

University of Toronto
Canadian Institute for Theoretical Astrophysics
Toronto, Ontario M5S 3H8

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The following is an abbreviated version of the 1996 CITA Annual Report. Due to space constraints, we have not included more than a very brief summary of the scientific activities at CITA in 1996. The full report is available on request (from citadmin@cita.utoronto.ca) or on the web at <http://www.cita.utoronto.ca>.

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 Doug Johnstone, John Dubinski, and Robert Malaney.

Research at CITA covers a broad range of fields in astrophysical theory. In 1996 the areas of study included:

cosmology: early universe, inflation, cosmic defects, big bang nucleosynthesis, microwave background anisotropies, large-scale structure, gravitational lensing, galaxy formation, Lyman alpha clouds;

intergalactic and interstellar medium: dust physics, molecular clouds, star-forming regions;

dynamics: galactic warps, globular clusters;

stars and compact objects: accretion disks, stellar winds, white dwarf cooling, stellar ages;

planetary systems: chaos, asteroid belts, long-period comets, extra-solar planets:

2. PERSONNEL

The research staff of CITA for the year 1996, along with their primary research interests, is listed below. (Notes: †has left CITA during 1996; ‡joined CITA during 1996.)

2.1 CITA Faculty

J. R. Bond, Professor and Director (after June 30) (Ph.D. Caltech, 1979) - *Cosmology: Very Early Universe, Evolution of Cosmic Structure, Dark Matter, Cosmic Background Radiation, Particle Theory*

N. Kaiser, Professor (Ph.D. Cambridge, 1982) - *Cosmology, Early Universe, Large Scale Structure, Galaxy Formation, Galaxy Clusters, Gravitational Lensing*

P. G. Martin, Professor (Ph.D. Cambridge 1972) - *Interstellar Matter; H₂: Collisional Rate Coefficients, Galactic Plane Survey; H II Regions: Orion, Chemical Abundances; Dust: Interstellar Polarization*

N. W. Murray, Assistant Professor (Ph.D. UC Berkeley 1986) - *Active Galactic Nuclei, Cataclysmic Variables, Solar System Dynamics, Helioseismology*

S. Tremaine, Professor and Director (to June 30) (Ph.D. Princeton 1975) - *Stellar Dynamics, Galactic Structure, Solar System Formation and Dynamics, Comets*

Changes In 1996

Scott Tremaine finished his second term as Director on June 30, 1996. Dick Bond became Director for a 5 year term beginning July 1.

2.2 Senior Research Associates 1996

R. A. Malaney (Ph.D. St. Andrews 1986) - *Nuclear-Neutrino Astrophysics and Cosmology*

D. Yu. Pogosyan (Ph.D. Tartu 1990) - *Cosmology, Large-scale Structure, Microwave Background Radiation*

2.3 Research Associates 1996

P. J. Armitage‡, (Ph.D. Cambridge 1996) - *Accretion Disks, Star Formation, Computational Hydrodynamics*

S. Basu‡, (Ph.D. Illinois 1993) - *Star Formation, Interstellar Medium, Solar Physics*

B. C. Chaboyer‡, (Ph.D. Yale 1993) - *Stellar Evolution, Stellar Populations, Galaxy Formation*

J. Chiang‡, (Ph.D. Stanford 1993) - *Broad Line Regions of QSOs; Line Emission from Cataclysmic Variables*

S. Colombi‡ (Ph.D. I.A.P., Paris 1993) - *Cosmology, Large-scale Structure, Statistics, N-body Simulations, Perturbation Theory*

R. G. Crittenden‡, (Ph.D. Pennsylvania 1993) - *Cosmology, Large-scale Structure, Microwave Background Radiation, Cosmic Defects*

J. Dubinski‡, (Ph.D. Toronto 1991) - *Cosmology, Galaxy Dynamics and Formation, Parallel N-body and hydro codes*

A. Jaffe‡ (Ph.D. Chicago 1994) - *Cosmology, Large-scale Structure, Statistics, Particle Astrophysics*

D. Johnstone, (Ph.D. Berkeley 1995) - *Destruction of Proto-Planetary Disks, Star Formation, Globular Clusters, Galactic ISM*

B. M. S. Hansen‡, (Ph.D. Caltech 1996) - *Stellar Evolution: White Dwarfs and Pulsars, Globular Clusters, Galactic Halo*

M. J. Holman, (Ph.D. MIT 1994) - *Nonlinear Hamiltonian Dynamics, Solar System Dynamics, Asteroids, Comets, Extra-solar Planets*

L. Knox, (Ph.D. Chicago 1995) - *Cosmology, Early Universe, Large Scale Structure, Cosmic Microwave Background*

S. J. Magorrian, (D.Phil. Oxford 1995) - *Galactic and Stellar Dynamics*

C. Murali‡, (Ph.D. UMass-Amherst 1996) - *Stellar Dynamics, Globular Cluster Evolution, Milky Way Structure, Galaxy Formation*

J. R. Murray, (Ph.D. Monash 1995) - *Computational Fluid Dynamics, Smoothed Particle Hydrodynamics, Magnetohydrodynamics, Fluid Instabilities, Magnetic Fields in the Early Universe, Accretion Disks, Cataclysmic Variables*

K. P. Rauch, (Ph.D. Caltech 1995) - *Stellar Dynamics, Relativistic Astrophysics, Active Galactic Nuclei, Gravitational Lensing*

D. C. Richardson,[†] (Ph.D. Cambridge 1993) - *Solar System Formation and Dynamics, Planetary Rings, Fractal Aggregates, Tree Codes, Data Visualization*

R. Scoccimarro[‡], (Ph.D. Chicago 1996) - *Cosmology, Large Scale Structure, Non-Linear Dynamics, Perturbation Theory*

T. Souradeep (Ph.D. IUCAA 1995) - *Cosmology, Large-scale Structure, Microwave Background Radiation, Early Universe*

J. R. Touma[†] (Ph.D. MIT 1993) - *Solar System Dynamics, Galactic Dynamics*

J. C. Tsai[†] (Ph.D. MIT 1992) - *Clusters of Galaxies, Dust in Elliptical Galaxies, Star Formation*

G. Wilson[‡], (Ph.D. Durham 1996) - *Weak Gravitational Lensing by Clusters of Galaxies, Cluster Luminosity Functions*

Although the bulk of the support for CITA's research staff comes from our NSERC Collaborative Special Program grant and from research grants to individual faculty members, support also came from NSERC Postdoctoral Fellowships (Chaboyer, Johnstone, Richardson).

Changes In 1996

Eight new staff joined CITA in 1996: P. J. Armitage (Cambridge University), S. Basu (Michigan State University), R. G. Crittenden (University of Pennsylvania), J. Dubinski (UC Santa Cruz), B. M. S. Hansen (Caltech), C. Murali (UMass-Amherst), R. Scoccimarro (University of Chicago), and G. Wilson (University of Durham). They joined senior research associate Robert Malaney, and research fellows Matthew Holman, Douglas Johnstone, Lloyd Knox, John Magorrian James Murray, Kevin Rauch and Tarun Souradeep. Dmitry Pogosyan became a Senior Research Associate.

A number of our research fellows left during the past year. Brian Chaboyer took up a Hubble Fellowship at the University of Arizona, James Chiang took up a Postdoctoral Fellowship at the Naval Research Laboratories, Andrew Jaffe took up a Postdoctoral Fellowship at the Center for Particle Astrophysics at Berkeley, Derek Richardson took up a Postdoctoral Fellowship at the University of Washington, Jihad Touma took up the Harlan J. Smith Postdoctoral Fellowship at the McDonald Observatory at Texas, and John Tsai became an analyst for Long-Term Capital Management. Stephane Colombi took up a faculty position at the Institut d'Astrophysique de Paris. He will return as a long term visitor to CITA.

2.4 National Fellows 1996

A program started in 1988 solicits nominations from universities across Canada for "CITA National Fellows."

These are research fellows who are jointly supported by CITA and the nominating university; although they work primarily at the nominating university, visits to CITA and collaboration with CITA staff are encouraged. CITA Council awards these fellowships using the same selection criteria as those for CITA research fellowships. The National Fellows in 1996 were:

M-H. Lee (Ph.D. Princeton 1991), held at Queen's University (1995-1997).

D. Craig (Ph.D. 1996, UC Santa Barbara), held at the University of Alberta (1996-1998).

Y. Gusev (Ph.D. 1996, Manitoba), held at the University of Alberta (1996-1998).

M. Hudson (Ph.D 1993, Cambridge), held at the University of Victoria (1995-1997).

2.5 Supervised Graduate Students

Faculty and research fellows have been involved in the supervision of several graduate students from the University of Toronto:

M. Casey (Norm Murray), Astronomy
H. Dahle (Nick Kaiser), Astronomy
C. Kerton (Peter Martin), Astronomy
J. Wadsley (Dick Bond), Astronomy
P. Wiegert (Scott Tremaine), Astronomy

2.6 Summer Student Research Program

CITA instituted a highly successful summer student research program this year, which brought undergraduates from a number of Canadian universities to CITA to work with Faculty and Research Associates. This year's participants were

David Charbonneau (Toronto)
Mike Gladders (University of Victoria)
Brian Ingalls (Dalhousie)
Martin Landriau (Université de Montréal)
Ariel Phillips (McGill University).

In addition, Dave Ballantyne was a co-op undergraduate student from Victoria in the Fall.

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.

3.1 Senior Visiting Fellows 1996

Hugh Couchman (University of Western Ontario)
Dick Henriksen (Queen's University)
Michael West (Saint Mary's University)

3.2 Long Term Visitors

H. Bi, Johns Hopkins University
M. Fich, Waterloo
P. Goldreich, Caltech
M. Mandy, University of Northern British Columbia
R. Pudritz, McMaster

L. Widrow, Queen's University

3.3 Shorter Term Visitors

In addition there were over sixty short term visitors to CITA in 1996.

4. CIAR AND CITA

The **Canadian Institute for Advanced Research (CIAR)** supports a number of Programs chosen for their high intellectual promise and interdisciplinary character. The CIAR Cosmology Program has nodes at UBC (Fellows Bill Unruh and Ian Affleck), at the University of Alberta (Fellows Valery Frolov, Werner Israel and Don Page) and at CITA, where Dick Bond and Nick Kaiser are CIAR Fellows. There is also a large distinguished network of CIAR Associates of this Program around the world. The Program went through its second five year review and received an excellent rating by an international review committee. The CIAR Board voted to continue the Program for another five year period. On July 1, Scott Tremaine joined the Program as the IMASCO Fellow and became its Director for a 5 year term, taking over from Bill Unruh, who had served two times as Director. In recognition of expanded interests of the Fellows, the Program was renamed Cosmology and Gravitation. 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.

5. SACKLER VISITING ASTROPHYSICIST

CITA has recently received a generous gift from the Raymond and Beverly Sackler Foundation to endow the **Raymond and Beverly Sackler Visiting Astrophysicist Program**. Each year CITA will invite an internationally distinguished scholar conducting research in theoretical astrophysics to give two lectures at the University of Toronto. The researcher will also meet 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 first Raymond and Beverly Sackler Visiting Astrophysicist will be Sir Martin Rees from Cambridge University. He will visit CITA from June 9 - 11; among his other activities he will give a public lecture titled "How Much Can You Believe of What Cosmologists Say?"

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 1996 were:

The Kuiper Belt, June 7-8 1996, Toronto, (organizers: M. Holman and S. Tremaine)

Cosmology: The Big Picture, August 8-10 1996, Iqaluit, (organizers: G. Starkman and S. Tremaine)

The Naramata Summer School on the Interstellar Medium, August 25-29, 1996, Penticton, (organizer: A. Gray)

Kingston Meeting: Computational Astrophysics, October 1996, Halifax (organizers: D. Clarke and M. West)

7. FACILITIES

CITA occupies the 12th floor of the McLennan Physical Laboratories at the downtown campus of the University of Toronto.

CITA's primary compute servers are Digital Alpha systems. A 64 Mbyte 3000/400S and a 256 Mbyte 3000/500S were the first two acquired (1993). CITA and CITA grantholders also own a 63% share in a pair of four-CPU AlphaServer 2100 systems (256 Mbyte and 1024 Mbyte) acquired in late 1994. The larger system was upgraded from a model 4/200 to a 5/250 in 1996, approximately doubling its computational power for most applications.

The compute servers are supplemented with a network of four Alpha workstations, eleven Silicon Graphics Indigos and Personal IRISes, eight Sun SPARCstations, a Pentium running linux, and approximately a dozen X terminals. The SGI systems are used to support research activity demanding 3-D scientific visualization. The disk capacity available to the network currently exceeds 100 Gbyte.

All CITA offices have been provided with fiber-optic and category 5 copper cabling, to provide a framework for higher-bandwidth network connections. A 100Base-TX hub and three fully-switched 10Base-T hubs were installed in 1996, replacing our old thinwire network. We now have a direct fiber connection to a campus router.

Acquisitions include a Tektronix dye-sublimation color printer, for producing high-quality color prints and transparencies; a Canon bubblejet printer, for low-cost color output; an HP LaserJet 5 Si/MX printer, for high-speed (and double-sided) printing; an HP color scanner, for digitizing images and OCR processing of textual data; and a DLT tape drive for high-speed, high-capacity backups.

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 seven members, five selected from the CITA Inc. membership of over 50 researchers in cooperation 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 1996 were:

Richard Bond, CITA Director
 John Britton (Vice-Dean, School of Graduate Studies, University of Toronto)
 Hugh Couchman, University of Western Ontario
 Werner Israel, University of Alberta
 Richard Henriksen, Queen's University
 George Mitchell, St. Mary's University, Chair
 Ralph Pudritz, McMaster University

9. SCIENTIFIC OVERVIEW 1996

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 provide a brief summary of the scientific activities at CITA in 1996. The full report is available (from citadmin@cita.utoronto.ca and on the web at <http://www.cita.utoronto.ca>).

9.1 Cosmology

In the 1990's, cosmology has evolved into a mature, detailed science pushed forward by an enormous amount of observational data. Research in cosmology at CITA covers most areas of current interest including studies of the early universe and the origin of the primordial density fluctuations (**Bond, Knox, Levin, and Souradeep**), the connection to the cosmic microwave background (CMB) temperature fluctuations and the nonlinear evolution via gravitational collapse into galaxies, clusters of galaxies and large-scale structure.

Bond, Crittenden, Jaffe, Knox, Pogosyan, and Souradeep, are involved in establishing and calculating the cosmological constraints that precise measurements of the CMB fluctuations will allow. Measurements from future satellites and ground-based experiments will constrain the fundamental cosmological parameters and the topology of the universe. **Knox** is a co-investigator on the MSAM Tophat balloon-borne experiment to measure CMB anisotropy.

The size and depth of galaxy redshift surveys will increase dramatically in the next few years and new statistics on the large-scale distribution of galaxies will be available for direct comparison to cosmological theories. CITA researchers are advancing the Cosmic Web paradigm (**Bond and Pogosyan**) and studying the observability of these structures by weak-lensing, secondary CMB fluctuations (Sunyaev Zel'dovich effect), and x-ray emission (**Bond, Wadsley, and Pogosyan**). Other studies at CITA include, analysis of gravitational instability in mildly non-linear regimes (**Scoccimarro, Colombi, Couchman, and Pichon**), simulations of Lyman-alpha absorption at high redshift (**Bond and Wadsley**), and development of sophisticated N-body and hydrodynamic codes for simulating the complex interplay between gravity, gasdynamics, atomic physics and magnetic fields (**Bond, Wadsley, J. Murray, Dubinski, Malaney, and Couchman**). The main problems that are being tackled with these codes are the evolution of the Lyman- α forest, the formation of galaxy clusters, and the study of galaxy interactions in merging pairs and in clusters. Some of these codes have been adapted for parallel processing (**Dubinski**) and can take advantage of a multi-processor architecture.

Gravitational lensing (**Kaiser, Squires and Wilson**) provides an independent method for mapping the mass distribution of clusters of galaxies and the large-scale structure. The mass of a cluster acts as a distorting lens according to Einstein's theory of general relativity and images of distant background galaxies are stretched and sheared in a predictable way. The **Kaiser and Squires** method for using this distortion to determine the mass distribution has been applied to several galaxy clusters including one massive cluster

at a redshift $z=0.82$. The determined masses are somewhat higher than predicted by galaxy kinematics and X-ray halos in clusters. The technique is still undergoing refinements and holds the promise of being an independent measure of the large-scale structure.

9.2 Galaxies and Stellar Dynamics

Understanding the complexity and richness of Newtonian mechanics and gravity in stellar systems such as galaxies and dense star clusters is another major focus of research at CITA. There are still many open problems on the dynamics of disk galaxies, globular clusters and galactic nuclei. Research focuses on the effect of dark halos on galactic disks and interacting galaxies (**Dubinski**), stability analysis and distribution functions for observed galactic disks (**Pichon**), and the evolution of stellar clusters in the center of galaxies with massive black holes (**Tremaine, Rauch, and Magorrian**). CITA researchers are determining black hole masses in a systematic way and the distribution is found to correlate well with galaxy total mass and brightness (**Tremaine and Magorrian**). The evolution of globular clusters and Galactic satellites also continue to be investigated (**Tremaine, Murali, West, and Johnstone**).

9.3 The Interstellar Medium

At CITA, active research on chemical processes in the ISM continues (**Martin and Kertin**). Fundamental analysis of collision cross-sections between hydrogen molecules in ISM settings will aid in determining the rate of excitation of this most abundant molecule. Determination of the chemical enrichment of star-forming clouds from observations of spectral lines has resulted in constraints on the iron content within the Orion nebula.

Computations of the collapse of magnetized cloud cores and the initial growth of stars produce a dynamic mass accumulation rate an order of magnitude larger than predicted by equilibrium theory (**Basu**). Magnetic fields in the Galaxy may also aid in the formation of dense star-formation sites based on models of the Parker instability, a process which funnels initially diffuse gas into small dense regions (**Basu**). Combining theory with multi-wavelength observations, including the neutral hydrogen radio survey of the Galactic Plane (CGPS) being undertaken at DRAO, is leading to insights on the modes of star formation and the environment surrounding star-formation sites (**Martin, Basu, Johnstone, Kertin, and Ballantyne**). **Pogosyan** has drawn attention to statistical properties of large-scale filamentary structure in the Galactic neutral hydrogen.

9.4 Stars and Compact Objects

While much is understood about the basic structure and evolution of stars, there are still many fundamental questions left unanswered. A number of the questions relate to associated circumstellar material occupying disk-like structures around many stars. Research at CITA has focused on warps in these disks, the interaction of stellar magnetic fields with disks, accretion through disks, and disk destruction (**Armitage, J. Murray, and Johnstone**). As disk material flows

towards the star, it heats, producing an outburst of luminosity. Recent CITA research provides evidence that superoutbursts occur when the disk becomes tidally unstable. Some disks produce distinct emission line features which can be attributed to disk winds, providing insight to their energetics and structure (**N. Murray** and **Chiang**). Using recent Hubble Space Telescope images of the Orion star-forming region, the hostile environment around massive stars has been analyzed. Nearby young stars have their protoplanetary disks heated and evaporated by the energetic neighbour (**Johnstone**).

Detailed stellar structure and evolution models are providing insight into the ages of globular clusters, the oldest known constituents of the Galaxy. Stellar seismology is opening a new vista on the astrophysics of stars. Research at CITA has been performed in conjunction with observations from the Global Oscillation Network Group (GONG) (**Chaboyer**). The stellar graveyard also provides many astrophysical enigmas. White dwarf cooling models provide age estimates for milli-second pulsars, allowing for a determination of their evolution (**Hansen**).

9.5 Planetary Systems

The Solar System poses both a local concern and a rich source of observational data. CITA continues to provide leading research in this field, conducting both analytic and detailed numerical simulations. Recent results include an understanding of the chaotic nature of the outer asteroid belt (**N. Murray** and **Holman**), the possibility of a long-lived belt of mass between Uranus and Neptune (**Holman**), the tidal-disruption of Earth-crossing asteroids (**Richardson**), and the evolution of long-period comets (**Tremaine** and **Wiegert**).

In the last two years the notion of extra-solar planets has been supported with more than a dozen observations of kinematic planetary signatures around nearby stars. At CITA the theoretical implications of these discoveries have been the topic of detailed research. New insight into the possible formation of the proposed extra-solar planetary system 51 Peg has been developed to explain its small orbital radius (**Richardson**). Several postulated planets have eccentricities and research at CITA has focused on mechanisms by which initially circular orbits might grow elongated due to the proximity of a binary star companion (**Tremaine**, **Holman**, and **Touma**). The stable regions for planetary orbits within binary and multiple stellar systems has also been investigated (**Holman** and **Wiegert**).

PUBLICATIONS

The publication list includes all papers published or submitted in 1996 by the CITA staff, or by visitors if a substantial portion of the work was done at CITA. Some papers published in this period were included as "submitted" or "in press" in the 1995 annual report.

Antia, H.M., Basu, S., **Chaboyer, B.**, et al., (21 authors, GONG inversions team), "The Seismic Structure of the Sun from GONG," in *IAU Symposium No. 181: Sounding Solar and Stellar Interiors*, in press.

Armitage, P.J. and Clarke, C.J., "The Ejection of T Tauri Stars from Molecular Clouds and the Fate of Circumstellar Disks," *MNRAS*, in press.

Armitage, P.J. and Livio, M., 1996, "Accretion Disks in Interacting Binaries: Simulations of the Stream-Disk Impact," *ApJ*, **470**, 1024-1032.

Armitage, P.J. and Pringle, J.E., "Radiation Induced Warping of Protostellar Accretion Disks," *ApJL*, submitted.

Baldwin, J.A., ..., **Martin, P.G.**, ..., 1996, "Physical Conditions in Low Ionization Regions of the Orion Nebula," *ApJ*, **468**, L115-L119.

Basu, S., "Self-Similar Evolution of Supercritical Cores," in Proc. of 7th Annual Maryland Astrophysics Conference, *Star Formation, Near and Far*, eds. S. S. Holt and L. G. Mundy, AIP, in press.

Basu, S., "A Semi-Analytic Model for Supercritical Core Collapse: Self-Similar Evolution and the Approach to Protostar Formation," *ApJ*, submitted.

Basu, S., Mouschovias, T. Ch., and Paleologou, E. V., "Dynamical Effects of the Parker Instability in the Interstellar Medium," *ApJL*, in press.

Bharadwaj, S., Munshi, D. and **Souradeep, T.**, "Skewness in the Cosmic Microwave Background Anisotropy from Inflationary Gravity Wave Background," *Phys. Rev. D*, submitted.

Bond, J.R. and **A.H. Jaffe**, "Cosmic Parameter Estimation Combining Sub-Degree CMB Experiments With COBE," to appear in the proceedings of the XXXIth Moriond meeting, *Microwave Background Anisotropies*.

Bond, J. R., **Pogosyan, D.** and **Souradeep, T.**, "Constraints on Compact Hyperbolic Spaces from COBE," in *Proceedings of the XVIIIth Texas Symposium on Relativistic Astrophysics*, ed. A. Olinto, J. Frieman, and D. N. Schramm, (World Scientific), in press.

Bond, R., Kofman, L., **Pogosyan, D.**, 1996, "How filaments Are Woven into The Cosmic Web," *Nature*, **380**, 603.

Boothroyd, A.I., Keogh, W.J., **Martin, P.G.**, and Peterson, M.R., 1996, "A Refined H₃ Potential Energy Surface," *J. Chem. Phys.*, **104**, 7139-7152.

Botke, W.F., Jr., **Richardson, D.C.**, Love, S.G. "Production of Tunguska-Sized Bodies by Earth's Tidal Forces," *Plan. and Space Sci.*, in press.

Botke, W.F., Jr., **Richardson, D.C.**, Love, S.G. "Can Tidal Disruption of Asteroids Make Crater Chains on the Earth and Moon?," *Icarus Notes*, in press.

Byun, Y.-I., Grillmair, C.J., Faber, S.M., Ajhar, E.A., Dressler, A., Kormendy, J., Lauer, T.R., Richstone, D., and **Tremaine, S.** 1996, "The centers of early-type galaxies with HST: II. Empirical models and structural parameters," *AJ*, **111**, 1889-1900.

Chaboyer, B., Kernan, P.J., Krauss, L.M., and Demarque, P. 1996, "A Lower Limit on the Age of the Universe," *Science*, **271**, 683 - 689.

Chaboyer, B., Demarque, P., and Sarajedini, A. 1996, "Globular Cluster Ages and the Formation of the Galactic Halo," *ApJ*, **459**, 558 - 569.

Chaboyer, B. 1996, "Halo Star Evolution," in *Stellar Evolution: What Should Be Done?*, eds. A. Noels, D. Fraipont-Caro, M. Gabriel, N. Grevesse and P. Demarque

- (Liège: Institut d'Astrophysique), 345 – 358.
- Chaboyer, B.** 1996, "The Age of the Universe" *Nuclear Physics B Proceedings Supplement*, **51B**, 10.
- Chiang, J.**, and **Murray, N.** 1996 "Reverberation Mapping and the Disk-Wind Model of the Broad-Line Region," *ApJ*, **466**, 704-712.
- Chiang, J.**, and **Murray, N.**, "Cataclysmic Variables as a Laboratory for Studying Disk Winds in AGNs," in Proc. of *Mass Ejection From AGN Workshop*, ed. N. Arav, I. Shlosman, and R. Weymann, in press.
- Chiang, J.**, and **Murray, N.**, "The Disk Wind Model of the Broad Line Region of Active Galactic Nuclei," in Proc. of IAU Conf. 163, *Accretion Phenomena and Associated Outflows*, in press.
- Christensen-Dalsgaard, J., Dappen, W., ... **Chaboyer, B.**, *et al.*, (33 authors, GONG modeling team) "The Current State of Solar Modeling," *Science*, **272**, 1286 – 1292.
- Colín, P., Carlberg, R.G. and **Couchman, H.M.P.**, 1996, "Evolution of Clustering in a Flat and Open Universe," *ApJ*, submitted.
- Colombi, S.**, Bernardeau, F., Bouchet, F.R., and Hernquist, L., "Extended Perturbation Theory for the Local Density Distribution Function," *MNRAS*, in press.
- Crenshaw, D.M., ... **Martin, P.G.**, ... 1996, "Multiwavelength Observations of Short Time-scale Variability in NGC 4151. I. Ultraviolet Observations," *ApJ*, **470**, 322-335.
- Crittenden, R.**, and Turok, N., 1996, "Looking for a Cosmological Constant with the Rees-Sciama Effect," *Phys. Rev. Lett.*, **76** 575-578.
- Couchman, H.M.P.**, 1996, "Simulating Cosmic Structure at High Resolution: Towards a Billion Particles," to appear in the *Proceedings of the 12th Kingston Meeting on Theoretical Astrophysics*, eds. Clarke, D. and West, M.
- Dougherty, S.A., ... **Martin, P.G.**, ... 1996, "The DRAO Galactic Plane Survey Project," *BAAS*, **28**, 1220-1220.
- Dubinski, J.**, 1996, "A Parallel N-body Treecode," *New Astronomy*, **1**, 133.
- Dubinski, J.**, Mihos, J.C., & Hernquist, L., 1996, "Using Tidal Tails to Probe Dark Matter Halos," *ApJ*, **462**, 576.
- Dubinski, J.**, "Dark Halos: Theory vs. Observation," in proc. of the workshop on "Aspects of Dark Matter in Astro- and Particle Physics," eds. H.V. Klapdor-Kleingrothaus and Y. Ramachers (World Scientific Press), in press
- Edelson, R.A., ... **Martin, P.G.**, ... 1996, "Multiwavelength Observations of Short Time-scale Variability in NGC 4151. IV. Analysis of Multiwavelength Continuum Variability," *ApJ*, **470**, 364-377.
- Faber, S.M., **Tremaine, S.**, Ajhar, E.A., Byun, Y.-I., Dressler, A., Gebhardt, K., Grillmair, C., Kormendy, J., Lauer, T.R., **Magorrian, J.**, and Richstone, D., "The centers of early-type galaxies with HST. IV. Central parameter relations," *ApJ*, submitted.
- Gebhardt, K., Richstone, D., Ajhar, E.A., Lauer, T.R., Byun, Y.-I., Kormendy, J., Dressler, A., Faber, S.M., Grillmair, C., and **Tremaine, S.** 1996, "The centers of early-type galaxies with HST: III. Non-parametric recovery of stellar luminosity distributions," *AJ*, **112**, 105-113.
- Gough, D.O., Kosovichev, A.G., ... **Chaboyer, B.**, *et al.*, (26 authors, GONG inversions team) "The Seismic Structure of the Sun," *Science*, **272**, 1296 – 1300.
- Hansen, B.M.S.** and Phinney, E.S., "The Pulsar Kick Velocity Distribution," *MNRAS*, submitted.
- Hansen, B.M.S.** and Phinney, E.S., "Stellar Forensics I: Cooling Curves," *MNRAS*, submitted.
- Hansen, B.M.S.** and Phinney, E.S., "Stellar Forensics II: Millisecond Pulsar Binaries," *MNRAS*, submitted.
- Holman, M. J.**, "A Long-lived Belt between Uranus and Neptune," *Nature* submitted.
- Holman, M. J.** and **Murray, N. W.**, 1996, "Chaos in High-order Mean Motion Resonances in the Outer Asteroid Belt," *AJ*, **112**, 1278.
- Holman, M.**, Touma, J., **Tremaine, S.**, "Chaotic Variations in the Planet Orbiting 16 Cygni B," *Nature*, in press.
- Jaffe, A.H.**, " H_0 and Odds on Cosmology," *ApJ*, **471**, 24, 1996.
- Jaffe, A.**, **Knox, L.**, and **Bond, J. R.**, "Data Compression for CMB Experiments," in *Proceedings of the XVIIIth Texas Symposium on Relativistic Astrophysics*, ed. A. Olinto, J. Frieman, and D. N. Schramm, (World Scientific), in press.
- Johnstone, D.**, Hollenbach, D., and Shu, F., 1996, "Externally Induced Evaporation of Young Stellar Disks in Orion," in *From Stardust to Planetesimals: Contributed Papers*, ed. M. E. Kress, A. G. G. M. Tielens, and Y.J. Pendleton, NASA CP-3343.
- Kaiser, N.**, 1996. "Weak Lensing and Cosmology" *ApJ*, submitted, astro-ph/9610120.
- Kaiser, N.** and **Jaffe, A.**, 1996. "Bending of Light by Gravity Waves" *ApJ*, 484, in press, astro-ph/9609043.
- Kim, S.-H., and **Martin, P.G.**, 1996, "On the Dust to Gas Ratio and Large Particles in the Interstellar Medium," *ApJ*, **462**, 296-308.
- Knox, L.**, "Observing Strategy Assessment," *Proceedings of the XXXIst Moriond Meeting "Microwave Background Anisotropies"*, ed. F. Bouchet, (World Scientific), in press.
- Knox, L.**, **Bond, J. R.**, and **Jaffe, A.**, "CMB Power Spectrum Estimation," in *Proceedings of the XVIIIth Texas Symposium on Relativistic Astrophysics*, ed. A. Olinto, J. Frieman, and D. N. Schramm, (World Scientific), in press.
- Knox, L.**, "Cosmic Microwave Background Anisotropy Observing Strategy Assessment," *ApJ*, in press.
- Kofman, L., Klypin, A., **Pogosyan, D.** and Henry, J. P., 1996, "Mixed Dark Matter in Halos of Clusters," *ApJ*, **470**, 102-114.
- Kofman, L. **N. Kaiser**, M.H. Lee, A. Babul, 1996. "Statistics of Gravitational Microlensing Magnification. I. Two-Dimensional Lens Distribution," submitted to *ApJ*, astro-ph/9608138.
- Kormendy, J., Bender, R., Richstone, D., Ajhar, E.A., Dressler, A., Faber, S.M., Gebhardt, K., Grillmair, C., Lauer, T.R., and **Tremaine, S.** 1996, "Hubble Space Telescope spectroscopic evidence for a $2 \times 10^9 M_\odot$ black hole in NGC 3115," *ApJL*, **459**, L57-L60.
- Kormendy, J., Bender, R., Ajhar, E.A., Dressler, A., Faber, S.M., Gebhardt, K., Grillmair, C., Lauer, T.R., Richstone,

- D., and **Tremaine, S.** 1996, “*Hubble Space Telescope* spectroscopic evidence for a $1 \times 10^9 M_{\odot}$ black hole in NGC 4594,” *ApJL*, **473**, L91-L95.
- Kormendy, J., Bender, R., Magorrian, J., Tremaine, S., Gebhardt, K., Richstone, D., Dressler, A., Faber, S.M., Grillmair, C., and Lauer, T.R., 1997, “Spectroscopic evidence for a supermassive black hole in NGC 4486B,” *ApJL*, submitted.
- Lauer, T.R., **Tremaine, S.**, Ajhar, E.A., Bender, R., Dressler, A., Faber, S.M., Gebhardt, K., Grillmair, C.J., Kormendy, J., and Richstone, D., 1996, “*Hubble Space Telescope* observations of the double nucleus of NGC 4486B,” *ApJL*, **471**, L79-L82.
- Lazarian, A., **Pogosyan, D.**, “Interstellar Filaments and the Statistic of galactic HI,” *ApJ*, submitted.
- Lee, M.H., A. Babul, L. Kofman, **N. Kaiser**, 1996. “Statistics of Gravitational Microlensing Magnification. II. Three-Dimensional Lens Distribution,” *ApJ*, submitted, astro-ph/9608139.
- Lin, D.N.C., Bodenheimer, P., **Richardson, D.C.**, 1996. “Orbital migration of the planetary companion of 51 Pegasi to its present location,” *Nature*, **380**, 606-607.
- Luppino, G., and **Kaiser, N.**, 1997. “Detection of Weak Lensing by a Cluster of Galaxies at $z=0.83$,” *ApJ*, **475**, 20.
- Luppino, G.A., **Kaiser, N.**, Clowe, D.I., Gioia, I.M., and Metzger, M.R., 1996. “Weak Lensing by X-ray Luminous Clusters of Galaxies at $z>0.5$,” *Nuc. Phys. B. (Proc. Suppl.)* **51B**, 107-113.
- Squires G.**, **N. Kaiser**, G. Fahlman, A. Babul and D. Woods, 1996. “A Weak Gravitational Lensing Analysis of Abell 2390,” *ApJ*, **469**, 73.
- Squires, G.** and **Kaiser, N.**, 1996. “Unbiased Cluster Lens Reconstruction,” *ApJ*, **473**, 65.
- Squires, G.**, **Kaiser, N.**, Babul, A., Fahlman, G., Woods, D., Neumann, D., & Bohringer, H., 1996. “The Dark Matter, Gas and Galaxy Distributions in Abell 2218: A Weak Gravitational Lensing and X-ray Analysis,” *ApJ*, **461**, 572.
- Maddison, S.T., **Murray, J.R.**, Monaghan, J.J., 1996, “SPH Viscous Instabilities in Accretion Disks and Rings,” *Publ. Astr. Soc. Australia*, **13**, 66-70.
- Malaney, R. A.**, 1996, “Evolution of the Cosmic Gas and the Relic Supernova Neutrino Background,” *Astroparticle Physics*, in press.
- Mandy, M.E. and **Martin, P.G.**, 1996, “Energy Transfer in Molecular Hydrogen: the Role of Open and Closed Shell Collision Partners,” in *23rd International Symposium on Free Radicals*,
- Martin, P.G.**, “Warm Interstellar Molecular Hydrogen,” in *Computational Astrophysics*, eds. D. Clarke & M. West, *PASP Conference Series*, in press.
- Martin, P.G.**, Rubin, R.H., Ferland, G.J., DuFour, R.J., O’Dell, C.R., Baldwin, J.A., Hester, J.J., and Walter, D.K., 1996, “Extinction Corrections and the Decrement of the He I lines in the Orion Nebula,” *BAAS*, **28**, 1416-1416.
- Martin, P.G.**, Schwarz, D.H., and Mandy, M.E., 1996, “Master Equation Studies of Collisional Excitation and Dissociation of H₂ Molecules by H Atoms,” *ApJ*, **461**, 265-281.
- Mihos, J.C., **Dubinski, J.**, & Hernquist, L., “Tidal Tails Two: The Effect of Dark Matter Halos on Tidal Tail Morphology and Kinematics,” *ApJ*, submitted.
- Murali, C.** and Weinberg, M. D. “The Effect of the Galactic Spheroid on Globular Cluster Evolution,” *MNRAS*, in press.
- Murali, C.** and Weinberg, M. D. “Globular Cluster Evolution in M87 and Fundamental Plane Ellipticals,” *MNRAS*, in press.
- Murali, C.** and Weinberg, M. D. “Evolution of the Galactic Globular Cluster System,” *MNRAS*, submitted.
- Murray, J.R.**, 1996, “SPH Simulations of Tidally Unstable Accretion Discs in Cataclysmic Variables,” *MNRAS*, **279**, 402-414.
- Murray, J.R.**, **Wadsley, J.W.**, **Bond, J.R.**, 1996, “MHD with SPH: Application to the High Redshift IGM” *BAAS*, **189**, #104.01.
- Murray, J.R.**, “Angular Momentum Transport in Simulations of Accretion Disks,” in *Computational Astrophysics, 12th ‘Kingston Meeting’ on Theoretical Astrophysics*, submitted.
- Murray, J.R.**, “Spiral Shocks in Accretion Disks with SPH,” in *Proc. of IAU Coll. No. 168 Accretion Phenomena and Related Outflows*, ed. D. Wickramasinghe, L. Ferrario, G. Bicknell, (*PASP*), in press.
- Murray, J.R.**, 1996, “SPH Simulations of Tidally Unstable Accretion Disks,” in *Proc. of IAU Coll. No. 158 Cataclysmic Variables and Related Objects*, ed. A. Evans, J. Wood (Kluwer Academic), p. 115-116.
- Murray, J.R.**, 1995, “Superhump and Simulations of Eccentric Disks,” in *Proceedings of the Abano-Padova Congress on The Inter-Relations of Cataclysmic Variables*, ed. A. Bianchini, M. Della Valle, M. Orlo, (Kluwer Academic), p. 374.
- Murray, N.** and **Chiang, J.** 1996 “Wind-dominated optical line emission from accretion disks around luminous cataclysmic variable stars,” *Nature*, **382**, 789-791.
- Nelson, R.W., and **Tremaine, S.**, “The dynamics of warped galaxies,” in *Gravitational Dynamics*, ed. O. Lahav, E. Terlevich and R.J. Terlevich (Cambridge: Cambridge University Press), 73-88.
- Neuforge, C., **Chaboyer, B.**, Christensen-Dalsgaard, J. & Noels A., “New Modelling of the Alpha Centauri system,” *IAU Symposium 181, Sounding Solar and Stellar Interiors*, in press.
- Norman, M.L., Beckman, P., Bryan, G., **Dubinski, J.**, Gannon, D., Hernquist, L., Keahey, K., Ostriker, J.P., Shalf, J., Welling, J., & Yang, S., 1996, “Galaxies Collide on the I-WAY: An Example of Heterogeneous Wide-Area Collaborative Supercomputing,” *International Journal of Supercomputing Applications*, **10**, 32.
- Pearce, F.R., Thomas, P.A., Hutchings, R.M., **Couchman, H.M.P.**, Jenkins, A.R., Frenk, C.S., White, S.D.M. and Colberg, J.M., 1996, “Simulating the Universe,” *IEEE Computer Society Press, Proceedings of 5th Euromicro workshop on Parallel and Distributed Computing*, ed. Hans P. Zima

- Pichon, C.** & Lynden-Bell, D 1996, "New sources of Kerr and other metrics: Rapidly rotating relativistic disks with pressure support," MNRAS, **280** (4), 1007-1026.
- Pichon, C.**, & Lynden-Bell, D 1996, "Equilibria for flat and round disks" MNRAS, **282** (4), 1143-1158.
- Pichon, C.**, & Cannon, R., "Numerical linear stability analysis for round galactic disks," MNRAS, submitted.
- Pichon, C.** & Bernardeau, F. , "Vorticity generation in large scale structure caustics," MNRAS, submitted.
- Rauch, K.P.**, and **Tremaine, S.**, 1996, "Resonant Relaxation in Stellar Systems," New Astronomy, **1**, 149-170.
- Rauch, K.P.**, "Collisional Stellar Dynamics Around Massive Black Holes in Active Galactic Nuclei," ApJ, submitted.
- Rodriguez-Pascual, P.M., . . . , **Martin, P.G.**, . . . , "Steps toward Determination of the Size and Structure of the Broad-line Region in Active Galactic Nuclei. IX. Ultraviolet Observations of Fairall 9," ApJ, in press.
- Rubin, R.H., DuFour, R.J., Ferland, G.J., **Martin, P.G.**, O'Dell, C.R., Baldwin, J.A., Hester, J.J., Walter, D.K., and Wen, Z., "[Fe IV] in the Orion Nebula," ApJ, in press.
- Scoccimarro, R.**, "Cosmological Perturbations: Entering the Non-Linear Regime," ApJ, submitted.
- Scoccimarro, R.**, **Colombi, S.**, Fry, J.N., Frieman, J., Hivon, E., and Melott, A., "One-Loop Corrections to the Bispectrum," ApJ, submitted.
- Syer, D., and **Tremaine, S.**, "Non-axisymmetric, scale-free, razor-thin discs," MNRAS, **281**, 925-936
- Syer, D., and **Tremaine, S.**, "Made-to-measure N -body systems," MNRAS, **282**, 223-233
- Szapudi, I., **Colombi, S.**, "Cosmic Error and Statistics of Large Scale Structure," ApJ, 470, 131.
- Tittley, E and **Couchman, H.M.P.**, 1996, "The Effect of Substructure on The Final State of Matter in An X-Ray Cluster," To appear in the Proceedings of the 12th Kingston Meeting on Theoretical Astrophysics, eds. Clarke, D. and West, M.
- Wiegert, P. and **Holman, M.** , "The Stability of Planets in the Alpha Centauri System," AJ, in press.
- Wilson, G.**, Cole, S. and Frenk, C. S., 1996, "Cluster Mass Reconstruction from Weak Gravitational Lensing," MNRAS, **280**, 199-218
- Wilson, G.**, Cole, S. and Frenk, C. S., 1996, "Constraining Ω_0 using Weak Gravitational Lensing by Clusters," MNRAS, **282**, 501-510
- Wilson, G.**, Smail, I., Ellis, R. S. and Couch, W. J., 1997, "The Faint End of the Luminosity Function in Intermediate Redshift Clusters," MNRAS, **284**, 915-930
- Wolff, M.J., Anderson, C. M., Clayton, G.C., Kim, S.-H., and **Martin, P.G.**, 1996, "Ultraviolet Interstellar Linear Polarization: Initial Modeling Efforts for the Astro-2 WUPPE Data," BAAS, **28**, 914-914.
- Wolff, M.J., Clayton, G.C., Kim, S.-H., **Martin, P.G.**, and Anderson, C. M., "Ultraviolet Interstellar Linear Polarization. III. Features," ApJ, in press.

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