Institute for Computational Astrophysics
Annual Report
2022-23

ICA Annual report, compiled by Marcin Sawicki, Interim Director

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ON THE COVER

The cover shows an image of the galaxy cluster MACS 0417 recently observed by James Webb Space Telescope as part of the CANUCS collaboration. The image, created by ICA member Dr. Vicente Estrada-Carpenter from JWST observations at different wavelengths, shows the core of the cluster. Many galaxies that are located behind the cluster are gravitationally lensed by the cluster's mass concentration. This includes the question-mark-shaped object, which is actually a pair of interacting galaxies whose light has been bent and - like a mirage - formed into multiple images by Einstein's gravitational lensing effect. This system is the subject of an upcoming paper by Estrada-Carpenter, other ICA members, and their colleagues in the CANUCS collaboration.

Image credit: NASA, V. Estrada-Carpenter, and the CANUCS team.

1. Overview

The ICA's mission is to promote the study of complex astrophysical phenomena by numerical simulation, a remit which also includes large-scale astrophysical data analytics. Throughout the past decade, the ICA has acquired access, through ACEnet and Compute Canada (organizations in which several ICA members have played very significant roles), to significant high performance computing resources required for these simulations and analysis. More recently, the ICA has also engaged in the processing and analysis of large astrophysical datasets and in the development of software in support of new astronomical instruments. A number of graduate students have been part of the ICA, and to date eighteen MSc degrees and eight PhD degrees were awarded to students supervised by ICA faculty members. In addition, the ICA has enriched the environment of the Department of Astronomy and Physics and of the University by hosting sixteen postdoctoral fellows to date as well as numerous short- and long-term research visitors.

As of August 2023, the ICA has six full-time faculty members: Dr. David Clarke, Dr. Ivana Damjanov, Dr. Vincent Hénault-Brunet, Dr. Marcin Sawicki (Acting ICA Director), Dr. Ian Short, and Dr. Robert Thacker. Additionally, two emeritus faculty members, Dr. Robert Deupree and Dr. David Guenther, continue their affiliation with the ICA.

Working with ICA faculty during AY2022-23 were 23 early-career researchers:

- Six postdoctoral fellows: Dr. Guillaume Desprez, Dr. Vince Estrada-Carpenter, Dr. Nick Martis, Dr. Gaël Noirot, Dr. Michele Pizzardo, and Dr. Robert Sorba,
- Ten graduate students (including one 18-month visiting PhD student): Yoshihisa Asada, Lingjian Chen, Maigan Devries, Nolan Dickson, Angelo George, George Ridgeway, Fraser Smith, Peter Smith, Shannon MacFarland, Devin Williams
- Seven undergraduates: Abigail Battson, Starling Cox, Rebecca Hamel, Katherine Myers, Joyo Smit.

The ICA also has three external members: Dr. Ralph Pudritz (McMaster University) Dr. Richard Henriksen (Queen's University), and Harrison Souchereau (Yale University). Ms. Shannon Rhode provides administrative support as ICA Assistant, splitting her support duties between the ICA (30%) and the Department of Astronomy and Physics (70%).

During AY 2019-20 the ICA carried out a self-study which a new direction for the Institute, namely that of growing the ICA's activity in the direction of Astrophysical Data Analytics (for details, see the ICA's 2020 Self-study Report). This new direction is closely aligned with the strategic plan of the Department of Astronomy and Physics. In particular, in addition to the resulting expansion in research scope and activity (see Section 2), ICA faculty Drs. Damjanov and Hénault-Brunet introduced course-based training in astrophysical data analytics for both undergraduate and graduate students at SMU. Since AY2021-22 the Institute has been hosting online ICA Data Analytics seminar series (see Section 3 of this report), and an Galaxy Evolution Discussions group that now attracts 12-15 researchers twice a week. Two more initiatives (the annual ICA Research Jamboree and the bi-monthly "Un-seminar" seminars will be inaugurated in AY2023-24) — see Sec. 5 for more details.

In parallel, the research capacity of the ICA has been rebuilding so that in AY2021-22 the Institute had six SMU-based faculty (compared to four in 2017-18) and six post-doctoral fellows (compared to just one one in 2017-18). This ramp-up coincides with expanding involvement of Institute staff in key roles within leading national and international astronomy projects of the present (exemplified by the recently-launched Webb Space Telescope) and the future (see Section 2.5).

The [ICA's website] provides up-to-date information about the Institute and its people.

2. Research

Astrophysical research is the primary goal of the ICA. Institute members engage in research in a number of areas of astrophysics using a range of research techniques. These range from numerical modelling to the analysis of complex datasets and development of new instruments and techniques;

they tackle a broad spectrum of topics from the atmospheres of stars to the formation of galaxies soon after the Big Bang. These are described in the following sections (Sec. 2.1-2.5), with a focus on progress in AY2021-22. Notably, this research has resulted in 31 papers published or submitted to journals in AY2021-22 (see Section 6).

2.1. Stellar atmospheres

During AY 2022-23, Dr. Ian Short continued development of the Chroma+ suite of stellar atmospheric and spectrum modelling codes written in Python and Java. The code now reads the VALD3 atomic line list in the near UV to near IR range containing 600,000 lines (34 Mbytes), and provides a much improved fit to the solar flux distribution. The spectrum synthesis calculation has now been automatically parallelized on the Compute Canada cluster Graham using the slurm ArrayJob facility, and now allows the entire visible band spectrum to be synthesized at high resolution for about ten models in a about a day. He has also commissioned the relatively new low resolution spectrograph at the Burke-Gaffney Observatory (BGO) and evaluated the quality of fit of Chroma+ synthetic spectra to BGO spectra for both early- and late-type stars. These results were published in "The ChromaStar+ modelling suite and the VALD line list", 2023, Short, C. Ian, 10.48550/arXiv.2307.01279 and in "The Burke-Gaffney Observatory: A fully roboticized remote-access observatory with a low resolution spectrograph", 2023, Short, C. Ian, Lane, David, J.& Fields, Tiffany, 10.48550/arXiv.2307.07022. See www.ap.smu.ca/OpenStars for additional information.

2.2. Magnetohydrodynamics

Dr. David Clarke, whose retirement took effect at the end of August, 2023, is primarily interested in performing magnetohydrodynamical (MHD) simulations to investigate open problems in astrophysics including astrophysical jets and the non-ideal effects of ambipolar diffusion. In addition, he maintains and provides the astrophysical community with the widely-used MHD code ZEUS-3D which has enabled numerous other investigators to do research in their areas of interest. Details of these activities have been given in previous ICA reports.

ZEUS-3D is a mature code that can be downloaded from www.ap.smu.ca/~dclarke/zeus3d complete with installation and user's manuals, and to date some 850 unique downloads of the code have been recorded. A user-friendly version of ZEUS-3D's successor, AZEuS (that incorporates adaptive mesh technology), remains under development and will be one of Dr. Clarke's "retirement projects".

For most of his last year on the full-time faculty, Dr. Clarke has spent his non-teaching hours completing his senior undergraduate level textbook entitled "A First Course in Magnetohydrodynamics". This 520-page text with 130 worked problems and projects has recently been submitted to Cambridge University Press with a tentative release date sometime in June, 2024.

2.3. Star clusters

Dr. Hénault-Brunet's research programme uses a combination of dynamical models, statistical methods, and observations (spectroscopic, photometric, and astrometric) to tackle open questions about the dynamics of globular star clusters and related astrophysical implications, in particular: (1) the black hole content of globular clusters and their contribution to rate of gravitational wave events, (2) the evolution of the stellar mass function of globular clusters and constraints on their initial mass function, (3) the dynamical interaction between globular clusters and the Milky Way and how this informs scenarios for the formation and evolution of these systems.

Some of the research topics pursued during the reporting period include:

(i) A survey of the stellar kinematics in the outer regions of globular clusters: A series of collaborative workshops that Dr. Hénault-Brunet coordinated in previous years resulted in two successful observing proposals (using the 2dF/AAOmega instrument on the Anglo-Australian Telescope, and the FLAMES instrument on the VLT) to obtain spectroscopy of hundreds of stars in the outskirts of several Milky Way globular clusters. The kinematics of stars in these external regions of globular clusters can reveal crucial information about their interaction with the Milky Way, including possible traces of dark matter around clusters. A second paper from this survey (led by PhD student Zhen Wan; University of Sydney) was published this past year. The study analyzes the kinematics and dynamics in the outskirts of four globular clusters, and by comparison with N-body simulations concludes that the observations can entirely be explained by tidal interaction with the Milky Way, with no need for dark matter around these four clusters.

(ii) Since March 2022, Dr. Hénault-Brunet has taken up the role of Near-Field Cosmology Science Working Group Lead for the Canadian Space Agency Phase 0 study for the CASTOR mission (the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research, which could launch by 2030). This involves coordinating a group of near-field cosmology experts to provide feedback on mission requirements, updating and designing proposed legacy surveys for the mission, and assessing and optimizing surveys for astrometric programs (proper motions and parallaxes). This role culminated in 2023 with significant contributions to a final report presenting a feasible and compelling proposal for the mission to proceed. Dr. Hénault-Brunet led the development of one proposed Legacy Survey proposal (the CASTOR Galactic Substructures Survey) featuring in this report, led the development of the astrometric science case for CASTOR (and how it would complement Gaia), and involved two of his students in the Phase 0 study. Graduate student Nolan Dickson performed crucial simulations of the Galactic stellar field to produce mock catalogues and observations in order to advance the Science Readiness Level of the proposed Legacy Surveys. Undergraduate student Rebecca Hamel explored the potential of CASTOR observations in the diffuse outskirts of globular clusters and also took a leadership role in implementing the Education and Public Outreach roadmap for the mission, developing educational material for social media campaigns.

(iii) Dr. Hénault-Brunet's group continues to work on dynamical modelling of globular clusters to provide new constraints on the dark remnant content of globular clusters (including black holes) and their (initial) stellar mass function.

Graduate student Nolan Dickson has been fitting multi-component equilibrium “mass models” that were recently developed by Hénault-Brunet and collaborators to a wide range of data, for a sample of ~40 Milky Way globular clusters. These models can be used to constrain the present-day mass in black holes and the initial mass function (IMF) of stars up to ~8 $M_\odot$ (locked in white dwarfs at the present day) by fitting them to detailed observations of visible tracer stars. One key finding that the IMF above 1 $M_\odot$ is generally consistent with the canonical Salpeter slope (Dickson, Hénault-Brunet et al., 2023), with no obvious indication of the shallower slopes at lower metallicities suggested by some star formation theories. This work also provides improved and independent constraints on the size of present-day BH populations in a significant sample of clusters (Dickson, Smith, Hénault-Brunet et al., submitted). In a companion study (Baumgardt, Hénault-Brunet et al., 2023), constraints on the global present-day stellar mass function within globular clusters to show that the IMF of globular clusters below of 1 $M_\odot$ was likely more bottom-light (i.e. lacking low-mass stars) than the commonly assumed canonical Kroupa or Chabrier IMF. This has significant implications for the evolution of GCs, the number of black holes (BHs) initially formed per unit cluster mass (and thus the rates of BH-BH mergers), the self-enrichment of GCs from massive star ejecta (and the problem of multiple populations), and the interpretation of the properties of distant GCs in the early Universe as probed by the James Webb Space Telescope.

In parallel, undergraduate research student Abigail Battson used Gaia DR3 data to perform a systematic search for high-velocity stars ejected from three-body interactions (between a single object and a binary) involving a “bully” BH in globular clusters. She has identified promising candidate high-velocity stars originating from BH interactions in several clusters (Battson, Hénault-Brunet et al., to be submitted). The properties of these high-velocity stars is another indirect probe of the presence of black holes in globular cluster cores.

One of the main limitations in understanding the co-evolution of black holes and globular clusters is the unknown initial density of globular clusters at the time of their formation ~12 Gyr ago. MSc student Maigan Devries has investigated how present-day populations of binaries (in particular their period distribution) can be used to constrain the initial density of clusters. Binaries are dynamically affected by their interactions within the cluster, potentially resulting in their disruption. Disruption (or ionization) occurs preferentially for binaries with a binding energy smaller than the average kinetic energy of a star in the cluster. As the average kinetic energy is related to the density of the cluster, denser globular clusters result in higher ionization rates and more effective destruction of long-period binaries. Since the majority of binary disruptions occur early on in the clusters evolution when a cluster is at its densest, the current population of binaries and their period disruption may be used to infer back to the initial density of the globular cluster. Using this idea, a novel hierarchical Bayesian method was developed (Devries, Hénault-Brunet, in prep.) to use multi-epoch radial velocity measurements in the cluster NGC 3201 (from the VLT-MUSE integral field unit spectrograph) to place constraints on the intrinsic binary period distribution in this cluster, with a particular emphasis on understanding the long period tail of the distribution.

2.4. The evolution of galaxies

Many ICA researchers study the evolution of galaxies. These are faculty members Drs. Ivana Damjanov, Marcin Sawicki, and Rob Thacker, as well as post-doctoral fellows Drs. Guillaume Desprez, Vince Estrada-Carpenter, Nick Martis, Gaël Noirot, Michele Pizzardo, along with several students.

Dr. Sawicki studies the formation and evolution of galaxies, with a specific interest in their earlier evolution, the so-called "high redshift Universe". This research allows us to look back in time to when the Universe and its content were only a fraction of their present age. This research area is making enormous advances at present following the spectacularly successful lauch of the James Webb Space Telescope (JWST) in December 2022. Several ICA researchers, led by Dr. Sawicki and including Drs. Desprez, Estrada-Carpenter, Martis and Noirot, along with students Yoshihisa Asada, Shannon MacFarland, and Katherine Myers are at the forefront of this work internationally. As key members of the CANUCS survey that uses 200 hours of guaranteed JWST observing time, they are leading Canada's exploration of the distant Universe with JWST.

CANUCS began taking JWST data in October 2022 and observations are scheduled to wrap up in December 2023. While the full dataset is growing, these ICA researchers have already made use of the early data from this project: Mr. Asada has led a paper on the discovery of two extremely-low mass galaxies undergoing a merger-induced starburst just 1 billion years after the Big Bang (when the Universe was just a few percent of its present age). These "baby" galaxies are being assembled through two processes long theorized to be key for building the first generation of galaxies: mergers of galaxies from smaller building blocks and intense bursts of star formation.

ICA researchers have also participating vigorously in the exploitation of early-release science observations by the JWST, particularly focusing on working with the imaging and spectroscopy of the SMACS 0723 dataset (the first JWST science data released to the community in mid-2022 and dubbed "Webb's First Deep Field" for its depth and image clarity. With these, ICA postdoc Dr. Gaël Noirot has led a project that uses observation of this field made with JWST's made-in-Canada NIRISS instrument to measure more than a hundred new redshifts to galaxies that were previously unknown. These were made world-public and described in a related peer reviewed paper; as the most comprehensive redshift catalog in Webb's First Deep Field, they have become a valuable resource to the research community. ICA members have also participated in several leading roles in the discovery and analysis of "The Sparkler" - a galaxy located in "Webb's First Deep Field" behind the cluster SMACS 0723 and glowing with some of the first star cluster to have formed after the Big Bang. Our work on The Sparkler and its star clusters, published in Astrophysical Journal Letters, has been the subject of extensive media coverage nationally and internationally.

The successful launch, on Canada Day, 1 July 2023, of the European Space Agency's flagship *Euclid* mission paves the way for science that will be highly complementary to that which JWST enables. While JWST can observe extremely faint and distant objects, Euclid specializes is studies of the more nearby (but still very distant) Universe but over much larger areas of the sky than is possible with JWST. Building on the continuing success of the CLAUDS survey (see below), Dr. Sawicki co-leads (with S. Arnouts of France) the Deep Euclid U-band Survey (DEUS) that is being carried out by a consortium of fifty Canadian and French astronomers, including ICA's faculty Dr. Ivana Damjanov, postdocs Drs. Desprez, Estrada-

Carpenter, and Noirot, and students Lingjian Chen, Angelo George, and Devin Williams. DEUS paves the way for the exploitation of the upcoming deep data from *Euclid* space telescope, and we look forward to using these combined datasets to study the distant Universe when the first internal (to the *Euclid* team) data release happens in late 2024.

The Euclid/DEUS project builds on its older sibling, the CLAUDS survey (a major Canada-France-China observing collaboration that he Dr. Sawicki continues to lead), which was undertaken with the Canada-France-Hawaii Telescope (CFHT), and its combination with the HyperSuprime-Cam Subaru Strategic Program (HSC-SSP) on Japan's national Subaru Telescope Together, these two surveys probe the distant Universe to an unprecedented combination of area and depth that will be unmatched until the next decade. The merged CLAUDS+HSC-SSP catalogs of galaxies and stars, which were recently finalized and validated, form the foundation of a number of scientific investigations, including a major data release to the community led by and described in a peer-reviewed paper by ICA post-doc Dr. Guillaume Desprez. For more information on the CLAUDS project see the CLAUDS Project Website.

A number of projects based on the merged CLAUDS and HSC-SSP datasets is now being led by ICA members (and many more by external collaborators). These including the study of galaxy stellar mass functions and massive galaxy environments led by PhD student Chen and studies of galaxy morphologies led by students George and Williams; both these projects are described in more detail further down. Altogether, over 23 peer-reviewed papers based on CLAUDS data have been published to date, 4 more are undergoing peer review, and many more are in preparation by ICA members and external collaborators.

ICA faculty member Dr. Ivana Damjanov utilizes large-area imaging and spectroscopic surveys to study the evolution of galaxies in the last 7 billion years, which corresponds to the second half of cosmic history. These studies provide crucially important constrains for the physical processes responsible for triggering, regulating, and halting star formation in galaxies and for the mechanisms that promote galaxy morphological transformation and growth after the cessation of star formation. Dr. Damjanov is actively involved in the HSC-SSP, CLAUDS, and DEUS imaging surveys mentioned earlier, as well as the HectoMap survey (a dense spectroscopic survey of 52 square degrees within the HSC-SSP footprint). Using measured structural and spectroscopic properties of non-star forming (i.e., quiescent) galaxies in HectoMap, Dr Damjanov has led the study that, for the first time, separates *and* quantifies the impact on the average quiescent size growth of (a) galaxies joining the quiescent population with time and (b) galaxies that are evolving after reaching quiescence within this population (Damjanov et al. 2023). The follow-up studies explore the connection between changes in sitellar population properties of quiescent galaxies (e.g., average age, metallicity, dynamics) and the reported structural evolution with a new approach based on the full-spectrum fitting performed on median HectoMAP spectra of galaxies segregated by stellar mass (Damjanov et al. 2023, to be submitted to the AAS Journals)

Dr. Damjanov is developing the optimal strategy for measuring sizes and shapes of galaxies in the CLAUDS+HSC-SSP using a combination of existing software and custom-built algorithm for the modelling of galaxy light profiles in large-area high-quality images obtained with a ground-based telescope. Two student-led projects are underway as part of this effort: working with Dr. Damjanov and Dr. Sawicki, PhD candidate Angelo George has been modeling the two-dimensional galaxy light profiles in the CLAUDS+HSC-SSP data. One of most intriguing recent results of this work is that the sizes of star forming galaxies measured from their light profiles that correspond to newly formed stars are always larger than the sizes from profiles that correspond to the light from older stellar populations. This work shows that over t 6 billion years of cosmic time star forming galaxies experience inside-out quenching: spatial distribution of older stars broadens with time, pushing the remaining star forming regions to the outskirts (George et al. 2023, submitted to MNRAS).

Starting as a summer undergraduate research assistant in 2018, Harrison Souchereau has been developing a versatile algorithm for the extraction of one-dimensional radial profiles of galaxies in the CLAUDS+HSC-SSP fields. After completing the undergraduate degree in April 2020 (with honours thesis project overseen by Dr. Damjanov) and joining the graduate program in Astronomy at Yale University, this student has continued to collaborate with Drs. Damjanov and Sawicki. The team is preparing a publication that will provide the technical overview of the code and accompany its public release (Souchereau et al. 2023, in prep). Devin Williams, the first-year PhD student under the supervision of Drs. Damjanov and Sawicki, has been using the software to measure radial profiles of several million CLAUDS+HSC SSP galaxies and examine the change in their outer regions as a function of galaxy mass, distance, star formation activity, and environment. The highlight of their MSc thesis (defended in August 2023) is a clear picture that favours mergers with low-mass satellites as the main mechanisms behind the observed growth of outskirts in massive galaxies, regardless of the current (global) level of star formation in them.

Using the funding for student researchers from the New Technologies for Canadian Observatories (NTCO) program[1], Dr. Damjanov started a project to develop deep (machine-) learning (DL) approach to the identification of galaxies that show signatures of (recent) past merger activities in deep HSC-SSP images (e.g., shells and/or streams). The lead of the program is a SMU undergraduate student Joyo Smit, and it is being developed in collaboration with DL experts Drs. Helena Domínguez Sánchez and Jesús Vega-Ferrero (Centro de Estudios de Física del Cosmos de Aragón and Universidad de Valladolid, Spain). During the summer or 2023 the student explored unsupervised DL method, so-called contrastive learning, and its adaptation to the classification of galaxy images. The first results are promising and thus the originally envisioned summer project will continue throughout the 2023/24 school year.

The HectoMap survey includes several hundred galaxy clusters. The most massive clusters in the survey display arcs surrounding their most massive galaxies. These arcs are light profiles of background galaxies (i.e., galaxies more distant than the cluster) which are bent (lensed) due to the effect that the gravity of both luminous and dark matter along the line of sight has on the light as it travels from observed distant galaxy. Measurements of the shapes of and distances to the lensed galaxies enable modelling of the distribution of dark matter within massive galaxy clusters. Dr. Damjanov has developed observing proposals to target these clusters in collaboration with staff astronomers at the W. M. Keck Observatory, the host of the largest-mirror telescopes on Earth. The first massive lensing cluster target was observed in June 2020. As part of their MSc thesis project, graduate student George Ridgeway has used the data to increase the number of known cluster members (by almost 100%) and investigate the internal properties of galaxies residing in different regions of the cluster that looks to be a unique analog of the local massive Coma cluster detected when the universe was only 60% of its current age. In their thesis (defended in August 2023), the student shows, using innovative statistical approach to account for undetected cluster members, that in this actively forming cluster a) galaxies are well mixed with no clear gradient in stellar age with respect to the distance from the cluster centre, and b) massive galaxies are, on average, 30% larger that their counterparts residing in lower-density regions.

Post-doctoral fellow Dr. Michele Pizzardo, who joined Dr. Damjanov's group in November 2022, has been very successful in exploring dynamical properties of galaxy clusters in IllustrisTNG simulations. In a series of publications , Dr. Pizzardo explores the reach of observational techniques based on spectroscopic surveys to probe underlying three-dimensional (3D) distribution of galaxies in clusters and thus trace the growth of structure in the aging universe. Pizzardo et al. (2023a) provide a simple calibration factor that translates observed galaxy cluster mass profiles (based on caustic technique) into their real (unobservable) 3D profiles. In the follow-up study, Pizzardo et al. (2023, accepted for publication in A&A) use simulated galaxy clusters to describe a technique for measuring cluster mass accretion rates that can be directly applied to observations. These publications are mapping out a pathway for employing future extremely large spectroscopic surveys and their statical samples of galaxy cluster to learn much more about the mass assembly of the densest corners of the universe.

On the theoretical side, Dr. Rob Thacker and graduate student Fraser Smith have been working to understand galactic star formation on a more statistical footing. Specifically, for theoretical

[1] https://www.uvic.ca/research/centres/arc/create/index.php

modelling of star formation it is useful to be able relate the overall time variation in star formation within an individual galaxy to the overall statistical variation observed in a sample of galaxies of similar size. The root concept behind this is ergodicity, namely the idea that a single system will, over time, occupy all possible states available to it, or in the case of restricted freedom to create so-called "partial ergodicity.". This is a significant simplification of evolutionary behaviour but for certain systems, such as gas contained within a box, it is actually an accurate description.

For the evolution of galaxies there is agreement that individual galaxy evolution is not truly ergodic, but the exact departure from this assumption has not been estimated, and neither has the impact of different physics within the galaxy formation process been considered as a part of this process. In particular one outstanding issue is whether there might be a mass dependence in the amount of variation seen, i.e. "partial ergodicity." The goal of this research is to put some constraints on the maximum evolution by considering the different physics at play in galaxy formation in a systematic fashion. Of course, it is challenging to recreate a precise sample of galaxies, so rather than simulating a larger volume, statistical modelling of selected Sloan survey galaxies has been used to create model galaxies with parameters drawn from distributions determined by the observed catalogue. While this does introduce the possibility of creating galaxies that are not allowed physically in nature, since the exact parameters are drawn from modelled distributions in practice the sampled galaxy parameters are reviewed to ensure physical plausibility. By the nature of their construction, they are statistically appropriate. These galaxies were created using the “make galaxy” code provided to us by Dr Volker Springel, augmented to include additional components such as substructure and a hot gas halo. To calculate evolution of the galaxies the GIZMO code was used, but in a step-by-step approach of adding different physics processes, including feedback and winds. The key outcome of this work, as defended in Smith's MSc thesis in August 2023, is that there is fairly strong evidence for a mass dependence in the level of ergodicity shown, i.e. partial ergodicity. We believe this to be the first time such a result has been demonstrated in the astrophysics literature. For his PhD research Smith intends to further extend this result to improve statistical robustness.

With honours thesis student Starling Cox, Dr. Thacker has investigated the transfer of energy from dark matter to gas in large scale simulations of collisions of clouds of dark matter and gas. Although heavily simplified as compared to evolution in the actual universe, these modelled collisions allow the precise exchange of energy to be evaluated under controlled conditions. Normally in any situation where there are different types of particles we expect equipartition of energy between the particles. However, hydrodynamics has distinctly different behaviour from the “collisionless” evolution of both dark matter and stars. For example, under high compression or high velocities gas will undergo shock heating which is an irreversible process leading to a different (higher) entropy state for the gas.

Low resolution studies of these kinds of collisions were undertaken quite some time ago, but as yet no higher resolution follow-ups have been conducted. The results of this research show that separating the gas distribution from the dark matter can lead to vastly larger (well over three times as much) energy transfer than for systems in which the centres of mass initially coincide. This means that in the rare cases where baryons are expelled from halos, we might expect some unusual dynamical properties in the later evolution. The one challenge remaining in this work is that the outcomes appear to be fairly strongly dependent on the overall resolution as the shock processes determine the overall level of energy transfer.

2.5. Development of new research tools

ICA scientists are involved in the development of new astronomy research tools.

2.5.1. GIRMOS

ICA astronomers Drs. Damjanov, Hénault-Brunet, and Sawicki, participate in the CFI-funded GIRMOS project to build a multi-unit field spectrograph for the giant 8-metre Gemini telescope in Hawaii. When coupled with Gemini’s new NSF-funded Adaptive Optics (AO) system now also under construction, GIRMOS will enable detailed spectroscopic studies of distant objects and will be complementary in that regard to the recently-launched JWST. All three are members of the

GIRMOS Science Team, where they help guide the development of the instrument's capabilities with reference to science goals. Dr. Sawicki leads the development of the GIRMOS data reduction software suite which will be vital for all users of GIRMOS in processing the instrument's raw data into science-ready products.

2.5.2. CASTOR

CASTOR is the #1 priority for space astronomy in Canada (source: Canadian Astronomy Long Range Plan 2020-2030) and is moving forward with development funding from the Canadian Space Agency, aiming for launch in the late 2020s. CASTOR is a project that has long-standing ICA connections that started in 2010 when Dr. Sawicki and then-graduate student Robert Sorba provided the first studies of CASTOR precursor's expected performance for measuring the Dark Energy equation of state, and continued through the subsequent years with contributions from ICA sabbatical visitor Dr. Ikuru Iwata, postdoc Dr. Thibaud Moutard, and student Martin Hellmich.

Starting in early 2022, CASTOR entered a period of accelerated development, and ICA plays key roles in several areas, supported by funding from the Canadian Space Agency. Notably, ICA received a third of the current CSA funding going to Canadian universities and ICA faculty Drs. Damjanov, Hénault-Brunet, and Sawicki, along with postdocs Drs. Gaël Noirot and Robert Sorba, and students Nolan Dickson and Rebecca Hamel have played key roles in the CASTOR project.

Dr. Hénault-Brunet is the Lead of the CASTOR's Near-Field Cosmology Science Working Group (SWG). This involves coordinating a group of near-field cosmology experts to provide feedback on mission requirement, updating and designing proposed legacy surveys for the mission, and assessing and optimizing surveys for astrometric programs (proper motions and parallaxes). As part of this effort, summer undergraduate research assistant Rebecca Hamel worked on simulating proper motion measurements with the CASTOR telescope and applications to kinematics in the diffuse outskirts of globular clusters. Nolan Dickson (MSc 2022, starting his PhD with Hénault-Brunet in September 2022) is also expected to contribute to this study in the near future.

Dr. Damjanov and Sawicki are senior members of CASTOR's Galaxy Evolution SWG, and Dr. Sawicki is also a senior member of the Cosmology SWG. Working under Dr. Sawicki's direction, Dr. Sorba has generated realistic photometric performance forecasts essential for assessing and optimizing CASTOR's performance in measuring the Deark Energy equation of state. He has also produced simulations of deep spatially-resolved CASTOR observations of distant galaxies, assessing how well CASTOR will do in studies of star-formation quenching in the distant universe. In parallel, Dr. Noirot has built a data simulator for CASTOR's slitess grism spectrograph (similar to that of JWST'S NIRISS but operating over a much wider field of view and in the ultraviolet instead of the infrared). The simulations from this have been used being used by the CASTOR science team to develop and assess CASTOR's observing strategy and finalize its science performance metrics.

As CASTOR moves to the next phase of its development and moves forward to seek full federal government funding, the ICA looks forward to continuing to contribute and grow its involvement in the project.

3. ICA Seminars and Meetings

In AY2021-22 the ICA began a new online series in Astrophysical Data Analytics. These seminars provide presentations by and follow-up discussions with leading data analytics experts, and are designed to appeal to faculty, postdocs, and research students from astronomy as well as computational sciences. Following on this successful launch, AY2022-23 saw the 2nd year of the program, with the following talks: Dr. Hossen Teimoorinia (NRC Herzberg / Canadian Astronomy Data Centre) and Dr. Viviana Acquaviva (City University of New York). Dr. Teimoorinia's talk was on *Mapping the Diversity of Galaxy Spectra with Deep Unsupervised Machine Learning*, while Dr. Acquaviva's presentation was on *Galaxy evolution with machine learning: the perilous road from simulations to data.*

The Galaxy Evolution Discussions Series consists of frequent (twice-weekly) regular forums for researchers interested in studies of the formation and evolution of galaxies. This field is an area of particular strenght of the ICA with much observational and theoretical research

This discussion series attract ~15 attendees, including 3 faculty members with the rest split roughly evenly between postdocs and graduate and undergraduate students.

Two new initiatives are being inaugurated int he coming AY2023-24: the first annual ICA Research Symposium and the bi-montly "Un-Seminar" seminars. For more detail see Sec 5.

4. Service

Members of the ICA play significant roles in service to the University and the community on local, national, and international levels. Some of these activities are summarized here.

4.1. Saint Mary's

Dr. Short was on leave during the reporting period. Dr. Thacker served as Director of the Saint Mary's Science Outreach Centre. Dr. Hénault-Brunet serves as the Director of the Burke-Gaffney Observatory since February 2022,and Dr. Sawicki continued to serve for the fourth year as the ICA's Acting Director.

As Director of the SMU Science Outreach Centre, Dr. Thacker coordinated Faculty open houses, student visits to the Faculty of Science, and Chaired of Faculty of Science Community Engagement & Outreach Committee. He conducted numerous outreach events – 93 in total, includiding 42 episodes of Science Files on the Todd Veinotte Show (CityNews Halifax); 43 episodes of CFRA Live! (580 CFRA Ottawa); 5 CTV interviews; plus three interviews in other outlets. Dr Thacker also completed the negotiation of the 2022-25 collective agreement as SMUFU's Lead Negotiator. Dr. Hénault-Brunet served as the Department's Science Atlantic representative, has served as the Vice-chair and Chair of the Physics & Astronomy division of Science Atlantic in 2022-2023, was the faculty liaison for Atlantic Undergraduate Physics and Astronomy Conference (AUPAC) hosted at SMU in 2023. He also coordinated the Department of Astronomy & Physics colloquium series and serves as the Director of the Burke-Gaffney Observatory.

4.2. National

On the national scene, Dr. Thacker served as Past President of the Canadian Astronomical Society (CASCA) and was extensively involved in student judging at the annual meeting.

Dr. Hénault-Brunet serves on the ACEnet Research Directorate, on the CASCA Sustainability Committee and chairs the CASCA Awards Committee. He also served on NSERC's selection committee for the Vanier Scholarship, is the SMU institutational representative to the ACURA council, and a member of the Nominating Committee for this council. Dr. Hénault-Brunet led the Near-Field Cosmology Science Working Group for the CASTOR mission.

Dr. Damjanov serves on three CASCA committees, including Ground-based Astronomy Committee and Equity and Inclusivity Committee (which she currently chairs). She is also a co-chair of the newly formed CASCA committee tasked to review the use of the optical and infrared (OIR) facilities that are currently available to Canadian astronomers and provide recommendations for (near-)future strategies in that domain (OIR Review Committee).

Dr. Sawicki continues to to serve as the Chair of the Astrophysics and Cosmology Panel of NSERC Discovery Grants allocation process.

4.3. International

Dr. Damjanov servs as one of two Canadian representatives on the Gemini Science and Technology Advisory Committee that advises Gemini International Observatory's Board of Directors on policy matters of long-range scientific and technological importance to the Observatory. Dr. Sawicki conitnues to serve on the Management Committee of the CFI-funded GIRMOS instrument project.

5. Upcoming Activities

The Institute has recently undergone a strategic planning exercise and submitted its result to the SMU Senate. We are now continuing with the implementation our new strategic plan, which focuses on increasing our strength in the area of astrophysical big data and data analytics. As part of this, Institute members play key roles in the development of future research tools that will both fuel and benefit from this effort, including major natinal/international-scale intitaitve that are CASTOR and GIRMOS (see Section 2.5).

In the coming AY2023-24, the ICA plans to continue to host its ICA Data Analytics Seminar Series and to continue to expand its Galaxy Evolution Discussion Group (open to all SMU-based researchers interested in this field of astrophysics and now attracting 12-15 regular participants twice a week).

Two new initiatives are planned for this year: The first annual ICA Research Symposium which over a day in (we expect) January 2024 will give a forum for ICA members from students to faculty to showcase their research and build connections. And the "un-seminars" seminar series, which will be discussion fora (workshops, discussion panels, discussion groups) that will meet bi-monthly to focus in rotation on a range of topics of interest to younger researchers, from, e.g., how to be a scientific referee to how to manage one's research time.

6. Finances

Research at the ICA is supported through grants from NSERC, Canada Foundation for Innovation (CFI), Research Nova Scotia Trust (RNST), and the Canadian Space Agency. As of the end of the present reporting period, the total amount of research funding for which ICA members are lead grand-holders is ~C$1.5M.

The Institute does not receive operating funds but has a small residual fund in its account. This year, the ICA supported the Atlantic Undergraduate Physics and Astronomy Conference with a $500 contribution. At the start of October 2023, the ICA fund contains $11,732.

The ICA welcomes external funding for its research from interested donors and would like to engage potential donors with the help of SMU Advancement.

7. Publications

ICA members primarily publish their research in high quality, high-impact refereed journals, including Astrophysical Journal (ApJ, with Impact Factor, IF = 8.4), Astronomical Journal (AJ, IF = 5.5), Astronomy & Astrophysics (A&A, IF = 6.2), Monthly Notices of the Royal Astronomical Society (MNRAS, IF = 5.2), and Nature Astronomy (Nat. Astron., IF = 15.6).

Papers published or submitted by ICA members and associated students and post-docs during AY 2022-23 are listed below.

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