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THE CANADIAN INSTITUTE FOR THEORETICAL ASTROPHYSICS

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1. INTRODUCTION

The Canadian Institute for Theoretical Astrophysics, which is funded by a Major Resources Support grant from NSERC, hosts one of the largest concentrations of theoretical astrophysicists in the world: 7 faculty and 25 research fellows in 2009. Of these, 11 were supported by the MRS grant; the factor of two leverage reflects in part the drawing power of CITA, attracting many portable fellowships. CITA users included more than 147 short term visitors, 3 long term visitors, 5 visiting sabbatical professors, 8 CITA National Fellows, 69 CITA Inc. members from across Canada, 21 University of Toronto graduate students being supervised by CITA faculty, 3 Visiting Pre-doctoral students, and 4 USRA summer students and 3 undergraduate students from the University of Toronto being supervised by CITA faculty. There were also many remote users. There were over 1000 participants in CITA Supported conferences, workshops, seminars and talks from January 2009 to December 2009.

Quoting from the most recent NSERC review (2006): "CITA is arguably one of the most visible and successful research activities in all of Canada, providing a high level of international recognition and a strong magnet for attracting talent to Canada. In addition, CITAs program for training and mentoring postdocs is without peer in Canada and has achieved similar worldwide recognition."

CITA was founded in 1985-1986, with a mandate to promote the development of theoretical astrophysics in Canada, to foster interaction within the Canadian theoretical astrophysics community, and to serve as an international centre of excellence for theoretical work. As noted below, some 19 CITA postdoctoral fellows and 4 CITA National fellows are now in tenure track or tenured positions across Canada, fulfilling the first mandate. The numerous awards and highly cited papers of the last 25 years show that CITA is a center of excellence.

CITA is supported by (and hosted at) the University of Toronto, by an NSERC Major Resources Support grant, by the Gravity and Cosmology program of the Canadian Institute for Advanced Research, and by the Canada Research Chairs program. It is governed by the CITA Council, chosen from members of CITA Inc. (which consists of professors across Canada working in theoretical astrophysics and related fields).

More information about CITA may be found on the website, http://www.cita.utoronto.ca which lists all upcoming events, CITAs latest news, information on current research initiatives, jobs, and visitor information. The website also provides archives on all talks, seminars, meetings, workshops and special lectures.

2. SCIENCE AT CITA

2.1. *Vision*

CITA has achieved top international stature (competing with major centres such as Princeton, Caltech, and Cambridge) by a unique focus on people power and theoretical investigations, giving Canada a large return in impact and prestige. CITA has made its reputation by nurturing the talent of a large contingent of post-PhD researchers, including 2-3 year CITA postdoctoral fellows and 3-5 year CITA senior research associates at Toronto and 2 year National Fellows across Canada. The ratio of research fellows to permanent faculty of roughly 3:1 is the inverse of the typical ratio in most departments. Most of CITAs support is directed to this young dynamic talent pool. This gives CITA the critical mass to respond in a timely and collaborative way (often spawning Canadian networks) to emerging hot fields of research, in a high level atmosphere with a positive friendly Canadian twist. As a result, CITA is not prone to stagnation and has been very resilient. While postdoctoral positions at most institution are contract-oriented, we give our young researchers the ability to be creatively independent and entrepreneurial. The phenomenal drawing power of CITA is enhanced by the excellence and breadth of the faculty, who have been honoured with the most prestigious Canadian and many international awards.

CITA is a theory institute. It is a fact that researchers at CITA have been involved in some of the most exciting observational projects in astronomy since the Institute was founded twenty five years ago. Examples include measurements of the cosmic microwave background using instruments such as BOMERanG, CBI, ACT, WMAP, and, currently Planck and Herschel (which also is used to study the interstellar medium of galaxies). Since the number of astronomical instruments and observatories continues to grow at an increasing pace, this facet of CITA will undoubtedly expand.

But the heart and soul of CITA is the development and application of theory to astronomical problems. Examples include predictions of the angular structure of fluctuations in the microwave background based on hierarchical Gaussian fluctuations in the primordial density field, the prediction of observational characteristics of highly magnetized neutron stars, the production of entropy after inflation in the early universe, and the proposal of novel mechanisms for the migration of planets. Other examples include calculations of the shapes and clustering properties of dust grains; the realization that such grains, acting as a source of opacity, could effect the large scale evolution of star-forming galaxies, and provide a means for massive black holes to influence their hosts.

In the last decade there has been a clear trend toward large scale computation in theoretical astrophysics. CITA

has been a leader in this regard as well. Examples include the highly detailed predictions of the 21 cm emission associated with reionization made by workers at CITA, and simulations of galaxy clusters and the Sunyaev-Zeldovich effect. CITA has also been involved in the birth of a new field, numerical relativity, solving Einstein's field equations to model the mergers of two black holes, and predicting the resulting gravitational wave radiation, to be compared to the data that will soon emerge from gravitational wave detectors such as LIGO.

2.2. *Cosmology and Early Universe*

Over the past decade, 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, 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. A recent focus has been on exploring string-inspired models of inflation, with an emphasis on predictions that can be tested by observations—one of the few areas where string theory can be compared to experiment.

Much of the work done at CITA is in support of large projects, such as BOOMerang, ACT, CBI, Planck and CHIME (see 21cm LRP white paper). For example, researchers at CITA have carried out some of the largest large scale computations of dark matter plus gas to aid in interpretation of cosmic data of all sorts.

2.3. *Galaxy Formation*

Galaxies form out of the gravitational collapse of cosmological density fluctuations in the early universe, settling into the spirals and ellipticals we see today. The visible signature of a galaxy consists primarily of stars, but galaxies also include dark matter (which dominates their mass budget), central massive black holes, and hydrogen gas. A complete understanding of galaxy formation and evolution requires detailed dynamical treatment of both dark matter and stars, and, crucially, the gas that forms the stars. In addition, it has become apparent from observations, including correlations between black hole masses and either stellar mass or stellar velocity dispersion, that there is a deep connection between stars and central black holes, a connection that is far from understood. Work at CITA runs the gamut from analytical theory to n-body simulations to full three dimensional magnetohydrodynamic simulations including stellar feedback.

2.4. *High Energy Astrophysics*

CITA has long been a leader in high energy astrophysics, first through clusters of postdoctoral fellows, and then anchored by CITA professor Chris Thompson (previously a CITA PDF). CITA provided real leadership, as this program was started at a time when there was very little activity in this research area at other universities in Canada, a situation which has improved markedly in the last decade. CITA's expertise in magnetars and the physics of pulsars and gamma ray bursts makes it a world leader to this day. For example, the current standard model for the binary pulsar, which relies on understanding the physics of the pulsar magneto spheres, was developed at CITA.

2.5. *Star Formation and the Interstellar Medium*

Stars are the most visible component of the universe, the objects that most people think of when they think about astronomy. The structure and evolution of stars are both rather well understood. How stars form, on the other hand, remains a rather unsettled subject. Part of the problem arises from the complicated nature of the gas, or interstellar medium, out of which stars from. However, the relevant physics is very rich; the gas is highly supersonic, and affected by self-gravity, magnetic fields, cosmic rays, and high speed shocks from supernovae and stellar winds. The dissipation of the supersonic motion in shocks leads to compression of the gas, which is crucial for star formation. Recently, work at CITA has shown that radiation pressure, from starlight acting on dust grains, is a major, perhaps dominant, dynamical form of feedback, i.e., how stars affect the interstellar medium.

2.6. *Planet Formation, Planetary Dynamics, and Exoplanets*

The subject of planet formation and evolution has exploded in the last decade, with the discovery of hundreds of planets orbiting other stars. The future lies in characterizing the atmospheres (and eventually the surfaces) of Earth mass planets, a data-driven enterprise. However, understanding the formation and evolution of planets is a problem for theory, albeit guided by the observational results. Theory can drive the observations. For example, work at CITA suggested that some planets, born in binary star systems, would migrate via a combination of orbital dynamics and tidal evolution, resulting in an orbit misaligned with the spin of the star. Subsequent observations have found that a substantial fraction (30%) of hot Jupiters do have such misaligned orbits. At an even earlier phase of the evolution, the physics of dust grain growth or coagulation to form planetesimals is crucial (work by CITA PDF Youdin and former CITA professor Rafikov); following the growth of planetesimals to make terrestrial planets and the cores of gas giants, the next step has also been a strength at CITA.

2.7. *Gravitational Wave Physics and Numerical Relativity*

In the coming decade instruments like Advanced LIGO are expected to directly detect gravitational waves for the first time. As detections become routine, gravitational wave astronomy will open a new observational window on the universe, in which black holes and neutron stars will be visible, and possibly supernovae and more exotic objects like cosmic strings. Gravitational wave detections will allow astronomers to test General Relativity, will measure

masses and spins of the compact objects, and will determine the astrophysical merger rate of compact object binaries.

CITA is ramping up efforts in Numerical Relativity, most notably simulations of compact object binaries to study strong field general relativity, and to aid detection and analysis of gravitational waves. This involves large scale computer simulations of black hole and neutron star binaries, following the last orbits and the mergers in full general relativity; deepening our understanding of post-Newtonian expansions, which are used to compute the inspiral phase; and applications in the area of data-analysis for the gravitational wave detectors.

2.8. *Future Developments—Numerical Astrophysics*

As should be clear from the preceding, the impact of large scale numerical simulations on astrophysics is both large and growing rapidly. We have already noted that CITA has been at the forefront of large scale astrophysical computation in Canada, and indeed the world. CITA was a key contributor to the GMRT software correlator, and is a major partner in the CHIME project (see 21cm LRP white paper). We plan to move even more forcefully into this area. CITA is about to purchase a graphics-processing unit (GPU) cluster capable of speeds approaching a petaflop, which should place in the top twenty or higher worldwide.

3. CITA AS A FACULTY RECRUITMENT TOOL FOR CANADA

CITA has been instrumental in creating a vibrant theory community across the country. Faculty are at the very heart of research power and CITA's contribution here is quite remarkable both for the consistency and the high quality of its alumni now in faculty positions. This is one of CITA's major accomplishment, justifying the vision of CITA founders Peter Martin and Dick Henriksen. There are over one hundred former CITA Fellows in tenured or tenure track positions world wide, an amazing accomplishment.As of 2009 there were 19 former CITA Fellows in tenured or tenure track positions across Canada:

S. Basu, L. Boyle, M. Choptuik, H. Chouchman, J. Fiege, A. Frolov, B. Gladman, G. Holder, N. Ivanova, D. Johnstone, L. Kofman, C. Matzner, L. Nelson, D. Pogosyan, C. Thompson, L. van Waerbeke, L. Widro, and **Y. Wu**.

In addition, there are four former CITA National Fellows in tenured or tenure track positions at Canadian Universities: **M. Hudson**, **R. Thacker**, **R. Ouyed**, **J. Wadsley**.

Couchman is the Scientific Director of SHARCNET, one of the most important computing networks in Canada. On a similar note, former CITA system manager (and astrophysicist) Chris Loken is Chief Technical Officer for SciNet, another leading Canadian computing network, housed at the University of Toronto.

4. NATIONAL PROGRAMS

One of the mandates mentioned in the Introduction was that CITA foster interaction within the Canadian theoretical astrophysics community. This is done via a number of programs:

CITA National Fellows: CITA supports national postdoctoral fellows working at other Canadian universities by providing half the stipend and research support. National Fellows are nominated by the host university and selected by CITA Council. Since the start of the program in 1988, we have named 47 National Fellows. CITA supported 8 National Fellows in 2009: Chris Cameron (St. Marys), Ian Dobbs-Dixon (McGill), Aaron Dutton (Victoria), Aaron Dotter (Victoria), Ed Pope (Victoria), Greg Stinson (McMaster), Elizabeth Tasker (McMaster), Marc van der Slyus (Alberta). Since the last LRP in 2000, there have been about thirty National Fellows (the number hired each year was raised from two to three in 2007).

Senior Visiting Fellows CITA supports salaries of faculty members from other Canadian universities to make extended visits to CITA. Awardees (since 2008-2009) include James Wadsley (McMaster), Denis Leahy (Calgary), Dimitri Pogosyan (Alberta), Eric Poisson (Guelph), and Rachid Ouyed (Calgary). In the last decade there have been twelve Senior Fellows. Typically the fellowships provide funding to release the fellow from teaching and administrative duties for one academic term, or for sabbatical top-up.

CITA Visitors Program: CITA supports short and long-term visits of Canadian and international researchers. In 2009 we had 155 long and short term visitors. In the last decade there have been more than 1,400 short term visitors.

Pre-doctoral Program: This program is offered to graduate students from Canada (and world-wide) to do research work at CITA for a number of months. Over the last several years we have hosted roughly three pre-doctoral students per year.

Undergraduate Summer Research Fellowships: CITA has had a program for training an average of 6 or 7 undergraduates every summer for the last 15 years, allowing future astrophysicists to learn in a hotbed of research. Past participants include Dave Charbonneau (professor at Harvard), Yoram Lithwick (CITA PDF, now professor at Northwestern) and Sabine Polano (professor at UofT).

Computational Undergraduate Students: CITA trains and employs two undergraduate students to maintain our computer system, typically from co-op programs. This offers students the opportunity to work with state of the art clusters, disk arrays, and so forth, providing excellent training.

CITA and High Performance Computing: CITA is spearheading the build-up of modern hardware for computational astrophysics. Currently CITA operates the 1600 core Sunnyvale cluster. We are providing access to these facilities through national programs and collaborations. Larger HPC capability for the astrophysics community is provided by SciNet, a UofT campus-wide network with a 33,000 core cluster in which CITA is one of the key members. A new initiative in GPU computing by CITA

Professor Harald Pfeiffer is in progress, with deployment expected in 2010.

Support for Scientific Meetings: The aim of this program is to promote interaction, collaboration, and exchange of scientific results within the Canadian and international astrophysics communities. This program has neither the intent nor the resources to replace the major sources of funding that should be sought from other bodies, including NATO, the IAU, and registration fees, but for major meetings this program might be used to complement other funding sources.

Web casting: CITA seminars are available to the community on the web, including live-webcasting, which allows the community to listen in real time and also ask questions (see http://hosting.epresence.tv/cita).

Support for visits by CITA Fellows–Canadian University Interaction: The aim of this program is to promote professional interactions within the Canadian theoretical astrophysics community, by helping to defray the travel costs of CITA fellows who are invited to visit Canadian universities outside Toronto.

Colloquia and Seminars: Both the CITA professors and postdoctoral fellows give numerous colloquia and seminars at institutions across Canada, North America, and around the world, as well as presentations at scientific meetings. The total number exceeded 100 during 2009.

5. OUTREACH

The public supports research at CITA through funding from the national and provincial governments. Outreach efforts are therefor appropriate, as a way to inform the public both as to how their funds are being spent, and to stimulate and inspire individuals to dream and to strive to enhance our knowledge of the universe we live in. Outreach also involves educating researchers in other parts of the world both about the work done at CITA, and about opportunities for doing research in Canada.

Distinguished Visitors Program: The Raymond and Beverly Sackler Visitor program sponsors a free public lecture once a year. Past lectures include Roger Blandford, Kip Thorne, Andre Linde, Peter Goldreich, and Lord Martin Rees.

Scientific Exchange Program Agreements: The purpose of this program is to enhance the scientific breadth of young researchers, as well as increase scientific interactions between CITA and the Kavli Institute for Theoretical Physics (KITP), the Max Planck Institute for Astrophysics (MPA), and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA).

Public Lectures: CITA professors, Fellows, and graduate students give dozens of public lectures every year, as well as visiting local public schools, judging science fairs, and engage in similar public outreach activities.

6. RECOMMENDATIONS FOR THE LONG RANGE PLAN

Great research is lead by great faculty members. Quoting again from the NSERC review in 2006: "[CITA] is a magnet for outstanding post-doctoral fellows, who come from all over the world and contribute to maintaining the vitality and excellence of Canadian theoretical astrophysics." Many of these Fellows stay on in faculty positions. **Maintaining support for CITA, so that it continues to attract the best researchers in the world to work in Canada, is a top priority**. Since the vast majority of the money given by NSERC is spent on postdoctoral fellows, any increase in support will go directly to recruit more world class researchers to Canada.

Numerous white papers, e.g. that on Exoplanets, and on AGN, make the point that more postdoctoral fellowships are needed. **Expanding the CITA National Fellows program** is one way to address this problem; since it is adjudicated by the national theoretical astrophysics community, through the CITA Council, it provides matching funds on a highly competitive basis, ensuring that the money is directed to the most promising research areas.