov (arriving as a Senior Research Associate from Stockholm Observatory), and Gary Felder and Nicole Lloyd-Ronning (both of whom received their PhDs from Stanford University in 2001).

CITA faculty received a number of distinctions during the 2000-2001 year. Director Dick Bond was appointed a University Professor of the University of Toronto. He was also elected to the Royal Society of London and became a Fellow of the Institute of Physics (U.K.). CITA faculty Ue-Li Pen and Chris Thompson both received Premier's Research Excellence Award from the Province of Ontario, each carrying with it a total of $150,000 in funding. (That completes a clean sweep of the PREAs by recent additions to the CITA faculty: Lev Kofman was awarded a PREA in 1997, and Norm Murray in 1999.)

3 CITA VISITORS

CITA has a vigorous visitors program bringing a number of Astronomy and Physics faculty members from other Canadian universities and from abroad for both extended stays and shorter visits. The following is a list of all CITA visitors for the 2000/2001 academic year.

Long term visitors:

- Omer Blaes - U.C. Santa Barbara
- Arnold Boothroyd - Caltech
- Kenji Kadota - U.C. Berkeley
- Sebastion Pichler - Ludwig Maximilians Universitat München
- Yacine Dolivet - L'ecole Normale Superieure (Paris)
- Martin van Kerkwijk - Universiteit Utrecht
- Margot Mandy - University of Northern B.C.
- Shinji Mukoyama - University of Victoria
- Aristotle Socrates - U.C. Santa Barbara
- Tak-Pong Woo - National Taiwan University
- Jun-Mein Wu - National Taiwan University

CITA senior visiting fellows:

- Sun Kwok, Calgary
- Norbert Bartel, York

Short term visitors:

- F. Adams - University of Michigan
- R. Allahverdi - University of Alberta
- N. Arav - U.C. Davis
- A. Atoyan - McGill University
- D. Ballantyne - IOA, Cambridge
- N. Bartel - York University
- S. Bashinsky - MIT
- S. Basu - University of Western Ontario
- A. Beloborodov - Stockholm Observatory
- F. Bernardeau - Saclay
- E. Berschinger - MIT
- L. Binette - Instituto de Astronomia
- E. Blackman - California Institute of Technology
- C. Borys - University of British Columbia
- R. Bousso - U.C. Santa Barbara
- B. Carr - Queen Mary College, London
- J. Cartwright - California Institute of Technology
- B. Chaboyer - Dartmouth University
- D. Charbonneau - CfA, Harvard
- M. Chen - SNO, Queen's University
- M. Choptuik - University of British Columbia
- P. Cottrell - Canterbury University, New Zealand
- H. Couchman - McMaster University
- R. Crittenden - DAMTP, Cambridge
- A. Cumming - ITP, U.C. Santa Barbara
- T. di Mateo - CfA, Harvard
- S. Dodelson - Fermilab

- L. Dones - Southwest Research Institute
- M. Duncan - Queen's University
- G. Efstathiou - IOA, Cambridge
- G. Evrard - University of Michigan
- G. Felder - Stanford
- G. Ferland - University of Kansas
- M. Fich - University of Waterloo
- B. Fisher - U.C. Berkeley
- W. Freedman - Carnegie Observatories
- V. Frolov - University of Alberta
- T. Fukui - University of Waterloo
- T. Fuller - University of Western Ontario
- N. Gnedin - University of Colorado
- C. Gordon - University of Portsmouth
- P. Goldreich - California Institute of Technology
- A. Gruzinov - IAS, Princeton
- Z. Haiman - Princeton
- B. Hansen - Princeton
- J. Heyl - California Institute of Technology
- R. Henriksen - Queen's University
- R. Hildebrand - University of Chicago
- M. Holman - Harvard Smithsonian
- M. Hudson - University of Waterloo
- I.-G. Jiang - ASIAA
- A. Karakas - Monash University
- C. Keeton - University of Arizona
- M. Kerscher - Johns Hopkins
- S. Kenyon - Harvard
- J. Kim - Seoul National University
- A. Klypin - New Mexico State University
- R. Kolb - Fermilab
- D. Koranyi - CfA, Harvard
- C. Kouveliotou - Marshall Space Flight Center
- S. Kulkarni - California Institute of Technology
- A. Kusenko - UCLA
- S. Kwok - University of Calgary
- D. Lai - Cornell University
- G. Lake - University of Washington
- K. Lake - Queen's University
- R. Larson - Yale University
- J. Lattanzio - Monash University
- A. Lazarian - University of Wisconsin
- Z.-Y. Li - University of Virginia
- A. Liddle - University of Sussex
- J. Lee - Academia Sinica
- M.-H. Lee - U.C. Santa Barbara
- J. Lesgourgues - SISSA, Trieste, Italy
- Y. Levin - U.C. Berkeley
- M. Lyutikov - McGill University
- C.-P. Ma - University of Pennsylvania
- J. Magueijo - Imperial College, London
- J. Martin - University of Jena, Germany
- S. Mashchenko - University of Montreal
- B. Mason - California Institute of Technology
- B. Matthews - McMaster University
- A. Mazumdar - Imperial College
- A. McDonald - SNO, Queen's University
- A. Melchiorri - Oxford University
- Y. Mellier - Institute d'Astrophysique, Paris
- K. Menou - Princeton University
- L. Mersini - University of Pisa
- C. Millar - University of Western Ontario
- S. Mukohyama - University of Victoria
- I. Murakami - National Institute for Fusion Science
- J. Murray - University of Leicester
- P. Myers - CfA, Harvard
- R. Myers - McGill University
- S. Myers - NRAO
- J. Navarro - University of Victoria
- F. Pearce - University of Durham
- T.J. Pearson - California Institute of Technology
- P.J.E. Peebles - Princeton University
- S. Perlmutter - U.C. Berkeley
- M. Pospelov - University of Minnesota
- R. Pudritz - McMaster University
- G. Starkman - Case Western University
- E. Pierpaoli - University of British Columbia
- J. Prochaska - U.C. Santa Cruz
- E. Quataert - Princeton
- P. Ricker - University of Chicago
- E. Rivera - Unvierstiy of Leuben, Belgium
- A. Rosencweig - ThermaWave
- J. Ruhl - U.C. Santa Barbara
- B. Ryden - Ohio State University
- V. Sahni - IUCAA, India
- D. Sasselov - Harvard University
- E. Scannapieco - U.C. Berkeley
- R. Scoccimarro - IAS, Princeton
- D. Scott - University of British Columbia
- S. Seager - IAS, Princeton
- S. Shandarin - University of Kansas
- J. Sievers - California Institute of Technology
- A. Smolyakov - University of Alberta
- G. Starkman - Case Western Reserve University
- P. Steinhardt - Princeton University
- J. Stil - Queen's University
- J. Stone - University of Maryland
- T. Souradeep - Kansas State University
- S. Talon - University of Montreal
- R. Thacker - McMaster University
- S. Tremaine - Princeton University
- P. Troischt - University of North Carolina
- A. Tseytlin - Ohio State University
- B. Unruh - University of British Columbia
- G. Ushomirsky - U.C. Berkeley
- A. Van Proeyen - University of Louvain, Belgium
- R. van de Weygaert - Kapteyn Institute
- L. van Waerbeke - Institut d'Astrophysique, Paris
- K. Verner - University of Kansas
- M. Voit - Space Telescope Science Institute
- S. Vogt - U.C. Santa Cruz
- J. Wadsly, - McMaster University
- D. Wands - University of Portsmouth
- M. West - University of Hawaii at Hilo
- L. Widrow - Queen's University
- G. Yepes - Universidad Autonoma de Madrid

4 CIAR AND CITA

The Canadian Institute for Advanced Research supports a number of programs chosen for their high intellectual promise and interdisciplinary character. The CIAR Cosmology and Gravity Program has nodes at UBC (Fellows Bill Unruh and Matt Choptuik), at the University of Alberta (Fellows Valery Frolov and Don Page), at the University of Victoria (Fellow Werner Israel and Scholar Julio Navarro), at McMaster University (Fellow Hugh Couchman), at Queen's University (Scholar Mark Chen), at the University of Toronto (Fellows Ray Carlberg, Scholars Barth Netterfield and Amanda Peet), at the Hertzberg Institute (Fellow Simon Lilly), at the Perimeter Institute (Fellow Rob Myers) and at CITA, where Dick Bond and Lev Kofman are CIAR Fellows and Ue-Li Pen is a CIAR scholar. There is also a large distinguished network of CIAR Associates of this Program around the world. The Program is in its third five year period and Scott Tremaine is the Director. The academic interaction between CIAR Fellows and other CITA visitors and researchers, and the administrative cooperation between CITA and CIAR in attracting excellent cosmologists, continues to make Toronto and Canada a lively place for research in theoretical cosmology. The Program has recently been renewed for a fourth five-year term.

5 SACKLER VISITING ASTROPHYSICIST

CITA received a generous gift from the Raymond and Beverly Sackler Foundation to endow the **Raymond and Beverly Sackler Visiting Astrophysicist Program**. Each year CITA invites an internationally distinguished scholar conducting research in theoretical astrophysics to give two lectures at the University of Toronto. The researcher also meets informally with faculty and postdoctoral fellows at CITA as well as researchers and students in the Department of Astronomy and other departments. The visit is intended to be the highlight of the academic year at CITA.

The fifth Sackler lecture, titled 'How Does the Sun Shine?', was delivered by Prof. John Bahcall of the Institute for Advanced Study (Princeton) on 1 November 2001 to an enthusiastic audience of students and faculty. Prof. Bahcall summarized his work, stretching back almost 40 years, on the production and detection of Solar neutrinos, as well as the brilliant efforts of hundreds of experimental physicists across the globe to detect these elusive particles. The longstanding mystery of the missing Solar neutrinos recently found a dramatic solution in the detection of neutrino oscillations by the Sudbury Neutrino Observatory. The next day, John Bahcall delivered a second, more technical, lecture on the properties of neutrinos as deduced from the latest Solar neutrino experiments.

This year's Sackler Lectureship was combined with a visit by Prof. Neta Bahcall of the Astronomy Department at Princeton University. She has spearheaded efforts to measure fundamental cosmological parameters through techniques such as the statistics of high redshift galaxy clusters. On Nov 1, Prof. Bahcall gave a comprehensive review of current measurements of the mass density, cosmological curvature, and cosmological constant, based on a variety of observational stategies, and demonstrated a remarkable convergence in the results of these independent methods.

The previous **Raymond and Beverly Sackler Visiting Astrophysicists** have been: Sir Martin Rees of Cambridge (1997); Peter Goldreich of Caltech (1998); Frank Shu of Berkeley (1999); and Jim Peebles of Princeton (2000).

6 CONFERENCES SUPPORTED BY CITA

CITA supports scientific workshops and meetings in Canada on subjects of interest to theoretical astrophysics. Meetings supported by CITA in 1999/2000 were:

- Kingston 2000 Meeting: "Directions in Theoretical Astrophysics at the Turn of the Millennium" 26-30 August 2000, Fields Institute, Toronto Organizers: D. Bond, D. Henriksen, L. Kofman, N. Murray, U-L. Pen, L. Widrow
- "Black Holes III: Theory and Mathematical Aspects" 19-23 May 2001, Kananaskis, Alberta Organizers: D. Page, V. Frolov
- "Ninth Canadian Conference on General Relativity and Relativistic Astrophysics" 24-26 May 2001, University of Alberta Organizers: H. Kunzle, S. Morsin, E. Woolgar
- "CITA Workshop on High Performance Computational Astrophysics" 31 May - 1 June 2001, Toronto Organizers: U-L. Pen, J. Dubinski, H. Couchman, J. Wadsley, R. Humble
- "White Dwarfs as Dark Matter" 19-22 August 2001, University of British Columbia Organizers: H. Richer, D. Scott

In addition, a collaboration between CITA, McMaster, Waterloo, and Queen's University has produced an active Star Formation Group in the Southern Ontario region which holds an annual Jamboree. At CITA, informal seminars also convene to discuss the physics of the early universe, and theories and observations of gamma ray bursts.

7 FACILITIES

CITA occupies the 12th floor of the McLennan Physical Laboratories at the downtown campus of the University of Toronto. The main-stay of CITA's high-performance computing resources is a Compaq "Wildfire" GS320 computer with 32 alpha processors and 64GB of RAM. This machine is intended primarily for cosmological simulations, cosmological hydrodynamics, simulations of galaxy formation, and CMB map analysis. However, it is available to any CITA researcher whose research depends on high performance parallel computing. This computer was obtained with a "Canadian Fund for Innovations" (CFI) grant, proposed by Peter Martin, Richard Bond, and Ray Carlberg, along with the Atmospheric Physics group and the Chemistry department. CITA also has two powerful Beowulf clusters. A dedicated 28 processor Intel cluster with 8GB of RAM is funded by John Dubinski and used for his research in galactic dynamics. A second Beowulf cluster with 1GB of memory is funded by Peter Martin in collaboration with M. Duncan (Queen's) and K. Innanen (York). This cluster is dedicated to computationally intensive simulations in molecular and atomic physics, as well as planetary dynamics. CITA also houses a large SCSI Raid array with a storage capacity of 550GB. CITA researchers also have access to several other multi-processor machines, including 4 Quad Alpha ES40s each with four 500 MHz processors and 4 GB of RAM, and a quad ES45 with 1 GHz processors. CITA also has two older multi-processor machines, including an 8 processor SGI Origin 2000 system with 4GB of memory, and a 4 processor Compaq AlphaServer 2100 system with 1GB of memory. CITA is about to take delivery of 8 Dell Quad Itanium servers with 512GB core memory.

Every researcher at CITA has a desktop computer for general use and smaller computational tasks. These are Intel and AMD-based personal computers running Linux, although there are several Compaq Alpha workstations, SGI Indigo workstations, SGI Personal IRISes, SUN SPARCstations, and X terminals. All of these systems are networked together, and used either individually or in parallel. All of these systems are supported by a Sun Ultra 5 back-end file and network server, with about 200 gigabytes of disk. CITA's network is fully switched, with 10 and 100 megabit connections to offices (depending on the computers present) and a 100 megabit link to the campus network and the Internet. Researchers also have access to a number of peripheral devices, including a high-quality colour laser printer, a dye-sublimation colour printer, several inkjet colour printers, a high-speed black-and-white laser printer capable of double-sided printing, an optical scanner, and various tape drives (e.g., an 8TB AIT-3 tape library).

8 CITA COUNCIL

CITA is both an Institute within the School of Graduate Studies of the University of Toronto, and a non-profit corporation (CITA, Inc.). Relations between the two CITAs are governed by a Letter of Agreement between CITA Inc. and the University of Toronto that was signed in 1989. The CITA Council consists of eight members, five selected from the CITA Inc. membership of over 50 researchers in co-operation with the Canadian Astronomical Society (of which they must also be members), and two *ex officio*: the Director of CITA and the Dean of the School of Graduate Studies of the University of Toronto or his designate.

Members of CITA Council for the second half of 2000 were:

- Richard Bond, CITA Director
- Richard Henriksen, CITA Chair, Queen's University
- Donald Cormack, S.G.S., University of Toronto
- Hugh Couchman, McMaster University
- Martin Duncan, Queen's University
- David Hartwick, University of Victoria
- Kim Innanen, York University

9 SCIENTIFIC OVERVIEW 2001

The research program at CITA encompasses all the major areas in astronomy broken down in the main categories of cosmology, galaxies, interstellar medium, stars and planets. In this report, we review the main activities at CITA during the 2000/2001 academic year.

9.1 Cosmology

Barkana, Haiman (Princeton) and Ostriker (Princeton) studied the constraints that high-redshift structure formation in the universe places on warm dark matter (WDM) dominated cosmological models. In WDM models, the dark matter particles are given random initial velocities. This smooths the density distribution on small scales, suppressing the densities and central concentrations of dwarf galaxies. These effects improve the agreement between the cold dark matter model and observations of the present universe. However, in WDM models the numbers of galaxies are strongly altered at high redshifts. The observed reionization of the universe, and the presence of massive high-redshift quasars, both place strong constraints on WDM models.

In light of recent observations of quasar spectra, **Barkana** has studied the observational signatures of different stages of the reionization epoch. The central stage of reionization is the overlap stage, during which the ionized-hydrogen bubbles produced by individual sources overlap each other and reionize the low-density gas which takes up most of the volume of the universe. Some neutral hydrogen remains in dense clumps which are then slowly reionized during post-overlap. **Barkana** showed that the recent observations are consistent with the post-overlap stage, and therefore further efforts are required for a conclusive observation of the overlap stage.

Barkana is developing detailed theoretical models of the various stages of the reionization of the universe. One goal is to show which physical parameters determine the character and the length of the reionization era. He is exploring a number of scenarios for reionization, depending on various possible ionizing source populations.

Barkana and Scannapieco (Berkeley) are developing an analytical formalism appropriate for studying structure formation in inhomogeneous environments. The standard derivation of the mass distribution of dark matter halos depends on the statistics of the density distribution in spheres of various sizes, all about a single random point. The authors extend this to a two-point formalism, and derive an approximate expression for the mass distribution of halos in the neighborhood of an object with a fixed mass and formation time. This formalism should be useful in many applications which involve the feedback effects of galaxies on their surroundings.

Over the past two years, Cosmic Microwave Background (CMB) data from the balloon-borne Boomerang and MAXIMA experiments and later from the interferometric experiments DASI and the Cosmic Background Imager (CBI) on sub-degree angular scales have revolutionized our knowledge of the Universe. CITA continued its strong efforts on CMB analysis, as members of the Boomerang and CBI teams, and determining their cosmological implications. The **CITA Boomerang group** consists of Dick **Bond**, Carlo **Contaldi**, Dmitry **Pogosyan** and Simon **Prunet**, along with Barth Netterfield of the Astronomy Department. They have been intensively engaged in analyzing the 10 days of Boomerang Long Duration Balloon flight data, determining the significance of the features in the measured power spectrum and deriving cosmological parameters from it. CITA hosted the entire Boomerang team and many smaller focus groups during this period.

The **CITA Boomerang group** along with Hivon (Caltech) have constructed a very fast method for the estimation of CMB angular power spectra. It involves the simulation of an observation in a Monte Carlo procedure to estimate the biasing terms in the measured power. The resulting estimator was applied succesfully in the power spectrum estimation in the latest BOOMERANG results. The method is currently one of the most competitive methods for the fast estimation of CMB power spectra.

Similar "FASTER" ideas are being applied by the **CITA group** to estimation of non-Gaussian components in the Boomerang data, using novel ways of estimating the reduced higher-point correlation functions in multipole space. Two summer undergraduate students, C. Armitage and S. Tonnesson, worked on this project as well.

The measured spectrum confirms the paradigm of adiabatic perturbations as the source of the structure in the Universe and is in agreement with the inflationary models of the early Universe which specify the seeds for these perturbations. The CITA group derived values on the main parameters governing the inflation-based adiabatic fluctuation model. They found that the Universe is nearly spatially flat, has baryon content in agreement with the predictions from the Big Bang nucleosynthesis calculations, and strongly indicates that the bulk of the energy in the Universe is dark, possibly in the form of vacuum energy.

The **CITA Boomerang group** and summer undergraduate student Kris Sigurdsen used the Boomerang and other CMB data, in conjunction with large scale structure and supernova data, to constrain the equation of state of the dark energy, finding it is compatible with a cosmological constant explanation, although rolling scalar fields are still a viable option.

The analysis of the unique CBI interferometric dataset has required the implementation of new analysis methods. A CITA group consisting of Dick **Bond**, Carlo **Contaldi**, Ue-Li **Pen**, Dmitry **Pogosyan** and Simon **Prunet** in collaboration with the CBI team have carried out the first analysis of mosaiced CMB interferometric fields of view. The results provide measurements of the CMB power spectrum at angular scales above $\ell = 1000$ (the end of the Boomerang range) where very few measurements have been carried out so far. The first round of results is to be published in early 2002.

The huge worldwide investment in CMB experiments should make the Sunyaev-Zeldovich (SZ) effect a key probe of the cosmic web in the near future. For the promise to be realized, substantial development of simulation and analysis tools to relate observation to theory is needed. The high nonlinearity and dissipative/feedback gas physics lead to highly non-Gaussian patterns that are much more difficult to analyze than Gaussian primary anisotropies for which the procedures are reasonably well developed. Historical forecasts for what CMB experiments might see used semi-analytic tools, including large scale map constructions, with localized and simplified pressure structures distributed on a point process of (clustered) sources. Hydro studies beyond individual cluster/supercluster systems were inadequate, but now large-volume simulations with high resolution are beginning to shift the balance. **Bond** and student Marcelo Ruetalo, in collaboration with James Wadsley (McMaster) and Mike Gladders, have illustrated this by applying "Gasoline" (parallelized Tree+SPH) computations to construct SZ maps and derive statistical measures. They believe rapid Monte Carlo simulations using parameterized templates centered on point processes informed by optical and other means on the observational side, and by hydro simulations on the theory side, should play an important role in pipelines to analyze the new SZ field data. They show that localized sources should dominate upcoming SZ experiments, identify sources in the maps under filtering and noise levels expected for these experiments, use the RCS photometric optical survey as an example of redshift localization, and discuss whether cosmic web patterns such as superclusters can be enhanced when such extra source information is supplied.

As an alternative to computing large-scale simulations of cosmic structure formation in ever larger periodic boxes, **Bond** and Wadsley have designed a relatively small set of modest sample patches constrained to have bulk physical properties which characterize the main statistical variations from sample to sample. Statistical quantities computed for each simulated patch are combined using Bayes theorem, with this importance sampling ending when a required accuracy is achieved. They have found that patch-smoothed shear values, spanning the range from void-like to overdense regions, are excellent control parameters for the constrained bulk properties, defining "shearing patches". It is essential to ensure that the mass resolution scale be small enough to capture the essential physics, and that the patches be large enough to avoid extreme tidal distortion over the redshift range of interest. Long wavelengths and tidal forces must be properly included for each shearing patch simulated. An advantage of this technique is that it can be naturally "parallel by shell". They have developed a fast and accurate TreePM-SPH code with low memory cost which allow them to evolve shearing patches with strong tides in single processors, with cross-talk only occurring at the post-processing level of the statistical quantities of interest, a radical compression of the patch information. Long waves are incorporated by optimally sampling k-space out to arbitratily large scales, and simulating non-periodically with multiple particle masses and linearly evolved external tides. They demonstrate the technique for the Lyman alpha forest, using a set of modest simulations resolving the essential Jeans scale (0.1 Mpc). The resulting dynamic patches combine to match the observed Lyman alpha absorber column density characteristics including the sharp change in dn/dN_{HI} slope at HI column depth 10^{14}. Exploring the Cosmic Web structures producing the QSO absorption features we find a strong association between columns above $10^{14.5}$ absorbers and dwarf galaxies.

Carlo **Contaldi** and Magueijo (Imperial) have developed a method for the generation of simulated CMB with a Bispectrum decoupled from the power spectrum. (This method is a restriction of transformation based simulation techniques.) The work involved the development and implementation of a "Harmonic" probability distribution function, a non-Gaussian PDF related to the well known Edgeworth Expansion around a Gaussian but with better mathematical properties (positive definiteness is ensured).

Henk **Hoekstra**, Howard Yee (Toronto), and Mike Gladders (Toronto) used the imaging data of the Red-Sequence Cluster Survey to measure the weak lensing signal induced by large scale structure. To date, 24the data have been analysed, and a significant lensing signal is detected. In particular, in combination with other (deeper) surveys, these measurements provide valuable constraints on cosmological parameters.

Henk **Hoekstra**, Yee, and Gladders used the RCS imaging data to obtain the constraints on galaxy biasing from weak gravitational lensing. The RCS data alone allow a measurement of the ratio of the bias parameter and the galaxy-mass cross-correlation coefficient as a function of scale. In collaboration with Ludo **van Waerbeke** and Yannick Mellier, a first attempt has been made to measure the bias parameter and the cross correlation coefficient separately. These results provide a unique, and important constraints on models of galaxy formation.

Henk **Hoekstra**, Mike Gladders, Howard Yee, and Erica Ellingson obtained follow-up observation of a z=0.78 cluster of galaxies which shows (for this redshift) unprecedented strong lensing features. A detailed modeling of the mass distribution and measured redshift for the arcs allows one to constrain the density parameter of the universe through a geometrical method: the location of the lensed features depend on the angular diameter distances, which in turn depend on the cosmology.

Modification of the new Tree-PM cosmological N-body code (Kim, **Dubinski**, Park) is being carried out to add SPH fluid dynamics for applications such as the Sunyaev-Zeldovich effect.

Mikhail **Medvedev** and Ramesh Narayan (IAS & Harvard) are attempting to explain the deficit of large clouds of cold gas in cooling flows of several galaxy clusters revealed by Chandra and XMM. Such clouds were expected to rapidly drop out of the flow because of runaway cooling. Preliminary theoretical results indicate that thermal conduction is such weakly collisional systems may be as high as a fraction of the Spitzer value, despite the presence of strong turbulent magnetic fields. This should be enough to inhibit fast mass drop-out.

Mikhail **Medvedev** developed a phenomenological model of self-interacting dark matter (SIDM) with quantum flavor mixing. He showed that this model possess all attractive features of both a conventional SIDM and an annihilating dark matter model, but does not suffer from their severe problems. In this model, different mass eigenstates of dark matter particles separate in the gravitational field of a galaxy. Heavy states remain bound in the halo (and, thus, form the halo) and light ones escape. As the density increases, scattering of mass states off each other converts some of the heavy states into the escaping light ones, which lowers the central density and flattens the core.

Mikhail **Medvedev** investigated the dynamics of flavor-mixed dark matter in the early universe. This consideration puts important constraints on the parameters of the model, such as the masses of dark matter particles. The allowed mass of the heavier mass-state is below a tenth of a GeV in the non-degenerate case and is somewhat larger, around or below a few GeV, in the most degenerate case.

In a series of papers, **Pen** together with J. Lee (Tapei), U. Seljak (Princeton), R. Crittenden (DAMTP), P. Natarajan (Yale), and T. Theuns (Cambridge) have calculated the statistics of galaxies alignments from linear theory, and compared the results with simulations and observations. The effects are consistent across the three fronts, and provide an estimate of the level of contamination for weak lensing surveys. The alignments themselves can be used to reconstruct the primordial gravitational shear field.

Pen and Zhang (Toronto) used analytic hierarchical correlation models to compute the two point statistics of the pressure fluctuations which determine the Sunyaev-Zeldovich effect. It was demonstrated how the redshift evolution of the SZ power spectrum can be deconvolved by the appropriate cross correlation with galaxy surveys.

Pogosyan, S. Colombi (IAP) and T. Souradeep (Kansas State) presented a numerical study of topological descriptors of initially Gaussian and scale-free density perturbations evolving via gravitational instability in an expanding universe. Independent of the degree of non linearity, the measured Euler number of the excursion set at the percolation threshold is positive and nearly equal to the number of isolated components, suggesting that these structures are trees. Their study of critical point counts reconciles the clumpy appearance of the density field at percolation level with measured filamentary local curvature. In the Gaussian limit, they found the 3D field percolates at threshold higher than 1sigma level, in contrast to widely held belief that percolation happens at 1sigma.

Szapudi, **Prunet**, **Pogosyan**, **Bond**, and Szalay (JHU) have proposed and implemented a fast, universally applicable method for extracting the angular power spectrum from CMB temperature maps by first estimating the correlation function. Their procedure recovers the C_l's using N^2 (but potentially $N \log N$), operations, where N is the number of pixels. This is in contrast with standard maximum likelihood techniques which require N^3 operations. This method makes no special assumptions about the map, unlike present fast techniques which rely on symmetries of the underlying noise matrix, sky coverage, scanning strategy, and geometry. This enables for the first time the analysis of megapixel maps without symmetries. The key element of the technique is the accurate multipole decomposition of the angular correlation function. The C_l error bars and cross-correlations are found by a Monte-Carlo approach. This technique was applied to a large number of simulated maps with Boomerang sky coverage, and it was shown that the technique provides an unbiased estimator of the C_l's. Even though the method is approximate, the error bars obtained are nearly optimal, and converged only after few tens of Monte-Carlo realizations. The published paper also discussed generalizations of the technique to a non-diagonal noise matrix, minimum variance weighting schemes, polarization, and higher order statistics.

Szapudi, in collaboration with Moore (CMU), Connolly (UPitt) and Nichol (CMU) present a new algorithm for the fast computation of N-point correlation functions in large astronomical data sets. The algorithm is based on kdtrees which are decorated with cached sufficient statistics thus allowing for orders of magnitude speed-ups over the naive non-tree-based implementation of correlation functions. They further address the use of controlled approximations within the computation which allows for further acceleration. In summary, our algorithm now makes it possible to compute exact, all-pairs, measurements of the 2, 3 and 4-point correlation functions for cosmological data sets like the Sloan Digital Sky Survey and the next generation of Cosmic Microwave Background experiments.

van Waerbeke, Hamana (IAP), Scoccimarro (IAS), Colombi (IAP), and Bernardeau (Saclay) have completed a study of the non-linear signal expected in cosmic shear surveys generated by the non-linear clustering of large scale structures. One aspect of this problem is studied in CITA-2000-48, where they compute the skewness of the convergence field using ray-tracing simulations (for different cosmological models), compared to the semi-analytical predictions based on an extension on the bi-spectrum in the non-linear regime (Scoccimarro). The results agree remarkably well, showing that we are already able to predict to a good accuracy (10%) the level of non-linearity in mass maps. Another aspect of the problem is the measurement of the non-linear signal itself on real data: this is know to be very difficult on reconstructed mass maps, because of the biases generated during the mass reconstruction process. With Francis Bernardeau and Yannick Mellier (IAP), **van Waerbeke** is developing a new estimator based on the shear 3-points function (which is directly measured on the data). This function would naively vanish for symetry reasons, and they are building an estimator which does not vanish but is also optimal for signal extraction.

van Waerbeke has continued a long-term project with Mellier (IAP), Radovich (Naples), Bertin (IAP), Dantel-Fort (Obs Paris), and other to measure the lensing effect by large scale structures. They obtained a cosmic shear measurement on two data sets: one is the VIRMOS-Descart lensing survey (16 $\deg^2$ in four colors, still in progress), and the other was obtained on the Very Large Telescope ANTU, and combined 0.64 $\deg^2$ of data over 1000 $\deg^2$ on the sky (astro-ph/0011251, 2001A&A...368..766). They measured for the first time various statistics simultaneously on the same data set: the shear top-hat variance, the aperture mass and the shear correlation function. They also provide a first estimate the mass density of the Universe Ω_M and of the normalisation of the mass power spectrum σ_8, which are in agreement with the cluster abundance constraints.

van Waerbeke, **Pen**, and Mellier (IAP) have investigated the decomposition of shear maps into E (Electric, i.e. curl free) and B (Magnetic, i.e. curl) modes. Gravity predicts only E mode to be non-zero on shear maps. Any B mode detection is an indication of the residual systematics amplitude in the data (either Point Spread Function correction residuals and/or intrinsic alignement effects). They find that the B mode contributes at most 20% of the E mode, which indicates a low level of residual systematics. Tools are developed which allows a fast and accurate computation of the different statistics from the shear 2-point function alone, as well as their noise matrices.

van Waerbeke, M. White (Berkeley), and J. Mackey (CfA) are investigating the statistics of peaks detected in shear maps. They have used ray-tracing numerical simulations to study how accurately the cluster mass function could be recover, from lensing selected peaks in a lensing survey. They have reached the pessimistic conclusion that the measured statistic suffers from several biases mixing observational and cosmological issues.

9.2 Galaxies and Dynamics

Dubinski and summer student Pritchard have developed a new code for following the evolution of systems of gravitating colliding hard spheres for studies of planetesimal accretion in the terrestrial region, planetary rings and asteroid and planetary collisions. The code has been tested on systems containing millions of particles and should push the field into a new regime of high resolution.

Robin **Humble** and collaborators have added a dusty gas phase model to a parallel asynchronous Smoothed Particle Hydrodynamics and N-body Tree code to enable direct modelling of dusty protoplanetary disks. Various gas-dust drag terms, viscosity formulations, initial conditions, dust masses and radii, and thermal properties of the gas disks are explored in order to determine the regime appropriate to planet formation. These are compared with linear analytic determinations of gravitationally instability timescales and modes.

It has been widely noted that the parent stars of planetary systems are metal rich. N. **Murray**, together with B. Chaboyer (Dartmouth) have been trying to decide if the high metallicities seen are primordial, or whether the stars have accreted metal rich material after reaching the main sequence. The best evidence that at least part of the effect is due to accretion is that the low mass stars that have planets are not as metal rich as the high mass stars with planets, as **Murray** and Chaboyer show. However, they point out that two selection effects, based on apparent V magnitude (it is hard to get good radial velocities for dim stars) and color (the current surveys discriminate against blue stars, since they have too few lines to determine radial velocity) could combine to produces this mass-dependent effect.

Unlike the planets in our solar system, most of the extrasolar planets discovered so far have very elongated, eccentric orbits. Furthermore, most of the extrasolar planets orbit much closer to their parent stars; apparently, they formed at distance comparable to the separation between Jupiter and the sun, and subsequently migrated inward. N. **Murray**, M. Paskowitz (CITA), and M. Holman (Harvard-CfA) have proposed that the large eccentricities arise as the migration proceeds. The migrating planets, which have masses comparable to those of Jupiter, capture smaller bodies and force them to migrate in lock step. The gravitational interactions between the two planets then drive up the eccentricity of both bodies.

Following up on a paper that appeared in Science magazine, B. Hansen (Princeton/UCLA), N. **Murray**, and M. Holman (Harvard-CfA) have been studying the interaction of a Jupiter mass planet with a massive planetesimal disk. Numerical simulations involving only two body interactions show that the massive planet efficiently ejects the smaller planetesimals, leading to an inward migration of the Jovian body. Simulations including several Jupiter mass bodies exhibit a variety of behaviors, depending on the initial location and mass of the large bodies. In most cases the planets repel each other, but in others two massive bodies may approach each other. In the latter case, the two planets may be locked into a resonance, so that both migrate inward keeping a fixed ratio of orbital periods.

It is widely believed that the asteroid belt originally contained 2-4 Earth masses of material; today it contains less than a Lunar mass. Mechanisms for the removal of this mass are not in short supply, but they all involve dropping about half the original mass onto the sun several hundred million years after the formation of the solar system. The surfaces of the terrestrial planets bear mute testimony to this process. A second indication that such a process occurred would be that the solar convective envelope, which has a mass only 2of the sun, would have a slightly higher iron abundance than the solar interior. Unfortunately, this enhancement is too small to be detected by helioseismology. N. **Murray**, together with B. Chaboyer (Dartmouth), P. **Arras** (CITA), B. Hansen (Princeton/UCLA), and R. W. Noyes (Harvard-CfA) realized that, if a similar process occurred around other stars, then those stars with smaller convection zones than the sun should appear more metal rich than stars with more massive convection zones. By looking at the spectroscopically determined iron abundances of 466 main sequence stars, they showed that such a stellar-mass dependent trend appears to be real, indicating that most stars in the solar neighborhood have accreted about one-half an Earth mass of iron.

Norm **Murray** has written a pedagogical article for Physics in Canada, describing recent advances in the understanding of chaotic motion in the solar system.

Norm **Murray** and M. Holman have written an invited review article for Nature, describing recent advances in our understanding of chaotic motion in the solar system.

Norm **Murray** with M. Lecar, F. Franklin, and M. Holman, has written an article for Annual Reviews which uses a simple analytic theory to explain why the planets are chaotic, and gives examples of chaotic motion in the asteriod and Kuiper belts, and in the motion of planetary satellites.

Among the 70 or so known extra-solar giant planets, many are so close to the host star that tidal dissipation have circularized their orbits. However, planet HD 83443b has the smallest semi-major axis yet has a substantial eccentricity. **Wu** and Goldreich (Caltech) have found that this is a result of forcing by the second, further out planet found in the system. Secular interactions combined with tidal evolution have delivered the two planets into periaps alignment, with eccentricities proportional to each other. The observed ratio of the two eccentricities can be reproduced, but only if one includes precessions due to general relativity, due to quadrupolar distortions related to tide and planet rotation. The authors also infer that the inner planet, with roughly Saturn mass, has to be at least as large as Jupiter. Moreover, the unique evolutionary state of this two-planet system allows one to constrain the rate of tidal dissipation in exoplanets.

9.3 The Interstellar Medium

Fiege, Matthews (McMaster) and Wilson (McMaster) have re-analyzed 850 micron SCUBA polarization data of OMC-3 region of the Orion A molecular cloud using improved software that was not available in 1998, when the data were taken. This region contains a bright filament that is partially fragmented into cores. Strong depolarization was observed toward the cores and along the spine of the filament. The polarization structure was modelled in detail using the technique outlined by Fiege and Pudritz (Ap.J, 2000, 544, 830), using their helical field model (Fiege & Pudritz, 2000, MNRAS, 311, 85). Excellent agreement with the data was obtained by bending the bottom part of the filament into a circular arc, and transforming the magnetic field self-consistently.

Fiege, Matthews and Moriarty-Schieven (JCMT) have used SCUBA polarimetry to map 3 star-forming systems of cores in Orion B. All 3 regions were found to contain polarization patterns that were indicative of highly ordered but non-uniform magnetic fields. Depolarization was found toward the bright cores in all 3 regions. NGC 2024 was the brightest and most interesting region mapped. 2 different models were proposed to account for the polarization data, and artificial polarization maps were computed for each model. Good agreement was found for a Fiege & Pudritz (2000, MNRAS, 311, 85) helical field model. Reasonable agreement was also found for a second model, in which the polarizing gas was assumed to be confined to a paraboloidal shell wrapped around the filamentary structure in NGC 2024. While the first model better explained the polarization data, the second model was in better agreement with existing independent Zeeman data.

Using an 850 micron SCUBA map of the dark globule CB068 – which contains a Class 0 Young Stellar Object (YSO) and an associated bipolar outflow – **Fiege**, Vallee (Herzberg) and Greaves (JCMT) have constructed a polarization model based on the Fiege & Pudritz model (2000, Ap.J., 534, 291) of magnetized prolate cores.

The formation and collapse of a protostar involves the simultaneous infall and outflow of material in the presence of magnetic fields, self-gravity and rotation. **Fiege**, in collaboration with Aburihan and Henriksen (Queens) and Lery (Dublin IAS), has used self-similar techniques to model self-consistently the anisotropic collapse and outflow. An exact, analytical solution was found, which may describe the simultaneous infall and outflow in young, magnetized protostars.

Powerful, highly collimated jets, surrounded by bipolar molecular outflows, are commonly observed near Young Stellar Objects (YSOs). The existing class of circulation models (Fiege & Henriksen, 1996, MNRAS, 281, 1038; Lery et al. 1999, AA, 350, 254) was extended by **Fiege** and collaborators Lery, Henriksen, Ray (Dublin IAS), Frank (Rochester) and Bacciotti (Arcetri). The new models involved joining together piecewise solutions for an accreting protostellar disk, a jet, and a wide-angle circulation region at intermediate polar angles.

Fiege & Henriksen are addressing the role of self-gravity in very young protostellar outflows, which often contain much more mass than the star forming at the centre. Their previous models used a central point mass and neglected self-gravity in the surrounding gas. Thus, the new models apply to a much younger stage of evolution. Early results indicate that the inclusion of self-gravity results in much more powerful outflows than have been found in their earlier central mass dominated circulation models.

Fiege & Lyutikov (McGill) are developing a time-dependent, self-similar model for the toroidal field driven formation and collapse of filamentary molecular clouds, taking into account self-gravity, magnetic fields, turbulent wave "pressure", and the dissipation of turbulence. Lyutikov & **Fiege** are working on a model for the injection of turbulent energy into the toroidal field-dominated filamentary molecular clouds. The basic idea is that m¿1 instabilities develop, which may lead to reconnection events, forming closed loops of toroidal flux. These sink though the plasma stirring up the turbulence in the process. Meanwhile, toroidal flux leaks into the filament from the surrounding gas to replenish the lost flux.

Martin is a permanent member of the scientific management of the Canadian Galactic Plane Survey, now expanded to form the International Galactic Plane Survey (IGPS). CGPS II is being carried out at the Dominion Radio Astrophysical Observatory and the newest thrust is an H I survey of the inner Galactic plane (first quadrant) using the Very Large Array (VLA). Rothwell has managed to carry out a lot of data reduction and has produced the first mosaiced spectral line data cubes in the H I line. Continuum mosaics from the end spectral channels are being used with infrared data to classify newly resolved continuum sources, some of which are supernova remnants.

The IGPS data base, covering all important constituents of the ISM, is particularly well suited to probing the responses of the ISM to the formation of massive stars. As part of her thesis with **Martin**, Karr (Toronto) has undertaken a major development of "intelligent" (pipeline) code for an extensive analysis of IGPS emission-line and continuum data. Her major goal is a statistical analysis of triggered star formation. A sidelight of her work has been production of a catalog of CO clouds which allows examination of how the size-linewidth relations in star forming regions compare to those from focused studies of more quiescent regions.

Compared to infrared images of star forming regions, submillimetre observations can reveal colder clouds of dust (and gas) in early stages of pre-stellar collapse. With JCMT/SCUBA observations of the KR 140 region **Martin**, Kerton (Herzberg), Johnstone (Toronto), and Ballantyne (Cambridge) have discovered a number of relatively cold submillimetre sources not visible in the IRAS data, ranging in size from 0.2 to 0.7 pc and in mass from 0.5 to 130 Msun. Several of the submillimetre sources are found at the H II molecular gas interface and have probably been formed as the result of the expansion of the H II region. Many of the submillimetre sources are gravitationally bound and most of these follow a mass-size relationship expected for objects in virial equilibrium with nonthermal pressure support. Interestingly then, not all stars in this region form at the same time.

Martin, Kerton and colleagues are examining the evolution of interstellar dust by exploiting the fact that different dust components have characteristic spectral emissivities. The HIRES-processed MIGA mosaics at 12 and 25 microns produced by Kerton and **Martin** trace transiently heated grains and PAH molecules and can be compared to complementary mosaics from data from the MSX mission and data anticipated from SIRTF. While MIGA provides a significant improvement in both resolution and image quality over previous IRAS infrared image products, the characteristics of the HIRES beam make accurate comparisons between the various IRAS bandpasses and between HIRES data and data at other wavelengths nontrivial. Kerton and **Martin** have presented a new, fast technique for the construction of HIRES beam-matched images that is especially well suited for the creation of large-scale (several square degree) ratio maps.

Key dust properties, like size distribution and chemical composition, show remarkable changes in different phases of the ISM. Far ultraviolet data from FUSE and HST on the extinction of starlight are being used by **Martin**, Wolff (SSI), and Clayton (LSU) to probe and constrain the properties of the small dust grains, such as abundance and size, and their connection to the very different environments observed. They are examining several types of sightline which possess distinct signatures associated with the small grain population and whose mid-UV extinction curves reveal vastly differing amounts of intermediate-sized particles.

The Orion Nebula is important in itself as a nearby star forming region, and because it provides a relatively simple nebular environment to test complex simulations. **Martin** is working intensely with a group (E. Verner, D. Verner and G. Ferland, Kentucky; J. Baldwin, MSU) investigating the Orion Nebula to derive a realistic model for the interaction geometry, dynamics, and emission-line spectrum. In this particular study, Verner and colleagues have identified the pumping routes that are responsible for the 40 [Fe II] emission lines that they have identified in recent high resolution and high signal to noise spectra.

Blagrave (Toronto), **Martin** and colleagues are using deep echelle spectra of the Orion Nebula to determine the line strengths and motions of key ions of oxygen, nitrogen, silicon, and iron. These sensitive measurements are making it possible to evaluate self-consistent models for the excitation mechanisms (fluorescence, recombination) of the faint permitted lines, the dynamics of the nebula, and its ionization structure.

Blagrave, **Martin** and colleagues have been focusing on what can be learned by combined analysis of co-spatial spectra from the ultraviolet, optical, and mid-infrared spectral regions. Modeling is being carried out using the photoionization code Cloudy to derive a realistic model for the interaction geometry, dynamics, and the entire emission-line spectrum. A thorough examination of abundances in the Orion Nebula will provide a critical benchmark for understanding distant extragalactic H II regions.

Rubin (NASA Ames), Ferland, **Martin** and colleagues have used HST/WFPC2 imagery for the planetary nebula (PN) NGC 7009 to evaluate the electron temperature (Te) and the mean-square Te variation across the face of the nebula. The preliminary map Te is rather uniform; almost all values are between 9000 – 10500 K, with the higher Te's closely coinciding with the inner He++-zone.

Unique diagnostics of the density, temperature, and velocity field in regions of star formation are provided by the quadrupole emission lines of molecular hydrogen (H2). Interpretation depends critically on collisional rate coefficients which **Martin**, Mandy (UNBC) and colleagues are calculating using quasiclassical trajectory techniques. As different reactions are explored, depending on different potential energy surfaces, it is important to check the QCT calculations where possible with quantum calculations (low energy and/or restricted geometry). This paper presents QCT calculations for the H2 + H2 system (H4 potential energy surface), contrasting the vibrational excitation behaviour seen in three restricted geometries.

Boothroyd (Caltech), **Martin**, and colleagues have completed their most recent potential energy surface (PES), in this case for the interaction of molecular hydrogen (H2) with H2. This 400-parameter fit spanning 6-dimensions was constrained by 48180 ab initio energies, 42079 newly calculated for this study. This PES represents a significant improvement over previous H4 surfaces, having an energy-weighted rms error of 1.15 millihartree relative to the 48180 energies, comparable to the estimated error in the energies themselves. The new PES also fits the van der Waals well to an accuracy of about 5

Boothroyd and **Martin** are completing a new potential energy surface for the interaction of helium with molecular hydrogen (He-H2) based on a large grid of ab initio energies they have calculated. The analytical fits optimized so far represent significant improvements over previous surfaces, having rms errors comparable to the estimated errors in the ab initio data. This will provide a sound basis for calculations of collisional rate coefficients.

Chris **Matzner** has argued that massive stars are the dominant sources of energy for the turbulent motions within giant molecular clouds, and that the primary agent of feedback is the expansion of H II regions (ionized nebulae). His work shows that the properties of the giant molecular clouds can be understood as an equilibrium between the input of energy by H II regions and its decay in turbulent motions, despite the fact that turbulence decays very rapidly. Such an equilibrium implies an evaporation rate, and therefore a lifetime, for clouds. This may explain the maximum cloud mass, since larger clouds would self-destruct more rapidly than they can be assembled. Clouds cannot be supported by H II regions in the high-pressure environments of starburst galaxies, and this may be related to the formation of massive star clusters in those galaxies.

Pogosyan and A. Lazarian (Wisconsin) have addressed a long-standing problem of obtaining statistics of interstellar turbulence from observational data using HI data as a test case of an optically thin line for which good data sets exist. They obtained the analytical description of the emissivity statistics in channel maps and on this basis developed a technique that allows to separate the contributions from density and velocity. The technique accounts both for turbulent and thermal velocities of emitting atoms. Together with Vazquez-Semadeni they successfully tested the technique using numerical simulations of compressible MHD flow. Their technique has been already applied to the Galactic and Small Magelanic Cloud data and it opens wide avenues for future research aimed at understanding interstellar turbulence.

Already in 1959, cosmic Rays have been suspected as having a climatic effect on Earth. A more recent discovery has shown that the galactic cosmic ray flux reaching Earth (which is modulated by the solar wind) is highly correlated with the low altitude cloud cover. This has led **Shaviv** to propose that passages through the galactic spiral arms, are responsible for the almost periodic appearances of ice-age epochs on Earth (each 150 Million years or so) – each time a spiral arm is crossed, a higher cosmic ray flux is responsible for a higher low altitude cloud cover and a reduce global temperature. Ample evidence was found to corroborate this picture: The expected periodicity in the spiral arms crossings, the periodicity observed in the cosmic ray flux variations as extracted from Iron meteorites and the periodicity observed in past Earth glaciation epochs all agree in period and in phase. Moreover, longer term global climate variations – such as the lack of glaciations between 1 and 2 billion years ago or their appearance between 2 and 3 billion years ago, were also found to correlate with the average star formation rate in the Milky Way.

van Hoof, Ferland, **Martin**, **Weingartner** and Volk (Calgary) have nearly completed the first major upgrade of the grain model in the photoionization-modelling code, Cloudy. Essentially every part of the code has been rewritten, resulting in a code that is much more flexible and yields more realistic predictions. The grain physics have been upgraded to the current state of the art. The user will notice the following improvements in the grain model. First, a Mie code for spherical particles has been included, giving the user complete freedom in choosing grain properties and size distributions. Second, size distributions can now be resolved to arbitrary precision, and physical properties are calculated for each bin separately. Third, non-equilibrium heating of the grains is now treated correctly for each size bin. A new grain charge model has been developed for Cloudy (CITA-2001-18). This new model enables a flexible approach to resolving the grain charge distribution. It allows the code to be efficient, while retaining sufficient accuracy at the same time. A refereed journal article applying the new model to the silicate emission in the Ney-Allen nebula is currently in preparation.

Weingartner and B.T. Draine (Princeton) have constructed size distributions for carbonaceous and silicate grain populations in different regions of the Milky Way, LMC, and SMC. These distributions include sufficient very small carbonaceous grains (including polycyclic aromatic hydrocarbon molecules) to account for the observed infrared and microwave emission from the diffuse interstellar medium, and also reproduce the observed extinction of starlight, which varies depending upon the interstellar environment through which the light travels. For several size distributions, they have evaluated the albedo and scattering asymmetry parameter, and have constructed model extinction curves extending beyond the Lyman limit.

Weingartner and B.T. Draine (Princeton) have modelled the photoelectric emission from and charging of interstellar dust, obtaining photoelectric gas heating efficiencies as a function of grain size and the relevant ambient conditions. Using their recently-constructed grain size distributions, they evaluated the net gas heating rate for various interstellar environments, finding less heating for dense regions than for diffuse regions. As one application of the model, they have found that photoelectric heating by dust can account for the observed variation of gas temperature with distance from the galactic midplane in the warm ionized medium.

Weingartner and B.T. Draine (Princeton) have modelled the forces on grains exposed to anistropic radation, due to the anisotropic emission of photoelectrons and photdesorbed adatoms. The "photoelectric" force depends on the ambient conditions relevant to grain charging. They find that this force is comparable to the radiation pressure when the grain potential is relatively low and the radiation spectrum is relatively hard. They adopt a simple, yet plausible, model for the surface physics and chemistry and find that the "photodesorption" force dominates the radiation pressure for grains larger than 0.1 microns exposed to starlight from OB stars. They also find that the anisotropy of the interstellar radiation field is of order 10visible and ultraviolet. They estimate size-dependent drift speeds for grains in the cold and warm neutral media and find that micron-sized grains could potentially be moved across a diffuse cloud during its lifetime.

With the high-resolution spectroscopy now available in the optical and satellite UV, it is possible to determine the neutral/ionized column density ratios for several different elements in a single cloud. Assuming ionization equilibrium for each element, one can make several independent determinations of the electron density. For the clouds for which such an analysis has been carried out, these different estimates disagree by large factors, suggesting that some process (or processes) besides photoionization and radiative recombination might play an important role in the ionization balance. One candidate process is collisions of ions with dust grains. Making use of their recent work quantifying the abundances of polycyclic aromatic hydrocarbon molecules and other grains in the interstellar medium, as well as their recent models for grain charging, **Weingartner** and B.T. Draine (Princeton) have estimated the grain-assisted ion recombination rates for several astrophysically important elements. They found that these rates are comparable to the rates for radiative recombination for conditions typical of the cold neutral medium. Including grain-assisted ion recombination in the ionization equilibrium analysis leads to increased consistency in the various electron density estimates for the gas along the line of sight to 23 Orionis. However, not all of the discrepancies can be eliminated in this way; they have speculated on some other processes that might play a role. They also noted that grain-assisted recombination of H^+ and He^+ leads to significantly lower electron fractions than usually assumed for the cold neutral medium.

Weingartner and B.T. Draine (Princeton) continue investigations of the alignment of grains with the interstellar magnetic field. Current work focuses on generalizing their previous treatment of the dynamics of irregular grains subject to torques due to the anisotropic starlight radiation field. With the new treatment, the evolution through periods of relatively slow grain rotation ("crossovers") can be followed. This will make possible a systematic study of the alignment efficiency as a function of grain size, shape, and composition. With these results, the model can be tested against observations of the wavelength dependence of starlight polarization.

9.4 High Energy Astrophysics and Stellar Physics

In rapidly rotating neutron stars, oscillation modes such as R-modes can become overstable through the emission of gravitational waves. The rotational energy of the star must be tapped in order to drive the mode and, as a result, the star can be spun down in a relatively short time. The gravitational radiation may be detected by LIGO. This mechanism has been proposed to limit the spins of accreting neutron stars in LMXB's, as well as rapidly rotating young neutron stars. A key parameter is the saturation amplitude of the mode. **Arras**, in collaboration with K. Schenk (UCSF), I. Wasserman, S. Teukolsky and E. Flannagan (Cornell) and S. Morsink (Alberta) are studying the nonlinear coupling of oscillation modes as a means of saturating the instability. When the R-mode reaches a critical amplitude, it will transfer energy to other modes at a rate which matches the driving rate. A simple estimate for the resulting saturation amplitude of the mode is (very roughly) 1/kappa*Q, where kappa is the size of the dimensionless interaction energy between modes and Q is the quality factor of the damped mode which couples to the R-mode. To obtain a more precise numerical result, **Arras** et al. are currently performing more detailed calculations of the nonlinear coupling, damping, and driving for the relevent modes.

Arras et al. have developed the mathematical formalism necessary to study linear and nonlinear oscillation modes in rotating stars, including the inertial modes and the usual p, g or f-modes. In rotating stars, the addition of the Coriolis force gives rise to a quadratic eigenvalue problem which determines the mode frequency and displacement field. The resulting oscillation modes are not orthogonal with respect to the usual inner product, and so a new inner product is devised. The time-dependent velocity field is then expanded in terms of the eigenmodes, and time-dependent equations for the expansion coefficients are found (correctly for the first time). **Arras** et al. have also derived formulae for the lowest-order nonlinear coupling between fluid waves in rotating stars. Several selection rules are identified governing the three-mode coupling of inertial waves. A time-dependent mode amplitude equation, including nonlinear coupling, is identified which can be put in a closely analogous form as in the case of a non-rotating star. Finally, the authors present an efficient numerical method for computing the nonlinear coupling coefficients.

There is one instance of a very weak gamma-ray burst (GRB) compellingly associated with a very enegetic supernova (SN). **Matzner**, Tan (Princeton), and McKee (Berkeley) propose that the GRB is a natural side product of such an over-energetic explosion, if the exploding star was compact and possessed a relatively dense stellar wind. For this to happen, a fraction of the SN energy must be channelled into relativistic ejecta as the SN shock front accelerates down the density gradient in the outer stellar envelope (as in the crack of a whip). Tan et al. study the process of shock acceleration across the transition to relativistic motion, and the continuing acceleration of ejecta as they expand into the region around a star, finding that previous works greatly underestimated the available energy of such ejecta. Also considered are the explosions of hypothetical "hypernovae" of extremely high energy, as well as the ejection of material from collapsing white dwarfs and neutron stars.

Mikhail **Medvedev** and Ramesh Narayan (Harvard) have discovered a new type of a hot, optically thin accretion flow onto a rapidly rotating neutron star or another compact object with a surface. This flow, called the "Hot Settling Flow", extracts rotational energy of the central star by viscous braking and radiates it via free-free emission. Unlike all other known accretion flows, the structure of a Hot Settling Flow and its luminosity are independent of the mass accretion rate, thus the flow may have a very large efficiency. The flow is cooling-dominated; it is convectively stable and may not have outflows. These results were confirmed by numerical models.

Mikhail **Medvedev** and Ramesh Narayan (IAS & Harvard) studied thermal conduction effects in hot accretion flows. Such flows are collisionless systems (because of a low density and a large temperature), thus the Spitzer theory fails. A theory of collisionless thermal conduction in tangled (MHD turbulent) magnetic field was considered. In application to known cooling-dominated (and hence thermally unstable) accretion flows, they demonstrated that thermal conduction cannot stabilize the Shapiro-Lightman-Eardley flow, but the newly discovered Hot Settling Flow is thermally stable in the presence of thermal conduction. This is crucial to prove that the flow can exist in nature.

Mikhail **Medvedev** and Norman **Murray** are studying the possibility that a Hot Settling Flow may form around a rapidly rotating black hole. The flow is torqued by a black hole via the Blandford-Znajek mechanism. Hence, it is natural to expect jet outflows in such systems as well. The model is applied to the galactic microquasars and dim galactic nuclei.

Mikhail **Medvedev** and Kristen Menou (Princeton) are studying the properties of hot accretion flows in several binary systems with a white dwarf as a primary, which experience regular outbursts separated by long quiescent phases. The study utilizes a numerical code written by **Medvedev**. Preliminary results indicate that a purely advection-dominated flow never forms, regardless of the star spin, whereas a hot settling flow exists around white dwarfs with sub-Keplerian rotation. The X-ray luminosity is a good indicator of an accretion rate in systems with slowly spinning stars, only.

In a series of papers Mikhail **Medvedev** elaborated the structure and properties of ultra-relativistic shocks which produce both prompt gamma-ray emission and delayed afterglows. He used the kinetic theory of plasma instabilities to demonstrate inevitable production of strong magnetic fields in such shocks and discussed their effects. He also elaborated the radiation mechanism operating in gamma-ray burst (GRB) shocks. He demonstrated that the synchrotron mechanism is unlikely given the structure of the shock and properties of the magnetic field. A newly discovered "Jitter" mechanism naturally explains several puzzles of spectra of prompt gamma-ray emission.

Mikhail **Medvedev** and George Rybicki (Harvard) finished the study of some very non-trivial properties of polytropic, self-gravitating systems. Such polytropes are often used as models of molecular clouds and stars. In particular, they found an approximate analytical solution of the Lane-Emden equation with the polytropic index close to 5. They also presented a continuous fraction approximation of a full solution.

N. **Murray** is one of a large number of workers involved in several observational efforts aimed at understanding outflows in quasars. For example, together with N. Arav (UC Berkeley) and others, he undertook a long STIS observation of PG 0946+301, a broad absorption line quasar. The absorption lines are not black, but they are clearly saturated, indicating that the outflow does not cover the continuum source. Consequently, the total column density of absorbing gas is much larger than would be inferred by a simple calculation of the optical depth based on the fraction of the continuum that is absorbed. The implication is that the outflow is much more massive than previous studies indicated, and more consistent with the large columns found by studies of broad absorption line quasars in the x-ray band.

Shaviv has been interested in luminous atmospheres shining close to and beyond the Eddington limit–The luminosity above which radiation pressure should be larger than the Gravitational pull. It was found that a super Eddington steady state could exist provided that inhomogeneities exist to reduce the effective opacity. This porosity naturally arises even in Thomson scattering atmospheres which were found to be unstable as they approach the Eddington limit. These super Eddington configurations were also found to have a predictable optically thick wind. This was applied successfully to explain the observed mass loss in classical nova eruptions and in the great eruption of the massive star eta Carinae. When combining the porous atmospheres with complete stellar structure equations incorporating nucleosynthesis, it was found that the core-mass-luminosity relation, which describes the luminosity of a degenerate object with shell burning Hydrogen, obtains a super-Eddington branch with a porous atmosphere. This branch naturally explains the super Eddington behavior seen in classical novae.

Shaviv and Heyl (Harvard) have been interested in the QED effects that the highly magnetized vacuum around neutron stars has on the propagation of photons. Since the vacuum is birefringent, the polarization state of photons evolves 'adiabatically' near the neutron stars. That is, a high energy photon (generally UV and beyond) emitted in one polarization state relative to the magnetic field direction will keep its polarization state up to a distance larger than the radius of the neutron star. The net result is that the vacuum birefringence tends to align together the polarization of the photons. Without it, the highly polarized light emitted from different surface elements will add up 'incoherently', to yield a small observed polarization. With the polarization alignment, large net polarizations are obtained. This allows more information to be extracted on the NSs. For example, the circular polarization obtained yields information non dipolar fields.

Thompson and **Murray** have considered the amplification and transport of a magnetic field in the collapsed core of a massive star, including both the region between the neutrinosphere and the shock, and the central, opaque core. A dynamical balance between turbulent and magnetic stresses within convective layers (both inside the star, and in the accreting envelope material) leads to flux densities of order ten to the fifteenth Gauss. Buoyant motions of magnetized fluid are greatly aided by the intense neutrino flux, and are calculated in the various regions of the core. The implications of these results for pulsar magnetism were investigated and applied to the case of late fallback over the first one thousand to ten thousand seconds of the life of a neutron star.

Thompson and Robert Duncan (U. Texas Austin) made a detailed comparison of the magnetar model with the extraordinary X-ray/gamma-ray flare recorded from the Soft Gamma Repeater 1900+14 on August 27, 1998. They proposed a triggering mechanism, whereby a helical distortion of the core magnetic field induces large-scale fracturing in the crust and a twisting deformation of the crust and exterior magnetic field. The envelope of the pulsating tail of the August 27 flare can be accurately fit, after ~ 40 s, by the contracting surface of a relativistically hot, but inhomogeneous, trapped fireball. The effects of direct neutrino-pair emission were quantified, thereby deducing a lower bound $\sim 10^{32}$ G-cm^3 to the magnetic moment of the confining field. The radiative flux during the intermediate ~ 40 s of the burst appears to exceed the trapped fireball fit – probably as the result of continuing seismic activity. This motivated a detailed analysis of the thermal stability of a confined thermal pair plasma in a super-QED magnetic field, and the critical heating rate above which there is a runaway to an ultrahot plasma (T ~ 1 MeV) in local thermodynamic equilibrium. In the later pulsating tail, the best fit temperature equilibrates at a value which agrees well with the regulating effect of photon splitting. The remarkable four-peaked substructure within each 5.16-s pulse provides strong evidence for the presence of higher magnetic multipoles in SGR 1900+14. The corresponding collimation of the X-ray flux has been related to radiative transport in a super-QED magnetic field.

Thompson, Maxim Lyutikov (McGill) and Shri Kulkarni (Caltech) have calculated the structure of a neutron star magnetosphere which is threaded by large-scale electrical currents, and the effect of resonant Compton scattering by the charge carriers (both electrons and ions) on the emergent X-ray spectra and pulse profiles. In the magnetar model for the SGRs and AXPs, these currents are maintained by magnetic stresses acting deep inside the star. They show, by constructing force-free equilibria with a power law dependence of magnetic field on radius, $B \propto r^{-2-p}$, that a large-scale twist softens the radial dependence to $p < 1$. The spindown torque acting on the star is thereby increased in comparison with a vacuum dipole, and the polar field deduced from spindown measurements might be reduced by a factor 3-10 with respect to a vacuum dipole in some of the SGR and AXP sources. Consideration of the stability of the twist may provide an explanation for the narrow measured distribution of spin periods. A magnetosphere with a strong twist has an optical depth ~ 1 to resonant cyclotron scattering at the magnetic equator, independent of frequency (radius), surface magnetic field strength, or charge/mass ratio of the scattering charge. When electrons and ions supply the current, the stellar surface is also heated by the impacting charges at a rate comparable to the observed X-ray output of the SGR and AXP sources, if the polar dipole field is $\sim 10^{14}$ G. Redistribution of the emerging X-ray flux at the ion and electron cyclotron resonances will significantly modify the emerging pulse profile. The non-thermal spectral tail generated through the Doppler effect is being calculated using a Monte Carlo approach. The sudden change in the pulse profile of SGR 1900+14 after the 27 August 1998 giant flare is related to an enhanced optical depth to electron cyclotron scattering, resulting from a sudden twist imparted to the external magnetic field.

van Hoof has continued a long-term collaboration with G. Van de Steene (RO Belgium), Peter Wood (RSAA Australia), P. **Martin** and G. Ferland (Kentucky), to establish a sampleR of infrared-selected post-AGB stars and study their properties. In 2000 and 2001 papers were published discussing near-infrared spectroscopic and photometric observations of these objects (CITA-2000-31, CITA-2000-59). A paper discussing the H alpha (an optical atomic transition of hydrogen) P-Cygni profiles (a type of emission line indicating severe mass loss) in some of these objects was published as well, refuting the commonly held idea that the wings in these lines were caused by electron scattering (CITA-2000-47). They recently obtained high-resolution echelle spectra with UVES on the VLT at ESO Paranal. Analysis of these data is currently underway, and will be aimed at obtaining mass loss parameters for these objects. Only very few post-AGB stars have known mass loss rates, and this sample will be a valuable addition.

Yanqin **Wu** and P. Goldreich (Caltech) have recently made some significant progress toward understanding the saturation of pulsations in a broad range of variable stars. They have found some simple scaling relations that discriminate between stars that have large pulsation amplitudes (RR Lyraes, Cepheids, Miras, etc.) and stars that do not (white dwarfs, subdwarf-B stars, some δ-Scuti stars, rapidly oscillating Ap stars, etc.). These scaling laws arise from the ability or inability for an unstable modes to couple effectively to damped modes. Stars that have large central-to-mean density ratios (giants) are likely to have large pulsation amplitudes, while those with mall ratios (dwarfs) should display small amplitudes. These results compare well with observations and are being prepared for publication.

Wu and van der Swaluw (Belfast) have proposed a method to infer the initial spin periods of radio pulsars residing in composite supernova remnants. This type of remnant consists of both a plerionic and a shell-type component, corresponding to the pulsar wind nebula driven by the spin-down luminosity of the central pulsar, and the blast wave bounding the supernova remnant. At some 1000-10,000 yrs after birth, a simple scaling law connects the relative radii of the two components with their relative energy content. One can use this scaling law to estimate the initial spin periods of pulsars residing in composite remnants, since the energy content of the plerion depending on the initial spin periods. Their analysis show that all pulsars in their sample are likely born with spin-rates well below break-up, and an early braking mechanism like r-mode instability is unlikely to operate.

Gamma-Doradus variables are early F-type dwarfs that pulsate with periods from 0.4 to 3 days, and with amplitudes below 0.1 magnitude. The pulsations are associated with non-radial gravity-modes. Yanqin **Wu** has shown that surface convection zones in these variables can drive pulsation via the 'convective driving' mechanism. This mechanism was first proposed and studied in the context of ZZ Cetis (hydrogen-envelope white dwarfs with g-mode pulsations) by Brickhill (1991) and Goldreich & **Wu** (1999). Here, it is applied to the different internal properties of gamma-Dors, which have a stronger super-adiabatic gradient and a weaker convective flux than white dwarfs. This leads to a spectrum of gravity-modes being excited in the observed temperature range. This explanation for the pulsation excitation is, however, still subject to uncertainties that need to be resolved, e.g., the roles of fast rotation and convective overshoot.

9.5 Early Universe

Andrei **Frolov** and Lev **Kofman** studied the behavior of a light cosmological scalar field (quintessence) in the strong gravitational field near a black hole. An analytical approximation of the field dynamics was developed and its accuracy confirmed by numerical calculations. They found that the field profile is merely delayed, not frozen, on the horizon, and that the long-range tails are formed outside the horizon because of the stiffness of the light scalar field. The rate of accretion of such fields by a black hole was calculated.

Andrei **Frolov** and Lev **Kofman** are working on brane-world models of the Universe. They developed a conformal transformation formalism that significantly simplifies the study of brane and bulk geometry and allows analytical treatment of a wide class of brane-world solutions. In particular, the Randall-Sundrum model is reduced to a flat manifold with empty boundaries. This formalism allows one to construct exact brane-world solutions with induced brane-world metric being an arbitrary Einstein spacetime. They also used this approach to derive and solve gravitational perturbation equations for such brane-world models. The normal four-dimensional gravitational waves are recovered as the zero mode of decomposition, while the higher-dimensional modes acquire effective 4D mass in a way similar to Kaluza-Klein theory.

9.6 Computational Astrophysics

Arras, **Wu** and **Pen** have developed an efficient numerical method to compute fluid oscillations in rotating stars. This method makes a limited number of approximations: (1) the background star has negligible centrifugal flattening; (2) the perturbations are adiabatic; (3) the Cowling approximation; and (4) the stellar rotation is uniform. The linearized Euler and continuity equations are solved including an external forcing term and a freely specified equation of state. As a result, any ratio of Brunt-Vaisalla and rotation frequencies is allowed, and compressibility effects are included. The equations are differenced on a grid of radius and polar angle, since the oscillation equations are not separable in these two coordinates. The code can be used to find the fluid response for a given external (e.g. tidal) forcing. In addition, **Arras** et al. have developed an efficient way of searching for eigenmodes using the inverse power iteration method, requiring just a few iterations per mode. A multigrid iteration scheme is under development (for a matrix which is not diagonally dominant, symmetric, or positive definite), which promises at least an order of magnitude better resolution.

In an ongoing project, **Dubinski** Koranyi (Harvard) and Geller (Harvard) have been studying the interactions of thousands of spiral galaxies in cosmological N-body simulations of cluster formation to understand the dynamics of clusters and the origins of the elliptical galaxies and the fundamental plane relations.

Dubinski, Kim (Seoul), Park (Seoul), and **Humble** have developed a new hybrid N-body code which combines the particle-mesh and treecode algorithms. The code is parallelized and has been used to run 134-million-particle simulations of structure formation.

Dubinski and summer student Aurelie Neveol have developed new software for the visualization of N-body simulations. The new software piggybacks on existing simulation software and produces image sequences from static and dynamic cameras immersed within the simulations producing exciting visual effects. The software is being used to produce High Definition Television animations of colliding galaxies and dynamically evolving galaxy clusters for NHK Television in Japan for an ongoing series in astronomy. **Dubinski** is featured in one program and discusses the fate of the Milky Way and Andromeda galaxies.

Dubinski, Brinkman (MPI) and Abraham (Toronto) are reviving the sticky particle method to treat star formation in young galaxies. A subset of particles are labelled as clouds and direct collisions are followed and assumed to induce star formation with a given efficiency. The code allows a detailed star formation history of a galaxy at high resolution. The results of these models can be fed into observational simulation software developed by Brinkman and Abraham for making direct predictions about the morphology and brightness of galaxies in different apertures.

Masters student O'Neill and **Dubinski** are re-examining the formation of bars in galactic disk and issues surrounding the buckling instability and its connection to bulge formation as well as dynamical friction drag on bars from the dark halo.

Garcia-Ruiz and Kuijken (Kapteyn) with **Dubinski** have shown that the warp of the Galaxy is not generated by direct tidal forcing or tidal amplification from the galaxy halos as suggested by some researchers. The source of the warp remains a puzzle.

Temperature profiles were determined by **Loken** and collaborators M. Norman and E. Nelson (UCSD), J. Burns (Missouri), A. Klypin (N.M. State), G.L. Bryan (MIT) and P. Motl (Missouri) for two samples of numerically-simulated galaxy clusters (in low density CDM and standard CDM cosmologies) and it was shown that they agreed remarkably well with the non-isothermal profiles claimed by Markevitch et al. (1998) from their ASCA analysis.

Chris **Loken** and collaborators P.L. Gomez (Carnegie-Mellon), K. Roettiger (Missouri), and J.O. Burns have performed a series of 2D simulations of the merger of a cooling flow cluster with an infalling subcluster. They found that the ram-pressure of the infalling gas is crucial in determining the fate of the cooling flow as disruption occurs when a substantial amount of subcluster gas reaches the primary's core. It was shown that, even in the case of disruption, a cluster can be classifed as a cooling flow and also exhibit substructure. The results make it possible to reconcile the high cooling flow frequency inferred by some observations with both high merger rates and a high frequency of substructure.

Chris **Loken**, C.A. Metzler (CfA) and M. White (CfA) used large-scale numerical simulations of structure formation in a lambda-dominated cold dark matter model to quantify the effect that large-scale structure near clusters has upon the cluster masses deduced from weak lensing analysis. It was concluded that a correction for the scatter in possible observed lensing masses should be included when interpreting mass functions from weak lensing surveys.

Pen and Trac (Toronto) are building a dedicated out-of-core machine, funded by the Canada Foundation for Innovation, which has 10 Terabytes of virtual memory with a bandwidth of 6 Gigabytes/second. This device will be sufficient for direct cosmological simulations of gas and dark matter on three-dimensional grids five thousand cells wide.

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