STellar Astrophysics and Relativity at Bishop's University*

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Abstract

Bishop's University has recently adopted a Strategic Research Plan that should greatly enhance the overall research effort. Specifically, the university invited proposals from various research groups from all disciplines to create well-defined research clusters. In 2009, the university selected four of these clusters based on their potential for research excellence. The STAR cluster (STellar Astrophysics & Relativity) was one of the clusters selected. The cluster is a natural extension of the work and accomplishments that had already been achieved in the area of astrophysics at Bishop's over the past two decades. This paper first provides some context and background for those unfamiliar with astronomy and astrophysics, and then describes the history leading to the formation of the cluster formed and outlines the goals it expects to achieve. Finally, the objectives of the cluster with respect to science outreach and how it directly affects the various communities within the Eastern Townships is discussed.

Résumé

L'Université Bishop's a récemment adopté un plan stratégique pour la recherche qui devrait globalement améliorer ses efforts de recherche. Plus précisément, l'université a invité différents groupes de chercheurs de toutes les disciplines à proposer la création de grappes de recherche bien définies. Quatre grappes furent sélectionnées en 2009 en se basant sur le potentiel d'excellence de leur recherche. C'est ainsi que la grappe STAR (un acronyme de STellar Astrophysics & Relativity) fut créée. Cette grappe est un prolongement naturel des travaux et des réalisations entrepris dans le domaine de l'astrophysique à Bishop's au cours des deux dernières décénnies. Cet article présente le contexte scientifique et propose de l'information de base pour les lecteurs non-initiés à l'astronomie et l'astrophysique; il passe en revue l'histoire menant à la formation de la grappe et résume les objectifs de recherche attendus. En dernier lieu, l'article discute des objectifs de vulgarisation scientifique et de leurs impacts sur les différentes communautés des Cantons-de-l'Est.

Who hasn't peered into the night sky and marveled at the immensity of the universe or been awestruck by the number of stars residing in it? Throughout the millennia, the celestial firmament has inspired poets to write epic odes to the beauty of the heavens and has motivated philosophers to explore new lines of reasoning. In one of the greatest pieces of American literature, *The Adventures of Huckleberry Finn*, Mark Twain penned the famous passage:

> … we had the sky, up there, all speckled with stars, and we used to lay on our backs and look up at them, and discuss about whether they was made, or only just happened …[1]

When this text was written more than a century ago, the answer to these questions was not at all known. It was thanks to the advancement of research in fundamental science that we now have definitive answers. However, in answering these questions, scientists have formulated a host of new and extremely challenging questions for which there is not yet an answer. These problems include the following: (1) What happened at the time of the Big Bang? Were many parallel universes spawned simultaneously? (2) What is the reason for the existence of the so-called Dark Energy that supposedly drives the expansion of the universe? (3) Most of the mass in the universe has not been detected (i.e., the dark matter). What is it and can we detect it? If history is any guide, we expect that the answers to these problems will have significant and very tangible benefits for humanity.

Bishop's University certainly recognizes the importance of fundamental research in the sciences and for that reason it has chosen the STAR cluster as one of the four primary clusters of research excellence (Figure 1). STAR is an acronym for STellar Astrophysics & Relativity and the cluster comprises five members from the faculty complement at Bishop's in addition to several graduate (and undergraduate) student researchers. The STAR cluster is truly interdisciplinary and brings together astronomers, physicists and mathematicians working in the areas of cosmology, astronomy, astrophysics, and gravitation. These disciplines are an important component of what was originally viewed as a liberal-arts education. Finding

Fig. 1: The logo of the STAR cluster.

its rudiments in the writings of Plato,[2] a university-level liberal arts education was composed of two separate groupings of subjects. The trivium comprised the subjects of grammar, rhetoric, and logic, while the quadrivium consisted of arithmetic, geometry, astronomy, and music. These seven subjects constituted the liberal arts and were considered as the basis for subsequent study of (natural) philosophy and theology. As such, the research work performed by the members of the STAR cluster dovetails nicely with the clearly defined liberal-arts mission of Bishop's University.

The Ascendance of Physical Science

The era of modern science can be traced back to the 17th century and received its greatest impetus from scientists such as Galileo and Newton. They concluded that mathematics was the language of the universe and that all of natural phenomena could be understood within a precise mathematical framework. Thus their view of the world was a very mechanistic (i.e., deterministic) one; they believed that a set of immutable Laws of Nature could be derived. We now regard this notion as somewhat naive but it would be fair to say that unlike their predecessors (notably Copernicus and Kepler who obtained many of the prerequisite observations on which Galileo's and Newton's work was based), they recognized how to exploit the power of mathematics to explain natural phenomena in a precise and logical manner. One of the great successes of Newton was that he was able to unite what was considered at the time to be two separate branches of physics, namely astronomical mechanics (e.g., the orbits of the planets) and terrestrial mechanics (e.g., the acceleration of a mass attached to a spring). With one set of mathematical equations he was able to explain the results obtained for both types of observations. Thus astronomy and physics became truly unified. Moreover, his mathematical equations had tremendous predictive power. It was the overall correctness of these predictions that gave scientists of the time enormous confidence in their validity.

The desire for this type of unification has continued over the centuries and physicists are now seeking the holy grail of nature: a single unified theory or TOE (theory of everything!). So why do physicists think that everything can be explained within one unified mathematical framework? Consider the following: two hundred years ago it was thought that electricity and magnetism were two very distinct and separate phenomena. Thanks to the brilliance of Maxwell in the middle the 19th century, he was able to use the power of mathematics to show that electricity and magnetism were manifestations of the same physical phenomenon (which we now refer to as electromagnetism).[3] Out of these seemingly esoteric equations came a fundamental understanding of optics that allowed us to understand how we could generate electromagnetic waves. This discovery enabled the first radio pioneers such as Reginald Fessenden[4] (a former resident of the Eastern Townships) to make their transmissions which then led to the subsequent invention of the television, cellular phones and other forms of communication that are so essential to our enjoyment of everyday life.

Hidden in Maxwell's equations are the elements of the theory of Special Relativity. This was the first of Einstein's famous contributions to physics that led to some amazing conclusions. In particular it asserted that moving objects age more slowly (time dilation) than objects at rest and that energy and mass can be viewed as being closely related (i.e., the famous equation $E=mc^2$). This latter conclusion allows us to calculate how much energy is produced by nuclear fusion in the sun[5] (i.e., the conversion of four hydrogen nuclei into a helium nucleus). Furthermore, these results are at the heart of our understanding of how much energy is produced via nuclear fission.

In 1915, ten years after his theory of Special Relativity, Einstein devised a truly brilliant theory of gravitation that built upon Newton's gravitational theory by viewing gravity as geometry (e.g., the bending of space-time). According to this theory, known as General Relativity, gravity acts to alter the path of a photon (i.e., light) by forcing it to move along a particular geodesic. This theory has enjoyed some spectacular successes. Every prediction that it has made has been validated by experiments over the past century. For example, the bending of light has been observed and we now know that the so-called dark matter in the universe can actually act as a lens that is capable of creating multiple images of a single source of light. But its most spectacular success has been the prediction that the universe is expanding. If we observe distant galaxies in the universe, we see that all of them are moving away from us. We say that their light is redshifted; in other words, due to the Doppler effect, the wavelength of the light emitted by the stars in those galaxies is shifted to the red end of the spectrum (i.e., longer wavelengths). This is somewhat analogous to the Doppler shift of the sound that we hear from sirens on fire engines as those vehicles move away from us. The frequency of the sound clearly decreases with a concomitant increase in the wavelength. Just because everything is moving away from us does not imply that we are located at the centre of the universe. Perhaps a good paradigm for the expansion of the universe would be to consider the rising of a loaf of raisin bread as it bakes (Figure 2). When the dough is uncooked, the raisins within it are relatively close to each other. We can imagine that each one of those raisins represents a cluster of galaxies and that we

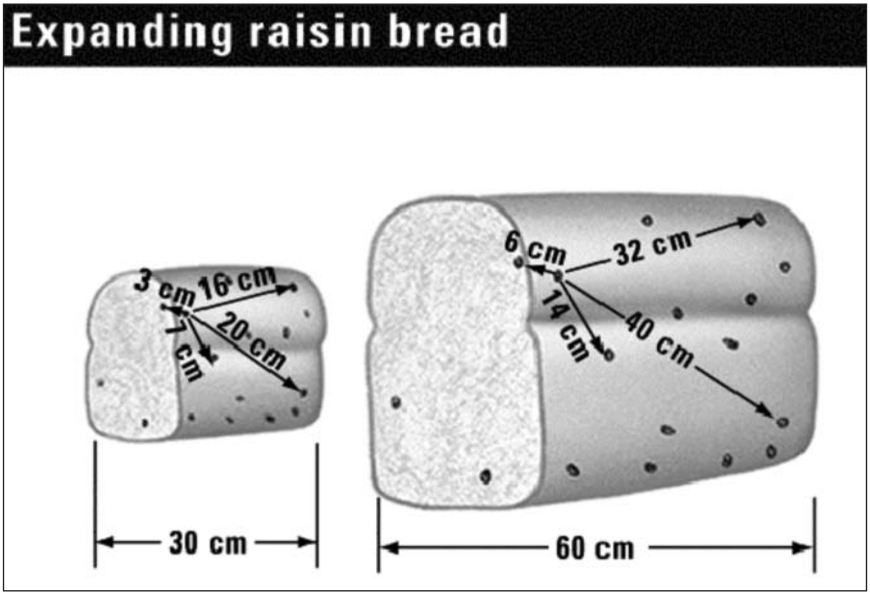

Fig. 2: The expanding universe analogue modeled as a loaf of rising raisin bread. From FRAKNOI. Voyages to the Stars and Galaxies, 2E. 2000 Brooks/Cole, a part of Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions

are observers on the surface of one of them. As the loaf expands when the bread rises, each one of the raisins moves proportionally farther apart from all of the other raisins. It does not matter on which raisin you are an observer (analogous to which galaxy cluster you live in), all other raisins will be moving away from you. In this sense, there is no preferred observing location in the universe. Another way of saying this is that the Big Bang "happened everywhere at once".

While our understanding of gravity on the largest distance scales in the universe has been revolutionized during the past century, we have also been amazed by the discoveries on the smallest distance scales (the microworld). We have come to understand through the development of quantum mechanics that the microworld is far more subtle and rich in physics than we had ever imagined. Astonishingly, we have discovered that matter can behave simultaneously as if it were a particle and a wave. Of course none of this formalism could have been developed if scientists had not first studied the behaviour of particles in the macroworld (i.e., deterministic mechanics) and the properties of various types of waves (e.g., sound and light waves). These insights have revolutionized technology and its impact on human development and interactions has been nothing short of astounding. For example, our fundamental understanding of the organization of the periodic table of elements would not have been possible without quantum mechanics. The development of the transistor could never have taken place without this seminal research. This implies that we would have no transistorized means of communication and that the digital analysis of information (computers) would have been greatly impaired. It also implies that the imaging chips known as CCDs (charge-coupled devices) that were pioneered by astronomers, who needed them to record images of celestial objects, and which are now ubiquitous in webcams and other digital video devices, would not have been invented. Clearly, mankind would find itself in a hugely different environment than it does today if it were not for the innovations that came about as a result of fundamental scientific research.

The Universe in Perspective

Our universe is so immense that we do not measure distances in metres but in terms of light-years. One light-year corresponds to the distance that it would take light to travel in one year. This is an enormous distance since light travels at 300,000 km/s. To provide some context and background consider the following: the radius of the earth is about 0.02 light-seconds in length; in other words it would take approximately 0.01 seconds for a light signal to travel from Europe to North America. It takes about 1.3 seconds for light to go from the earth to the moon and about 8 minutes for light to travel from the sun to the earth. Thus if the sun were suddenly to go dark at noon tomorrow, we would not find out about it until 12:08 pm. It takes about 6 hours for light to propagate from the sun to Pluto. The distance to the nearest star from the sun is an incredible 4 light-years. There are about 200 billion stars similar to our sun all moving around a black hole at the center of our galaxy in various types of orbits. We know that our sun is located in the disk of our own Milky Way galaxy and that it takes roughly 250 million years for it to make one revolution around the central black hole. Our galaxy has a diameter of a little larger than 100,000 light-years and the nearest large galaxy closest to us (the Andromeda galaxy) is approximately 2 million light years away. It is also known that galaxies cluster in what are known as superclusters of galaxies. These superclusters typically contain 100,000 galaxies and can extend over distances of more than 100 million light-years. There are approximately one million superclusters in the observable universe thus leading us to conclude that there are at least 100 billion galaxies in the universe. If each star has (on average) one planet, then the number of planets that would be able to host intelligent life must be enormous. The distance scale of the observable universe is an impressive 10 billion light-years.

All of these astronomical inferences were made in lock-step with the fundamental discoveries made in physics, math, and chemistry. With all of this information, astrophysicists have been able to create a reasonably robust picture of the evolution of the universe. We believe that the universe emanated from incredibly hot, dense matter when the four fundamental forces of nature (gravity, electromagnetism, the weak force, and the strong nuclear force) were all of roughly equal importance. The universe subsequently went through a period of rapid inflation that caused it to become geometrically flat (light rays traveling along a path that is initially parallel will continue to travel along a parallel path and will neither intersect nor diverge). After the first 3 minutes following the Big Bang, the universe would have consisted mostly of ionized hydrogen (90%) and would have fused some of its hydrogen into helium (10%) and trace amounts of other light elements such as lithium and beryllium. After 400,000 years the expansion of the universe would have allowed it to cool sufficiently so that the ionized hydrogen could recombine into its atomic form. This marks the dividing line between the radiation-dominated era (the early universe) and the matter-dominated era (the epoch in which galaxies and other large-scale structures formed). At this time it is thought that the universe consisted of a more or less uniform density of hot hydrogen gas (including some helium gas). As a result of perturbations in the density of this material, some of the gas started to contract under its own gravity, allowing for the formation of the first generation of stars approximately 200 million years after the Big Bang. These massive stars produced enormous amounts of ultraviolet radiation that tended to re-ionize the hydrogen gas in the universe. Eventually the stars became gravitationally bound into larger groupings from which galaxies formed and finally superclusters of galaxies formed after that (about one billion years after the Big Bang).

We also know that the Big Bang occurred approximately 13.7 billion years ago and that our galaxy was formed 12 billion years ago. Our sun is approximately 4.6 billion years old and we expect it to live for another 6 billion years before it becomes a red giant and eventually grows so large that it envelops Mercury's orbit, then Venus's orbit until its atmosphere eventually gets close to the earth. At that time it will pulsate violently and shed most of its hydrogen gas back into the interstellar medium. What will remain is the burned-out core of our sun that is composed mostly of carbon and oxygen. This remnant is known as a white dwarf. So how can we predict, with any certainty, the future of our sun? The answer is that we can use the "laws" of physics combined with sophisticated computer modeling to simulate the birth, life, and death of our sun. Moreover, we can actually observe

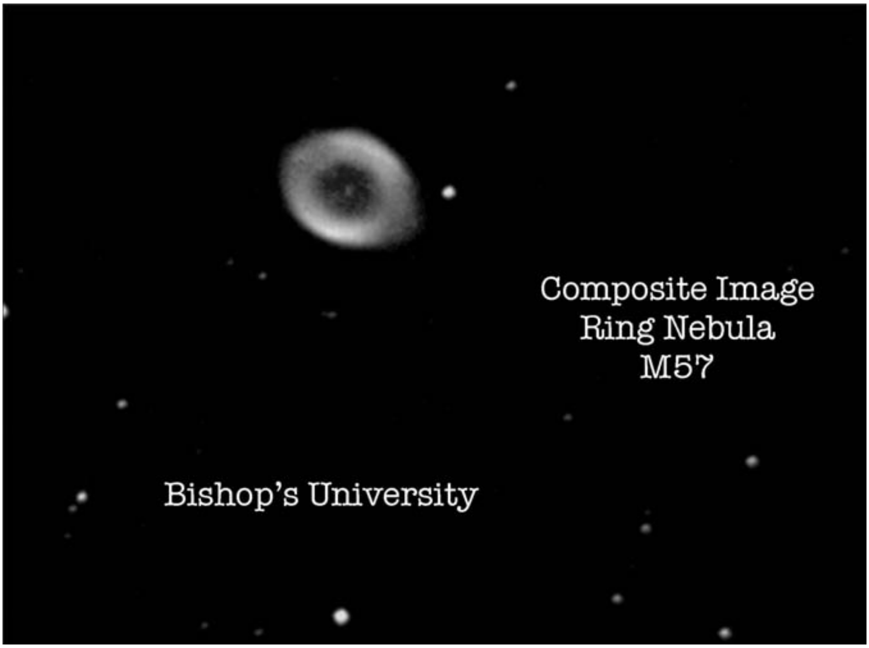

Fig. 3: The Ring Nebula (M57) as observed from the Bishop's University Astronomical Observatory. The ring around the central white dwarf was produced by the pulsating (dying) red giant about 1600 years ago.

the same process happening to stars similar to the sun in our Milky Way galaxy that are undergoing their final death throes (Figure 3).

It would seem as if we have amassed a huge amount of information concerning the formation and evolution of our solar system, our galaxy, and the universe. Although this is true, these determinations are often based on the assumption that we understand all of the physical phenomena that occur in our universe. This is certainly not the case. In particular, given all of its successes, Einstein's theory of General Relativity has not been tested in the limit of extremely strong gravitational fields or on cosmic distance scales. It is entirely possible that the theory will need serious revision. Moreover, we do not understand what makes up the dark matter that constitutes 95% of the matter in the universe nor do we understand the nature of the dark energy that constitutes 75% of the mass-energy of the entire universe. These are extremely important questions that must be addressed along with other subtle issues that have not yet been resolved and could have a significant impact on our understanding of the answers to these larger questions. These are some of the questions that are being addressed by the astronomers and physicists of the STAR cluster.

History Leading to the Formation of the STAR Cluster

Prior to 1988, Bishop's University had an extremely limited acquaintance with astronomy. This was a very unfortunate situation especially given the fact that a very large Observatory housing a 1.6 metre telescope was constructed in 1978 at Mont Mégantic[6] (about 70 km east of Sherbrooke). Bishop's had been offering one liberal science course in astronomy but no research was being done in this area. In 1988, Bishop's decided to hire an astrophysicist (Dr. Lorne Nelson) as a faculty member in the Department of Physics. Since that time the university has had a vigorous astronomy and astrophysics research program. Almost all of the Honours students in physics have been hired as summer research assistants (about 83% of the Honours students at Bishop's subsequently went on to graduate school to obtain Ph.D. degrees). They primarily carried out numerical simulations of stars and binary evolution using computers. Professor Nelson's main research interests were: (i) the study of brown dwarfs (failed stars that bridge the gap between ordinary stars such as our sun and giant gas planets such as Jupiter); and (ii) the development of a unified picture of the evolution of close interacting binaries (one star cannibalizes its orbital companion) containing compact objects such as white dwarfs, neutron stars, and black holes. In 2002, Professor Nelson was awarded a Tier 1 Canada Research Chair in astrophysics and was able to build significant research infrastructure such as cluster computers (i.e., dedicated supercomputers), to create a graduate (MSc) program and to hire postdoctoral fellows (Dr. Ajaja and Dr. Turcotte). With the subsequent hiring of Professor Valerio Faraoni in 2005 (who has considerable expertise in General Relativity and alternative theories of gravity), and the hiring of Professor Ariel Edery, astrophysics-related research became even stronger. In 2009 the STAR cluster was formally created and subsequently selected by the university as one of the four major areas of research focus. The current members of the cluster include Dr. Valerio Faraoni (Physics Department); Dr. Patrick Labelle (Physics Department); Dr. Lorne Nelson (Physics Department); Dr. Sylvain Turcotte (Physics Department); and Dr. Brad Willms (Mathematics Department).

Objectives of the STAR Cluster

The STellar Astrophysics & Relativity (STAR) research cluster's main areas of research in fundamental and applied physics include cosmology, astrophysics, general relativity, alternative theories of gravity, effective theories for low-energy quantum gravity, gravitational waves, the astrophysics of compact objects, interacting binary stellar systems, and high-energy astrophysics. The cluster and its members are also involved in the organization of conferences, workshops, and local seminars, host visitors for collaborative work and lectures, participate in various international activities (e.g., the time allocation process for the Gemini and Canada-France-Hawaii telescopes), and coordinate the outreach activities of the Bishop's University Astronomical Observatory.

Outside of the university, the members have many international collaborations and partners. Specifically, members of the cluster have ongoing collaborations with the Kavli Center for Space Research (Massachusetts Institute of Technology), Cambridge University, Oxford University, University of Chicago, Université de Montreal, University of Cape Town, University of Naples, University of California at Santa Barbara, International School of Advanced Studies (Trieste), the Chinese Academy of Sciences, Nagoya University, and the Albert Einstein Institute.

The main research themes that are being investigated by cluster members include the study of strong gravitational fields and the search for a good approximation to the fundamental theory of gravity with applications to cosmology, and the study of compact objects in various astronomical contexts with a focus on topics relating to high-energy astrophysics. Cosmology and compact objects (neutron stars and black holes), and the science of gravitational waves are the main areas of application of relativistic gravity and encompass a wide variety of astrophysical objects and phenomena that need to be understood. Research on compact objects (isolated or in binary systems) include studies of their formation history, number densities throughout the universe, and the signatures of gravitational waves radiated by them.

As mentioned previously, the "standard" theory of gravity is (naively) believed to be Einstein's theory of General Relativity (hereafter abbreviated as GR). However, when one tries to formulate a quantum version of gravity, a unification that has been done for the other three fundamental interactions, this theory leads to mathematical difficulties that cannot be eliminated without substantially modifying the theory. Quantum physics and high-energy physics necessarily modify GR, generating a wide spectrum of extended theories that deviate only a little from GR at low energy (and solar system) scales, but with large deviations at higher energy. These deviations can, in principle, manifest their effects on large (cosmological) scales, or possibly even at spatial scales intermediate between solar system scales (where GR is well tested and known to be obeyed in the weak-gravity regime) and cosmological scales (i.e., the scales of galaxies and galaxy clusters).

Cosmologists are also trying to explain the 1998 discovery that the current expansion of the universe is accelerated. This discovery, obtained by studying the relation between the luminosity of Type Ia supernovae and their distance, does not fit the model of a decelerating (yet expanding) universe that had been accepted until 1998. To remain within the context of GR and explain the cosmic acceleration, it is necessary to postulate a mysterious and otherwise undetected dark energy with extremely exotic properties (highly negative pressure). This dark energy could even take a very exotic form that violates the second law of thermodynamics cherished by physicists. It is prone to violent instabilities and may cause the universe to end in a Big Rip singularity at a finite point in time in the future. Many researchers dissatisfied with this ad hoc fix believe that the current cosmic acceleration could well be the first detected deviation of gravity from Einstein's theory. The corrections picked up by GR in the high energy regime may manifest themselves in cosmic rays, in highly energetic astrophysical events near black holes, or in gamma-ray bursts in binary systems. The gravitational waves emitted by these astrophysical objects carry with them the signature of the theory. No gravitational wave has been detected directly yet, but their discovery is expected sometime in the next ten years. Their detection and the study of their spectrum and polarization properties would shed light on the correct theory of gravity. We also note that the progenitors of Type Ia supernovae are unknown (a 40-year old problem in astrophysics) and thus it is critical that we determine their origin.

Cluster members plan to address the following problems:

- What are the modifications to GR that one can reasonably expect given a few basic assumptions about gravity? What are their effects on cosmology (expansion history, evolution of voids, formation of galaxies/clusters)?
- What is the gravitational wave content of extended gravity, how are gravitational waves generated, and what signatures of the theory should we look for in experiments detecting these waves?
- How would different descriptions of the gravitational radiation reaction affect the evolution of close interacting binary systems, and could these differences be detected?
- What model can be proposed that would explain the salient observations of Type Ia supernova explosions and also account for their observed frequency? Are these models consistent with the frequencies for all galaxy morphologies?

In order to achieve these objectives, some of the cluster members who have need of massive computing power will use the supercomputer at

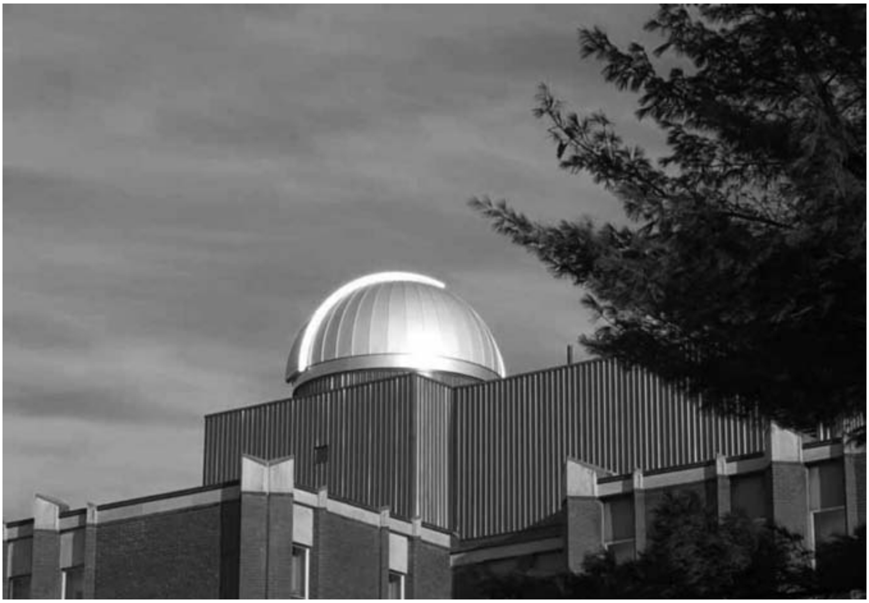

Fig. 4: The Bishop's University Astronomical Observatory on top of the roof of Nicolls building.

the Université de Sherbrooke of which we are full partner in the Réseau québécois de calcul de haute performance (RQCHP). The research effort will also benefit from the collaboration of undergraduate and graduate students who will be working on these problems under the supervision of cluster members. The training of Highly Qualified Personnel (HQP) will clearly be an important legacy of the cluster initiative.

Public Outreach in the Eastern Townships

From the earliest times, astronomy has provided civilizations with very significant stepping stones in the progression of human development. For example, our systems for timekeeping are largely derived from astronomical observations. Moreover, our calendars were developed so that our agrarian ancestors could plant their crops at the optimal times of the year so that they were less likely to lose them due to frost damage while at the same time maximizing the growing season and thus increasing the overall production. An intimate understanding of astronomy was also of paramount importance to sailors and other people who wished to circumnavigate the earth. Much of our mathematics and some of our geometry were developed in order to satisfy the needs of astronomical research. For example, the Greek astronomer Hipparchus devised a method for carrying out trigonometric calculations. Isaac Newton invented calculus primarily for the purpose of understanding astronomical observations (in relation to those on the earth). Things are not much different today as astronomical observations require huge amounts of computational resources. Not only are computers needed to carry out detailed simulations of various phenomena that we observe in our cosmos, but some astronomical projects amass more than one terabyte of data per day. These requirements drive computer-related industries to significantly improve their hardware and software offerings. It would not be an overstatement to say that astronomy has made a huge contribution to the improvement of the human condition.

We also cannot forget that astronomy plays an important role in educating our youth in getting them excited about science. Given the rate at which scientific knowledge increases, the ordinary citizen must have the literacy to appreciate some of the public-policy issues that arise from technological developments and have the ability to make informed decisions. Members of the STAR cluster are keenly aware of these issues and have been taking concrete steps to educate the public at large. In particular, through the generosity of its donors, Bishop's was able to build an astronomical observatory in 2006 (Figure 4). The observatory serves to educate and train our own undergraduate and graduate students, but it also serves the community's need for science outreach (Figure 5). The observatory has entertained K–11 students, CEGEP students, cultural groups, and the general public during its open-house events. Since its inauguration, nearly 3500 visitors have seen the observatory, and many of them have also been present for a lecture that is normally given before the observing sessions. This Powerpoint presentation is entitled "A Brief Tour of the Universe" and it is a powerful way for astronomers to convey the vastness and beauty of the universe to the general public. It is also a valuable way for individuals to interact with scientists and have their questions answered on an individual basis.

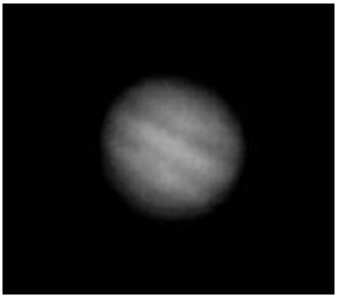

Fig. 5: The planet Jupiter as taken with the telescope at the Bishop's University Astronomical Observatory. Note that various colour bands can be seen in the atmosphere of Jupiter.

So why is astronomy so important? The bottom line is that it has made significant contributions within the cultural, technological, and scientific contexts. Astronomy is important in how it influences human creativity and how it inspires the creation of poetry and music.[7] From a scientific viewpoint, it allows us to ponder the important questions concerning where we came from, how it all started, and how it will all end. Technologically, astronomy has driven the development of complex pieces of optical equipment such as digital cameras and pushed the envelope when it comes to construction of supercomputers.

But above all else, when it comes to our understanding of why we participate in the scientific process and why we are so enthralled with the discoveries that we make, we should remember the words of Aristides Bastidas[8] who said "Science must be like the light of the sun, it must shine for everyone."

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NOTES

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1 Quoted from chapter 19 of *The Adventures of Huckleberry Finn*, by Mark Twain.

2 See the seventh book of Plato's *The Republic*.

3 Technically electromagnetism has been unified with the Weak force of nature yielding the Electroweak force. Further unifications are possible with the Strong (nuclear) force leading to the Grand Unified Theory (GUT).

4 Reginald Aubrey Fessenden was born on October 6th, 1866 in East Bolton (QC). He was enrolled as a student in Bishop's University but left in 1884 having nearly completed his degree. Although not completely definitive, Fessenden seems to have been the first person to ever make an audio radio transmission in 1900.

5 Note that the mass of four hydrogen nuclei is slightly greater than the mass of one helium nucleus. This difference (known as the mass defect) is reason for the energy generation.

6 The Observatoire Mont Mégantic (OMM) is continuing to be a mainstay of Quebec astronomy. Bishop's University is now a full-fledged member of the Centre.

7 For example, Bishop's professor Andrew MacDonald's tribute to the heavens: *Pleiades Variations; The Great Square of Pegasus*.

8 This quote was part of Bastidas' acceptance speech for the 1980 International Kalinga Prize awarded by UNESCO recognizing his contributions to the popularization of science and technology.