Report on Science Research and Science Support Activities at NRC's Herzberg Astronomy and Astrophysics Research Centre

Demographics: NRC's Herzberg Astronomy and Astrophysics Research Centre (HAA) comprises approximately thirty (30) research astronomers in continuing positions, making it on par with the largest astronomy centres across Canada. The astronomers are divided between the DAO site in Victoria, BC and the DRAO site near Penticton, BC. HAA scientists are typically hired, or evolve at least in part, to fill specific programmatic roles within HAA. Thus, formal non-research duties and responsibilities, as well as individual amounts of scientific research time, vary significantly across the staff. A number of scientists have extremely limited time for research.

Recognizing the importance of research excellence as a prerequisite for success in its mandated role of stewardship of Canada's national astronomical facilities, HAA maintains a strong research science culture. Indeed, three of the five senior management positions are held by active astronomers, including that of the Director-General. Furthermore, over the past decade, HAA staff have been posted or recruited to support international astronomy facilities, a tangible recognition of their skills and reputation. These facilities include the SKA, JCMT, ALMA, Gemini, TMT, and MSE.

Among the continuing staff at HAA, only four are female (13%). Three of the continuing staff received their PhDs before 1980, twenty staff received their PhDs between 1980 and 2000, and seven after 2000. All female staff received their PhDs within the last thirty years. The unbalanced age distribution of HAA's continuing staff suggests that a large cohort, ten to fifteen, are likely to retire over the next decade and a half, necessitating careful succession planning (see Future Directions).

Along with the continuing staff, there are typically three to six research associates at HAA. These positions include the named Plaskett (DAO) and Covington (DRAO) Fellowships that attract international early career scientists ready for independent research. Additional research associate positions are funded directly from on-going instrumentation projects. More recently, a new NRC post-doctoral fellowship program has become available, competed across NRC through individual staff project proposals. HAA staff have been very successful during the three NRC-wide competitions held so far, attracting six out of the thirty-six research associate positions across all of NRC. On completion of their time at HAA, past research associates have moved to tenure-track positions at Canadian and international universities, international observatories, and, in a few cases into continuing positions at HAA. Table 1 provides a twenty-year record of the success of HAA research associates.

The two HAA sites also host a significant number of post-retirement scientists and engineers, at least ten individuals over the last decade, who participate significantly in research and project development, as well as partake in Canadian and International committees. Furthermore, HAA has long attracted, worked with, and benefitted from long-term or sabbatical visits by outstanding scientists from across Canada. Such visitors are welcomed and encouraged.

Although a large number of scientists work at HAA, there remain a few situations where the available research effort suffers from small numbers (i.e., critical mass). The separation of staff across two sites, Victoria and Penticton, provides one clear example – with only six continuing staff members situated at DRAO. This particular situation has improved markedly in the recent past, however, through the collaborative effort between HAA and the Canadian university-led CHIME project, resulting in significant numbers of visiting research scientists at the Penticton site. As well, there will soon be dedicated research associate positions held jointly between DRAO and the Perimeter Institute (Waterloo).

Table 1: List of HAA Research Associates and their Current Employment

Sawicki, Marcin	2001 – 04	Professor, Astronomy and Physics, St Mary's University
Fiege, Jason	2002 – 04	Professor, Physics and Astronomy, University of Manitoba
Willott, Christopher	2002 – 06	Astronomer, Canadian Astronomy Data Centre, HAA
Johnson, Jennifer	2002 – 05	Professor, Department of Astronomy, Ohio State University
Peng, Eric	2004 – 07	Faculty Research Fellow, Department of Astronomy, Peking University
Geha, Marla	2006 – 07	Professor, Astronomy, Yale University
Matthews, Brenda	2004 – 08	Astronomer, Millimetre Astronomy Group, HAA
Onken, Chris	2005 – 08	Deputy Gemini Scientist, Australian Gemini Office
Puzia, Thomas H.	2006 – 10	Professor, Astronomy, Pontificia Universidad Católica de Chile
Peng, Chien-Yi	2007 – 10	Scientific Programmer, Giant Magellan Telescope
Marois, Christian	2008 – 09	Astronomer, Optical Advanced Technology Program, HAA
Wolleben, Maik	2008 - 11	Proprietor & CEO, Skaha Remote Sensing, BC, Canada
Schnee, Scott	2009 – 10	Aerospace Corporation
McConnachie, Alan	2008 – 11	Astronomer, Advanced Technology Program, HAA
Geisbuesch, Joern	2010 – 14	Research Associate, Karlsruhe Institute for Technology, Germany
Mann, Rita	2010 – 15	Astronomer, Victoria
Fraser, Wesley	2011 – 14	Contract Researcher
Robishaw, Tim	2011 – 14	Astronomer, Radio Astronomy Program, HAA
Kirk, Helen	2012 - 15	Astronomer, Millimetre Astronomy Group, HAA
Rodiger, Joel	2013 - 16	Astronomer, Optical Astronomy Program, HAA
Sanchez-Janssen, Ruben	2013 - 16	Royal Observatory, Edinburgh
Rosensteiner, Matthias	2013 - 16	Research Associate, Karlsruhe Institute for Technology
McConnell, Nicholas	2015 - 16	STEM Education Manager, Institute for Scientist and Engineer Educators
Lawler, Samantha	2015 - 19	Assistant Professor, Campion College
Scholtz, Paul	2016 - 19	Research Associate, Dunlap Institute
Henault-Brunet, Vincent	2017 - 19	Assistant Professor, Sant Mary's University
van der Marel, Nienke	2017 - 19	Banting Fellow, University of Victoria
Guillaume, Thomas	2017 -	Current Fellow, HAA
Ngo, Henry	2017 -	Current Fellow, HAA
Abedin, Abedin	2018 -	Current Fellow, HAA

Scientific Highlights: Research at HAA covers a wide range of astrophysical areas and any list of accomplishments is likely to be biased toward results which reflect the interest of the compilers of this report. In the following, the highlighted results presented are intended to showcase the breadth of HAA research topics, the leadership roles HAA scientists take within large Canadian and international consortia, and the utilization of national and international facilities.

Next Generation Virgo Survey (NGVS): HAA astronomers conceived and led the NGVS (Ferrarese et al. 2012), a ~900 hour CFHT/MegaCam Large Program that ran from 2008 to 2014. The NGVS has provided deep, high spatial resolution, contiguous coverage of the Virgo cluster from its core to its virial radius, for a total area of 104 square degrees, in *u,g,i,z,* to unprecedented depth (25.7 mag in *g* at 10 sigma). Follow-up imaging and spectroscopic programs were awarded over ~400 hours at MMT, AAT, CFHT, Magellan, VISTA, VLT, Gemini and Keck. The NGVS counted 46 CoIs in Canada, US, China, Chile, France, Italy and the UK. At least 17 students and 14 postdoctoral fellows have been involved, to various degrees, in the analysis of NGVS data. To date, the NGVS collaboration has published 33 papers in refereed journals, spanning a wide range of topics, a number of which are ancillary to the original science goal. These include the discovery and characterization of Kuiper Belt objects (among these, an Oort Cloud member with the second largest perihelion distance among known solar system objects; Chen et al. 2013); the characterization of the Galactic white dwarf population (Fantin et al. 2017); a tomographic analysis of Milky Way substructures (Lokhorst et al. 2016); and the discovery and measurement of weak lensing masses of high redshift galaxy clusters (Parroni et al. 2017). In Virgo, the NGVS has more than doubled (from ~1400 to ~3600) the number of galaxies believed to be a certain or probable member of the cluster; more importantly, the newly discovered galaxies have pushed the characterization of the galaxy luminosity function by over two order of magnitude in mass (Ferrarese et al. 2016), to a depth that had only been reached in the Local Group. Additional NGVS papers explored the population of Virgo intracluster globular clusters (e.g., Longobardi et al. 2018); presented Surface Brightness Fluctuation distances to an unprecedented number of cluster members (Cantiello et al. 2018); addressed the dark matter content of Ultra Diffuse Galaxies (Toloba et al. 2018); inferred the intrinsic shapes of dwarf galaxies (Sanchez-Janssen et al., 2016); and studied the population of Ultra-Compact Dwarf galaxies (e.g., Liu et al. 2015).

Additional CFHT Surveys: Major HAA science efforts over the past decade have been centred around three CFHT Large Programs: The Pan-Andromeda Archaeological Survey (PAndAS), the Canada-France Imaging Survey (CFIS), and the Canada-France High-z Quasar Survey (CFHQS). All of these surveys attracted large international teams of researchers and were led by HAA scientists. The PAndAS Survey culminated in over 40 refereed publications, including two *Nature* publications. CFIS, which is ongoing, is one of the largest optical observing programs undertaken by Canadian astronomers. The survey has additionally leveraged membership in the ESA Euclid mission to a team of some 30 Canadian astronomers. Separately, CFHQS pioneered the study of low-luminosity accreting supermassive black holes during the epoch of re-ionization. The project was based on CFHT imaging with confirmation and follow-up spectroscopy from the Gemini, Keck and VLT telescopes. Furthermore, ALMA follow-up was

used to determine the properties of the host galaxies. In total, the nine CFHQS papers led by HAA astronomers have been cited over 1000 times.

DAOPHOT and DAOSPEC: DAOPHOT is a widely used computer program for extracting stellar photometry in crowded fields from digital images (Stetson 1987). Since its initial distribution in the mid-1980's the program has been distributed to approximately 800 individual users. It is also used by many instructors in undergraduate laboratory exercises. According to a recent NASA/ADS search, the character string "DAOPHOT" appears in 6,602 publications, 5,191 of them refereed. DAOSPEC was developed in 2001, and is used for automatic equivalent-width measurements of absorption lines in digital stellar spectra (Stetson & Pancino 2008). It has been distributed to of order 100 users. The character string "DAOSPEC" appears in 160 publications. These two computer programs continue to be requested at a rate of approximately 30 times per year.

JCMT Legacy Surveys: The JCMT Gould Belt Survey (GBS) was one of the first large legacy programs approved at the JCMT, and utilized hundreds of hours to map thermal dust emission over many square degrees, as well as line emission over a more focused area, within molecular clouds, with the aim of characterizing nearby star formation. Six continuing staff at HAA are involved in the JCMT GBS; serving as the Canadian co-PI of the survey and leading the bulk of the data reduction and data characterization efforts (e.g., Kirk et al. 2018). The survey has generated about 30 refereed publications to date, with over 700 citations. Science topics addressed by the survey include the evolution of dust grains (e.g., Sadavoy et al. 2013), the virial properties of dense cores (e.g., Pattle et al. 2017), the influence of protostellar heating on dense cores (e.g., Rumble et al. 2015), the clustering properties of dense cores (e.g., Kirk et al 2016), and the properties of filamentary structure (e.g., Salji et al. 2015). The GBS data are also providing an important base dataset for a wide variety of other large surveys including the Green Bank Ammonia Survey (Friesen & Pineda et al. 2017) and the first dedicated foray into the submillimetre time-domain (JCMT Transient Survey: Herzceg et al. 2017), as well as individual PI-led surveys such as an ALMA search for substructure within dense cores in the Ophiuchus molecular cloud (Kirk et al. 2017).

Protoplanetary Disks: HAA astronomers were involved in the first ALMA observation of ringed structure in a protoplanetary disk (ALMA Partnership et al. 2015), a result which suggested that the formation of planets around stars may proceed significantly earlier than anticipated. More recently, large ensembles of ALMA-observed protoplanetary disks with visible structure have been carefully investigated (van der Marel et al. 2018, Long et al. 2018, Lodato et al. 2018), effectively ruling out snow-lines as an important contributor to the observed features, while predicting the as yet unobserved exoplanet population that would be required if planets carve the features.

Debris Disks: Identification and characterization of debris disks in the far-IR and submillimetre using *Herschel*, JCMT, SMA, and ALMA by HAA scientists has led to many important results, including the detection of the most asymmetric debris disk (Draper et al. 2016a); a correlation between observed debris disks and lambda Boo signatures in the central star (Draper et al.

2016b); an increase in disk incidence and brightness toward planetary hosts (Matthews et al. 2014); a trend of more disks being detected around sub-Jupiter mass planet hosting stars (Marshall et al. 2014); and the detection of the extent of the far-infrared halo of the HR 8799 disk (Matthews et al. 2014); and improved high resolution characterization of the planetesimal belt with SMA and ALMA (Wilner et al. 2018). Importantly, an Annual Review of Astronomy and Astrophysics article on debris disks was co-written by an HAA astronomer (Hughes, Duchene, & Matthews 2018).

Exoplanets: HAA scientists are playing key roles in a number of exoplanet projects. An HAA scientist led the first large scale exoplanet imaging campaign around more massive stars, the International Deep Planet Survey (Marois et al. 2010). This 1,000h 300 massive stars campaign executed at the Gemini North and South, Keck, Subaru and the VLT telescopes produced more than 30,000 images, and was, at the time, the most extensive survey for imaging exoplanets (Galicher et al. 2016). The IDPS campaign led to the first directly imaged multi-exoplanet system (HR 8799, published in *Science* and *Nature*, Marois et al. 2008/2010, these two papers have accumulated more than 1,500 citations). Spectroscopy of the same system produced a later *Science* paper (Konopacky et al. 2013). To date, 140 papers have been published on this system. HAA scientists are essential members of the Gemini Planet Imager Exoplanet Survey (GPIES) team, a campaign to search for exoplanet and debris disks around more than 600 nearby young stars. This large campaign involves 75 researchers worldwide (13 Canadian), and NRC researchers are member of its steering committee and co-leading its data processing team, a group of more than 30 international scientists. The GPIES campaign has produced more than 30 refereed papers to date, with more coming, and has discovered the lowest mass and coolest exoplanet to date, 51 Eridani b (Macintosh et al. 2015), published in *Science*. NRC scientists are also involved in targeted campaigns for Alpha Cen A & B, such as leading the TIKI 10 microns imager project at Gemini South. In a complementary effort to the GPIES campaign, HAA scientists are science team members of an infrared Pyramid wavefront sensor and a fiber-fed spectrograph upgrade to Keck Observatory. They are also leading a direct imaging survey for giant planets around lower mass stars, utilizing the longer wavelengths and the new vector vortex coronagraph at Keck**.** Additionally, HAA scientists have co-led and co-supervised student research developing machine learning approaches to characterize the performance of new Keck instrumentation and demonstrate the effectiveness of new image post-processing algorithms with this dataset (Xuan et al. 2018, Ruane et al. 2019). On the analysis side, HAA scientists are also co-leading an international orbit-fitting software project 'orbitize', releasing the first version of the software in 2018 (Blunt et al., DOI: 10.5281/zenodo.1475226).

Solar System: HAA solar system researchers have worked in a close collaboration with NASA since 2012, playing a key role in the NASA *New Horizons* (NH) mission to Pluto, as well as the extended NH mission to the Kuiper Belt. HAA scientists provided detailed Pluto positional observations that were used to navigate the spacecraft throughout its journey. Moreover, for the post Pluto-Charon encounter by NH, HAA played a significant role in discovering and tracking the Kuiper Belt object 2014 MU_{69} (New Horizons' last target), thus making the extended mission possible. HAA scientists continue to collaborate with the NH team to determine the formation and evolution of these distant objects. Apart from the *New Horizons*

mission, HAA scientists conducted the CFHT OSSOS survey of Kuiper Belt objects, resulting in the largest catalogue of sources with secure orbits and a well-documented survey selection function. HAA played a leadership role in establishing this project and led the data acquisition. OSSOS is highly impactful in the TNO community (e.g., OSSOS. VII. 800+ Trans-Neptunian Objects—The Complete Data Release; Bannister et al. 2018). Furthermore, a separate HAA-led investigation determined that the widely separated binaries within the Kuiper Belt can be utilized to constrain strongly the collisional environment in this region, requiring that planetesimal accretion be initiated by instability processes, not agglomeration. Most recently, HAA astronomers are leading an HST Treasury Survey (+200 orbits of HST) to search for more binaries within the Kuiper Belt.

Solar Astronomy: HAA operates the solar radio flux monitor, continuing an NRC activity dating back to 1947. The 2.8-GHz flux values are distributed worldwide in real time as a scientific service, and find use in space weather and environmental research and in many industrial applications. HAA research based on these data includes ongoing studies of the apparently changing relationship between optical sunspot number and radio flux. A new flux monitor has been constructed, operating at 1.4 GHz, 2.8 GHz, and 4.7 GHz.

Radio Polarization: HAA researchers play major roles in research into Milky Way magnetism, traced by linearly polarized synchrotron emission and by Zeeman splitting of spectral lines. In particular, HAA astronomers lead the Global Magneto-Ionic Medium Survey (GMIMS), a consortium of 32 scientists that includes 12 Canadians. GMIMS is mapping polarized emission from the entire sky using large single-antenna radio telescopes, covering 300 MHz to 1800 MHz with thousands of frequency channels. Rotation Measure synthesis (Faraday tomography) analysis, provides new insights into the strength and configuration of the Galactic magnetic field. The overall aim is to reveal field strengths and configurations and to probe the role of magnetic fields in interstellar processes. Northern observations with the DRAO 26-m Galt Telescope (1270-1750 MHz) are complete. Southern surveys using the Parkes 64-m Telescope (300-480 MHz and 1300-1800 MHz) are also complete. The 300 MHz to 480 MHz data have been made public through the CADC, and a paper describing the survey published in AJ (Wolleben et al. 2019). Five additional science papers have also been published. Further northern surveys with CHIME (400 MHz to 800 MHz) and the Galt Telescope (900 MHz to 1700 MHz) are planned. On smaller scales, the DRAO Synthesis Telescope continues to provide wide-field polarization data of unmatched quality. Employing techniques developed for the Canadian Galactic Plane Survey (CGPS), a team led from HAA has recently discovered extensive polarized emission associated with high-velocity atomic hydrogen clouds, providing key information on their magnetic fields.

Fast Radio Bursts: Fast Radio Bursts (FRBs) are single pulses of radio emission. They are highly dispersed and probably originate at distances well beyond our Galaxy. Given their large apparent distance, the radiated power must be extremely high. From presently available data, the all-sky rate of FRBs is hundreds per day. Nevertheless, the origin of FRBs is presently not understood. The CHIME/FRB instrument began commissioning in July 2018 and a Fast Radio Burst was detected in the first few days of operation. Commissioning has continued into 2019,

but science results are flowing rapidly. The CHIME/FRB Consortium, led by Vicky Kaspi (McGill), includes an HAA Covington Fellow and one HAA scientist. In early January 2019, two FRB papers were published in *Nature*. The first paper details 13 FRBs discovered by CHIME, and demonstrates that some show emission down to 400 MHz, the bottom of the CHIME band. The second paper reports discovery of a second repeating FRB; this is a significant discovery because repeated bursts allow follow-up studies and precision localization using other telescopes. With its large instantaneous sky coverage (>200 square degrees), CHIME/FRB has now detected many more FRBs than all other telescopes put together, including several new repeating FRBs. This wealth of new discoveries, all from one telescope, will allow statistical studies of burst properties, bringing us closer to understanding these enigmatic objects. CHIME now dominates FRB searching, but the large beam of the telescope makes it hard to associate the bursts with a particular galaxy or other object. Localization using interferometric techniques is the next challenge. HAA is presently hiring a research associate to lead the design and construction of an "outrigger," a small telescope to be placed at a distance of about 100 km from DRAO. Triggered by detection of an FRB at CHIME, the outrigger station will record a short data segment, and VLBI techniques will be used to measure FRB position. Successful demonstration of the first outrigger may lead to the construction of others, possibly at distances up to several thousand kilometres.

Quantum Gravity: Tests of quantum gravity can be performed using distant extragalactic sources (Steinbring 2015). The effect to be observed is no less than a fundamental decoherence of wave fronts emitted by distant sources that is induced by the 'foamy' nature of space-time itself. There remains debate as to whether this effect can be observed using gamma rays, where the measurement should be stronger than in the optical. There is also hope that JWST will be sensitive enough to observe this phenomenon and an HAA researcher is taking a leadership role.

Machine Learning: HAA staff have been undertaking a variety of Machine Learning (ML) and AI projects at HAA since 2017, using CADC facilities. One project searched for interesting objects in *HST* images such as strong lens candidates. (Indeed, some new candidates have been uncovered, and a paper is in preparation.) A second project using ML techniques obtained a result that highlights a potentially serious problem in contemporary models of galaxy evolution (Bluck et al. 2019). Furthermore, in a Quality Assessment project of large images of CFIS data, HAA astronomers have presented an ML-based approach that uses a small fraction of image pixels (representative images) to determine the quality of the observation. The representative images are ∼800 times smaller than the original images, significantly reducing the time required to train the algorithm. This technique has been tested on independent data and obtained more than 97% accuracy. The method has already been applied to greater than 220,000 exposures within the CADC database, in a fully automated way. The result of this project was presented at the *Astroinformatics* conference in Heidelberg-Germany 2018, and submitted to *MNRAS*. HAA researchers also have been involved in developing deep learning methods for the first time with stellar spectroscopy (published in MNRAS), determining stellar properties directly from spectra. Benchmarks against calibrated stars and non-ML state-of-the

art techniques showed that the approach was not only extremely fast but also had good accuracy and precision.

Adaptive Optics: HAA scientists maintain a close connection to the optical/IR adaptive optics instrumentation work that takes place at HAA, including work on RAVEN (CFI-funded) and NFARIOS (TMT MCAO). HAA scientists led the first two papers demonstrating the success of RAVEN (Davidge et al. 2015, 2016) and the first two papers demonstrating the Gemini GeMS MCAO (Davidge et al. 2013, 2014). HAA scientists have also recently established the first Canadian high-contrast imaging laboratory, NEW EARTH (PI: C. Marois). Its main objective is to develop new frontier technologies for imaging and characterizing exoplanets, toward the goal of finding life signatures in the atmosphere of Earth-like exoplanets. Its first innovation is a new kind of advanced coronagraph mask that allows fast KHz focal plane wavefront sensing (FAST, Gerard et al. 2018).

The Cosmological Advanced Survey Telescope for Optical and uv Research (CASTOR): Since 2011, the Canadian astronomical community has been developing plans for a Canada-led wide-field imaging space telescope, a concept first identified in the 2010 Long Range Plan for Canadian Astronomy. This proposed mission, now named *CASTOR*, was developed extensively over the last decade by a consortium of Canadian university, industry, and government partners, with scientific leadership provided by HAA. The 1-m *CASTOR* telescope would produce panoramic imaging of the UV/optical (150-550 nm) sky, using a three mirror anastigmat design to provide *HST*-like image quality over a wide field of view (0.25 sq. deg.) in three filters, simultaneously. Operating from low-earth orbit, *CASTOR* would be optimized for wide-field surveys, although the telescope may also feature low- and medium-resolution spectroscopic capabilities over the 150 nm to 400 nm region. A recent science maturation study conducted by the CSA and led by HAA involving roughly one hundred scientists has demonstrated a wide range of research programs that would be enabled by this facility, including dark energy and weak lensing; time domain and multi-messenger astrophysics; galaxy evolution and AGNs; star formation, ISM, & IGM; stellar & galactic astronomy; compact objects; exoplanets; and trans-Neptunian objects. As a versatile CSA 'smallSAT'-class mission, CASTOR would surpass any ground-based optical telescope in angular resolution, and would have powerful synergies with upcoming dark energy missions (*Euclid*, *WFIRST*) and the ground-based LSST. Combining one the largest focal planes ever flown in space with an innovative optical design that delivers *HST*-quality images over a field nearly two orders of magnitude larger than *Hubble*, *CASTOR* would survey about 1/5th of the sky to a (*u*-band) depth 1.3 magnitudes fainter than will be possible with LSST, even after a decade of operations. The *CASTOR* concept has drawn the attention of several prospective international partners, including JPL/Caltech, India, and the UK.

HQP Training: HAA staff members play an important role in the training of scientific HQP within Canada. Indeed, HAA staff employ at least four different types of supervisory and training functions. First, undergraduate co-op students from Canadian universities are directly supported by NRC/HAA funds and provide opportunities for students to work on a wide variety of research investigations, often directly connected to on-going instrumentation/facility projects. Second, HAA staff members supervise graduate students, either through funds made available by instrumentation projects or through NSERC Discovery grants held by staff in their role as adjunct professors at Canadian universities. Third, HAA staff members are directly involved in multi-institute NSERC CREATE awards specifically designed for broad training of graduate students. Finally, HAA staff members indirectly support many additional graduate students, domestically and internationally, in collaboration with professors at their home institutions.

On average, fourteen undergraduate students are supported by NRC/HAA funds each year. Most of these students are taking co-op programs at Canadian universities and spend four months at HAA working directly with research or instrumentation staff. A fair number of these students continue on to graduate work in astronomy, and eventually a few become faculty. Many other students go on to successful careers in industry. The opportunity to spend a work term at HAA provides undergraduates with an understanding of what drives scientific excellence and the tools required to make research and instrumentation projects succeed.

NSERC Discovery grants, held through adjunct appointments at Canadian universities, provide funds to HAA research staff *solely for the training of HQP* (primarily graduate students but also occasionally undergraduates). Over the last decade, more the two million dollars have been competitively awarded to HAA staff for their direct support of students. Presently, seventeen staff members are adjuncts at Canadian universities and twelve hold NSERC Discovery grants totaling about three hundred thousand dollars ($300K) per year. Some HAA staff members are further connected with two NSERC CREATE awards (see below).

On average, fifteen graduate students are supported by HAA staff members in their roles as adjunct faculty, primarily through NSERC funding. Predominantly, the University of Victoria hosts these students, due to its proximity to DAO, but graduate students have also been supported at other Canadian universities, such as the University of Alberta and UBC Okanagan. HAA-supervised graduate students have achieved significant research success during and after their studies, including two winners of CASCA's Plaskett Medal for the best Canadian Astronomy thesis. Former HAA-supervised students are now members of the faculty at Canadian universities, in continuing positions at international observatories, or working within Canadian industry.

HAA research staff members are involved in two different CREATE grants: "New Technologies in Canadian Observatories (NTCO), allocated in 2017 (PI, Kim Venn), and "Technology for Exo-planetary Systems (TEPS)," allocated in 2016 (coordinated by John Moor and Nick Cowan). The CREATE grants are solely for the training of HQP through partnerships with industry. Indeed, astronomy instrumentation lends itself well to CREATE opportunities. For example, graduate

student Ben Gerard (supervisor: C. Marois) has been funded through TEPS for two internships, one at Comdev in Ottawa for four months and an international internship in Paris Meudon for two months. Under NTCO, graduate students Robert Gleisinger (supervisor: JJ Kavelaars) and William Thompson (supervisor: C. Marois) are receiving partial funding. William will undertake a 4 month internship at NUVU in Fall 2019 and Robert will undertake an internship before the end of his doctoral work (2021). The NTCO annual meeting of members will be held in Penticton in November 2019.

In addition to direct support of graduate students, many members of the science staff at HAA are actively involved in the broad support of Canadian (and international) students directly through their programmatic responsibilities. Examples include supporting graduate students in the development of observing proposals, the preparation for observations for successful proposals, and help with data reduction for national facilities (e.g., Gemini, ALMA).

Support of Science: Across HAA science staff members are deeply involved in both the pursuit and support of scientific research. Indeed, many of the primary programmatic responsibilities of science staff are directly related to science support. As examples, we provide below a few of these activities.

Dominion Radio Astrophysical Observatory (DRAO): DRAO is Canada's only nationally-owned radio astronomy observatory, and the DRAO site is an important asset for Canadian astronomy. Operated by NRC as part of its mandate to manage and operate facilities for scientific research, it is used by researchers from across Canada and a large international user community who participate in collaborative national and international research projects. The excellent minimal radio frequency interference (RFI) environment of the DRAO site is essential for the extraordinarily sensitive astrophysical observation instruments being developed and operated by DRAO and by other organizations in collaboration with DRAO. The site is protected from RFI both physically, by the ring of surrounding mountains, and through regulation, at the federal, provincial, and municipal levels of government.

HAA staff at DRAO operate two on-site telescopes, the Synthesis Telescope and the John A. Galt Telescope (26-m), as national facilities, and the solar radio flux monitor as a scientific service (prominent nationally and internationally). The Synthesis Telescope has been used as a testbed for new receiver technology (from University of Calgary) and correlator technology (Calgary and Toronto). Over the past ten years, DRAO has been host to the university-led CHIME project, initially for an experimental interferometer and the CHIME Pathfinder, and now for the full CHIME instrument in its cosmology, Fast Radio Burst, and pulsar activities. DRAO has provided infrastructure support (power, internet, space for computer equipment, office and laboratory facilities, machine shop, on-site accommodation) for CHIME as well as extensive help from HAA staff. DRAO is now beginning along a similar path for the funded project CGEM (Canadian Galactic Emission Mapper) and for the proposed project CHORD (Canadian Hydrogen Observatory and Radio transient Detector), both university initiatives with HAA staff participation. DRAO shares costs for three postdoctoral scientists who are key contributors to CHIME. DRAO previously developed and built the JVLA correlator, cementing Canada's role in the JVLA and ALMA, and contributed the reference designs for the correlators/beamformers for SKA1_Mid and the ngVLA. The DRAO composite antenna technology group uses a large area on site for development and testing. Their work is playing a major role in CHORD, HIRAX, and MeerKAT, and has provided the reference design for the ngVLA 18-m reflector antennas. A Canadian company (SED, Saskatoon) now has on the market composite reflector antennas for deep-space communication based on technology learned from the HAA group at DRAO.

Millimetre Astronomy Group (MAG): The MAG supports the ALMA telescope as members of the North American ALMA Science Centre (NAASC), through partnership with colleagues at NRAO in Charlottesville, VA. As members of the NAASC, MAG researchers act as astronomers-on-duty at the telescope, assist PIs with Phase II generation of scheduling blocks, act as contact scientists for North American PIs, revise documentation at each proposal cycle, contribute to NA helpdesk support and are members of various ALMA working groups. MAG members have

also participated in community training days and still produce the ALMA Primer, originally intended as a side project for North American support, but quickly adopted internationally by the ALMA project. On behalf of the NAASC, the MAG also handles all NA calibrator survey data effort for the Joint ALMA Observatory. The MAG has also organized two of the annual NAASC science meetings, one in 2011 focussed on Spectroscopy and also the most recent, "New Horizons in Planetary Systems," held in Victoria in May 2019. Scientists in the ATD also support the maintenance and upgrades of the Canadian-contributed ALMA Band 3 receivers and the ALMA archive through the CADC. Efforts are currently underway to create a stable, user-friendly cloud-computing infrastructure for ALMA data reduction and analysis, a collaboration between MAG and CADC scientists.

Canadian Gemini Office (CGO): The CGO is the main interface between the Gemini Observatory and the Canadian astronomical community. CGO astronomers use their operational and research expertise to provide support to Canadian users of the Gemini telescopes, from Phase I (submission of proposals) to Phase II (preparation of observations), as well as for data reduction. This support includes the biannual Phase I observing proposal application process. The CGO processes the proposals and assesses their technical feasibility, often interacting directly with PIs if adjustments are required, and reporting this information to the Canadian Time Allocation Committee. Members of the CGO work with those astronomers who have been assigned observing time to set up observing programs that are efficient and will allow the scientific goals to be realized. Canada is unique among Gemini partners in having a significant fraction of its programs (20%) led by MSc or PhD students. The CGO interacts extensively with these students for their observation preparations and later on during data reduction. The training that the CGO provides covers many observational techniques that go beyond Gemini and will be useful for future optical/infrared projects, such as good choices of calibrations or general data reductions tips. The CGO thus plays an important role in helping these students develop general astronomy skills. The CGO is also responsible for promoting Gemini capabilities within the Canadian astronomical community. CGO members have given numerous talks at Canadian universities and special workshops on Gemini capabilities. Importantly, the CGO organizes Gemini lunches held during the annual CASCA meetings, with presentations by CGO members or Gemini staff that are followed by open discussions with the Canadian community.

Canadian Astronomy Data Centre (CADC): The HAA research astronomers working with the CADC make direct contributions to a broad range of research programs. The CADC development model is to embed astronomers within the development activities. These astronomers act as proxies for the general research community. Both by doing their own research and by aiding external astronomers to conduct research using the archive systems, CADC astronomers push the systems to their boundaries and aid in the design of new access and processing systems. In addition, over the last decade, CADC research staff have provided extensive high-level data products for the CFHT MegaPrime instrument, recalibrated and stacked *HST* imaging, supernova detection and measurement and spectroscopic data processing for science teams using CFHT, Gemini, and DAO. These data products are retrieved

by scientists from around the world, enabling research in areas as diverse as asteroid tracking to studies of the ISM to the determination of the dark matter content of clusters. These efforts strongly inform the development of archive services both within the CADC and internationally, via CADC's participation in the International Virtual Observatory Alliance. Finally, over the last ten years, the CADC has worked with Compute Canada to provide cloud storage and processing facilities to Canadian astronomers. This system provides both a generic virtual machine-based interface, as well as a specialized ALMA data processing environment.

Along with the work done directly as part of staff duties, HAA staff further support the Canadian astronomical community's science through a large number of external committee activities. The following metrics provide evidence of the range of these important roles and responsibilities undertaken by HAA staff.

Boards of Directors:	Four staff members support Canadian involvement in ALMA, CFHT, and the SKA.
Advisory Committees:	Fifteen staff members provide expert advice for Canadian and international facilities including TMT, ngVLA, Gemini.
Time/Proposal Allocation:	Typically, more than five staff members are involved in both national and international time/proposal allocation committees each year.

An extremely important requirement for effective scientific research is interpersonal interaction. HAA staff members play an important role, on behalf of Canadian astronomy, through involvement in conference organization, hosting of research visitors, and providing science talks at conferences and institutions.

Conference Organization:	Staff are involved in the organization of at least five Canadian and international scientific conferences per year.
Hosted Visitors:	HAA hosts over fifty research visitors per year, including colloquium speakers and science collaborators.
Science Talks:	Staff provide more than sixty talks on their research to Canadian and international institutions/meetings per year.

Dissemination of science to the general public is also an activity keenly undertaken by HAA science staff. A few of these activities are directly supported by HAA funds but the majority are either provided *pro bono* or through the support of outside organizations, such as the BC Scientists and Innovators in Schools program and the CASCA-Westar Lectureship series.

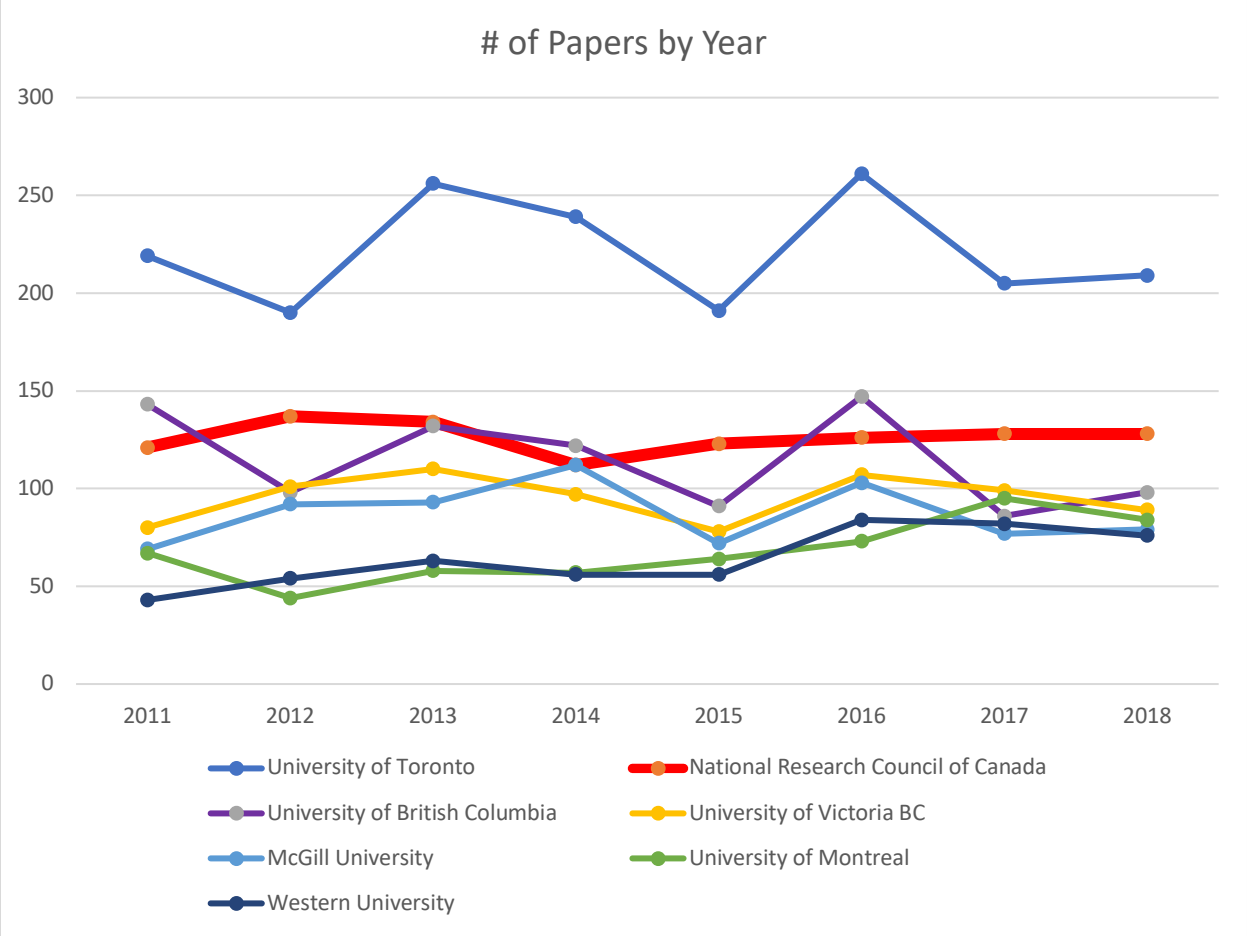
Public Outreach Activities: At least fifteen outreach activities to the general public are undertaken by HAA science staff each year.

School Outreach Activities: At least twenty classroom visits are undertaken by HAA science staff each year.

Bibliometrics: Bibliometric information on research paper production can provide a useful tool for measuring the health of science departments. The information presented below is based on the research methodology of HAA's Dennis Crabtree, whose published metrics have become a standard international reference. A larger analysis of bibliometric measures across Canadian universities and institutes will be provided in a separate report to the 2020 Long-Range Plan panel. Therefore, here we concentrate specifically on the strength and resiliency of HAA research output.

Including all HAA continuing science staff, research associates, and retired but active scientists, HAA publishes more than 120 refereed papers per year (Figure 1), a number that has held remarkably constant over the last decade.

Figure 1: Papers published per year.



Providing a determination of the impact of these many publications, bibliometric measures across entire departments for both HAA and a subset of Canadian universities involved in astrophysics research are shown below in Table 2. The metrics presented here include the

number of papers published (by continuing staff only), and the institutional values for the H-index, M-index, the TORI- parameter, and the RIQ parameter. These metrics are also shown for first author papers with the metric preceded by "FA" (e.g., FAH).[1]

These institutional metrics are based on the published papers over the total career of current staff in each department/institute. Therefore, the institutional H is determined from the papers published by all staff members. These aggregate metrics are thus greatly influenced by the size of each department/institute. They do, however, provide evidence of the scientific importance of each group in the context of Canada's overall research impact. HAA, comprising the largest research group in Canada, stands out as having the largest overall research impact.

Table 2: Aggregate Research Metrics for Departments

Institute	H	M	Tori	RIQ	# Papers	FAH	FAM	FATori	FARIQ	# FA Papers	# Faculty
HAA	160	3.08	790.37	540	3191	86	1.69	473.79	426	631	30
Toronto	183	3.45	504.05	423	2093	88	1.66	243.55	294	372	20
UBC	148	2.55	411.26	349	1591	67	1.24	169.31	240	282	12
McGill	142	3.74	355.10	495	1464	71	1.87	169.16	342	268	11
Montreal	116	2.47	275.86	353	1345	54	1.15	124.15	242	199	10
Western	85	2.83	127.31	376	746	42	1.40	51.20	238	157	10
McMaster	121	2.52	289.90	354	1073	52	1.08	102.53	215	198	9
Alberta	93	2.74	119.36	321	649	44	1.52	35.80	206	120	7
Victoria	131	2.26	382.15	337	939	55	0.95	208.14	248	181	7
Waterloo	107	2.61	165.45	313	707	57	1.58	87.92	267	162	7
CITA	144	2.88	447.16	422	1051	64	1.28	221.50	297	179	5

The next table (Table 3) provides the mean and median values of a subset of the metrics produced from the individuals within the departments/institutes as well as aggregated over all Canadian departments excluding HAA (non-HAA). For example, the Mean H is taken by averaging the H values of each member of the group. These metrics loosely represent the research impact of the typical researcher within each group. Using this approach, HAA performs at the average of Canadian departments.

[1] An individual's M-index is simply the H-index divided by the number of years the person has been publishing. The TORI (Total Research Impact) and the RIQ (Research Impact Quotient), developed by the NASA ADS, are indices which measure the total research impact of an individual and this impact averaged over a person's career. These indices are designed to measure individuals and aggregates of individuals such as departments.

Table 3: Mean and Median Research Metrics for Departments

Institute	Mean H	Mean RIQ	Mean # Papers	Median H	Median RIQ	Median # of Papers
HAA	35.47	153.80	107.33	33.5	130.5	101.5
Non-HAA	40.10	177.27	115.24	36	178	94.5
Toronto	41.20	193.65	105.60	40.5	209	70
UBC	47.25	195.33	133.50	47.5	201	114.5
McGill	45.82	178.09	134.00	41	173	87.5
Montreal	28.40	156.40	75.50	32.5	176.5	87
Western	37.00	178.50	135.40	28.5	159	77.5
McMaster	41.44	172.89	120.11	45.5	187	106
Alberta	40.14	195.14	101.86	33	221	95
Victoria	48.29	227.86	135.00	45	214	113
Waterloo	36.00	195.86	93.57	36	202	101
CITA	67.8	256.4	211.00	61	276	171

Finally, it is worth noting that HAA staff members are extremely collaborative in their research. Taking the roughly six hundred papers published by HAA staff over the last five years, there are forty international departments and institutions which have had been co-authors on at least 10% of these HAA publications. The top thirteen international institutions with which HAA staff members collaborate are:

HAA Collaborator	Country	# of Papers
University of Victoria BC	Canada	255
CNRS	France	243
California Institute of Technology	United States	138
European Southern Observatory	Germany	129
Harvard University	United States	124
Royal Observatory	United Kingdom	117
University of Toronto	Canada	116
University of Cambridge	United Kingdom	114
University of Hawaii at Manoa	United States	107
University of Edinburgh	United Kingdom	103
National Institute for Astrophysics	Italy	103
Universite Paris-Saclay	France	102
Leiden University	Netherlands	100

Future Directions: As noted near the beginning of this report (Demographics), it is likely that a significant fraction of the HAA research staff will retire over the next decade and a half. In light of this fact, in November 2017 a SWOT Analysis (Strengths, Weaknesses, Opportunities, Threats) was undertaken across HAA by its science staff. Below is a slightly modified and expedited version of that report, primarily concentrating on those aspects that are external to the functioning of HAA within NRC.

STRENGTHS

- The scientific and technical staff has a demonstrated record of success based on external reviews, publication statistics, peer awards and high-quality instrumentation and data management/analysis projects. This science/technology partnership model has proven to be unique and powerful in international astronomy.
    - HAA scientists are actively engaged in (and often leading) important community initiatives in scientific research, informatics, and instrument and facility development.
    - CADC's expertise in data mining, processing, and archiving enriches the HAA research environment, while the ATD provides expert technical knowledge in instrumentation.
- As a direct result of NRC's parliamentary mandate "to operate and administer astronomical observatories on behalf of the Government of Canada," HAA scientists have an expert knowledge of the national facilities. This advantage is important for cutting-edge scientific research, and is to the benefit of Canadian university researchers.
- HAA enjoys close academic and industrial connections — both domestically and internationally — that have been fostered over many years. Thanks to these connections, HAA has maintained an exemplary level of interaction with NRC's stakeholder communities. The connections with academia are especially important, for several reasons: e.g.,
    - Adjunct faculty members can secure NSERC funding to support graduate students who are trained in scientific research and technology development.
    - Some of these HQP will go on to become leaders in academia and industry, thereby strengthening NRC's ties with its stakeholders.
- NRC provides a stable environment for science.
    - The staff at DAO (Victoria) is large enough to accommodate a broad range in expertise, which is needed to maintain effective communications with the national community.
    - Stable funding profiles are advantageous for long-term and forward-looking scientific and technical initiatives.
    - The named Plaskett and Covington Fellowships are independent postdoctoral programs that are both widely recognized and highly regarded by the national and international communities. These fellowships have been an extremely effective channel for preparing HQP for academia and industry.
    - The NRC's programs for undergraduate STEM work experiences have long provided valuable training and research opportunities for Canadian undergraduate students.

WEAKNESSES

- The low number of science hires at NRC during the past decade has inevitably led to HAA being less representative of the broader community (i.e., NRC's stakeholders). This problem, and those that follow, may hinder HAA's ability to recruit the best researchers.
  - The Canadian community has diversified during this period, as it responded to new priorities and research opportunities. HAA has been hampered in its ability to adjust in a similar way.
  - For the same reason, there is now an unbalanced age distribution amongst the scientific staff, with a very large turnover in 10-15 years that may present continuity issues. The lack of junior scientists in continuing positions has been an on-going weakness and long-term threat to HAA.
  - The HAA scientific staff has poor gender and racial diversity.
  - The small number of scientific staff at DRAO (Penticton) is below critical mass.
- HAA is an integral part of the Canadian astronomical community whose research efforts are primarily funded by governments. HAA's ability to carry out world-class research, and ultimately deliver on NRC's parliamentary mandate, is highly dependent on funding and support from the government and NRC management, and is thus subject to changing higher-level priorities over time.
- HAA's own analysis of research priorities for the international community in the coming decade (see below) suggests that it will soon lack specialized expertise in fields that will be important for the Canadian community. These include:
  - The early universe and cosmic microwave background; dark matter and dark energy; gravitational lensing; redshift surveys; time-domain astrophysics (transients and explosive events); high-energy (x-ray and gamma-ray) astrophysics; exoplanet and planetary system atmospheres .
  - HAA currently has no 'in house' expertise in several disciplines that, while not obviously linked to NRC's mandate, have nevertheless become increasingly important in modern research: e.g., theoretical astrophysics, numerical simulations, algorithms and post-processing, and applied mathematics.
- Some critical decisions that affect HAA's ability to meet NRC's parliamentary mandate are made at government levels.
  - HAA scientists have only limited access to external funding sources (NSERC, CFI, CSA) that are needed to support the scientific or technical initiatives we lead. The "lead from behind" philosophy that HAA has been compelled to adopt is not only ineffective, but it puts HAA staff at a competitive disadvantage in promoting projects and is anathema to researchers who aspire to be world leaders.
  - Repeated rebranding has diminished HAA's visibility amongst NRC stakeholders (i.e., HIA → NSI → Herzberg → HAA, all within one decade).

OPPORTUNITIES

- NRC's parliamentary mandate in astronomy requires a national perspective for all scientific and technological initiatives. HAA thus provides an important complement to academia, where it can be difficult for NRC's stakeholders to lead or develop such initiatives.
- The post-*Dialogue*[2] era within NRC is a good time to begin the scientific revitalization of NRC and HAA. This opportunity coincides with community efforts to establish the 2020 Long Range Plan (LRP) for Canadian Astronomy.
  - HAA can work with our stakeholders (i.e., the Canadian academic community) to renew capacity and build expertise in research areas of the future. Priorities should be placed on junior-level scientist positions and increased support for postdoctoral researchers.
  - NRC's avowed post-*Dialogue* support for postdocs represents another exciting opportunity to expand HAA's scientific capacity, and to strengthen ties with the university community.
  - One ambitious, long-term goal would be an HAA observational and instrumentation postdoctoral program that mirrors that of CITA, the existing and highly successful community program in theoretical astrophysics. It is likely that such an initiative would be met with enthusiasm in the community.
  - It may be possible to utilize the Astronomy Research Centre at the University of Victoria to bolster HAA's science and technology initiatives.
  - Similarly, HAA should explore possible scientific or technical collaborations with TRIUMF and other NRC groups, particularly those working on machine learning and augmented intelligence.
- HAA has in the past provided significant scientific leadership in Canadian space astronomy. NRC and CSA should now explore the possibility of HAA assuming a greater role in the planning, design, fabrication and operation of space observatories.
  - Within the framework of LRP2010, the leading candidates are *WFIRST*, *CASTOR*, and/or *SPICA*, although other priorities will surely arise and need to be considered for LRP2020.
- HAA should aim for significant involvement in the next generation of large astronomy projects (including international efforts that may not have NRC involvement at this time). Possibilities include:
  - Stage IV cosmology projects, wide-field imaging and spectroscopy surveys, radio astronomy initiatives, and opportunities in data mining, processing, archiving and visualization.
- HAA's sites and infrastructure offer exciting opportunities in research, technology development, HQP training, and outreach: e.g.,

[2] *Dialogue* is an internal NRC-wide initiative begun in 2017 to reorient NRC's research activities with consultation and input from its staff.

- DRAO (Penticton) — a unique, radio-quiet site in Canada — is home to CHIME, a powerful new facility that was developed in a partnership between Canadian universities and NRC.
- In consultation with the Canadian community, HAA should explore the possibility of adding the DAO (Victoria) optical telescopes to the Las Cumbres Observatory telescope network.
- At both HAA sites, a renewed emphasis could be placed on technology development efforts using the local facilities.
- Appropriate infrastructure at both sites, most notably the Centre of the Universe at DAO (Victoria), should be re-dedicated to EPO efforts.

THREATS

- There are significant risks associated with the largest LRP projects (e.g., TMT, SKA) that impact HAA's (and Canada's) ability to plan, advocate, build, and operate a portfolio of observing facilities for the Canadian community.
  - Specific risks include the uncertain TMT construction situation; the challenging project scope of the SKA; and, in space astronomy, the lack of clearly defined processes to build and maintain a space mission portfolio.
  - Some of these risks are beyond the control of HAA and NRC, and are leading to lost opportunities for the Canadian community. For example, Canada has no intellectual leadership or instrument involvement in the major wide-field optical/IR astronomy initiatives that will dominate US and European astronomy in the 2020s (e.g., LSST, *Euclid*, *WFIRST*).
  - It is likely that the Canadian community will need to adjust its research and facility priorities as these telescopes begin operations, and the role of HAA within this new landscape is unclear without a significant Canadian contribution (cf., MSE, *CASTOR*).
- CFI has emerged as the major infrastructure funding mechanism for Canadian scientists. This poses two distinct challenges to NRC/HAA:
  - Participation by NRC in CFI proposal remains complicated. HAA staff still cannot lead CFI proposal that they should, given their leadership roles.
  - For CFI-funded projects, the role of NRC in operating and administering astronomical facilities after their nominal five-year lifetime is unclear, i.e., will NRC be expected to operate a network of CFI-initiated projects?

Scientific Perspective: Expected Research Priorities in the 2020s

In our assessment of the opportunities and threats facing scientific research at HAA in the next decade, we have identified three broad research areas that will likely have high priority. A range of new observing facilities, both on the ground and in space, is expected to drive this research, with an increased emphasis on wide-field and time-domain astrophysics.

1. **Are We Alone?**
   - Exoplanets: demographics, atmospheres, surfaces, and interiors.
   - Formation and evolution of our Solar System and other planetary systems.
   - Astro-chemistry and astro-biology (biomarkers).
   - Search for Extraterrestrial Intelligence (SETI).

2. **The Dark Universe.**
   - Dark matter and dark energy.
   - Inflation, exotic matter, and the early universe.
   - Growth of cosmic structures, including the Milky Way, from cosmic dawn to the present day.

3. **Fundamental Physics from Astrophysical Sources and Data.**
   - Degenerate objects: white dwarfs, neutron stars, and black holes (from stellar to super-massive scales).
   - Gravity, equations of state, explosive phenomena.
   - Gravitational wave astronomy and the characterization of sources across the electromagnetic spectrum.

Summary: Although there have been headwinds, the research health of HAA remains robust, benefitting significantly from its strong and sustained culture of research excellence. HAA staff members play an important role as part of the larger Canadian astronomical research environment. We are productive authors of refereed publications, we supervise significant numbers of undergraduate and graduate students, and we provide an excellent environment for the personal growth of research associates. HAA has a strong record of promoting these students and research associates into Canadian and international departments and institutes. HAA scientists also play an important role in supporting and promoting research science within the larger Canadian community.

Over the next decade and a half, there will be a major transformation of the research staff at HAA. To maintain the historical role that HAA has played, and to continue to support and lead astronomical research within Canada, it is imperative that HAA keeps a steady focus on renewal while monitoring and adapting to the quickly changing astronomical landscape. As such, we look forward to recalibrating the HAA science *Future Directions* discussion after the publications of LRP2020 to make sure that HAA stays well aligned with the long-term plans of Canadian astronomical communities.

ACRONYMS

ALMA	Atacama Large Millimetre/submillimetre Array
ATD	*Astronomy Technology Division*
CADC	*Canadian Astronomy Data Centre*
CASTOR	*Cosmological Advanced Survey Telescope for Optical and uv Research*
CFHT	Canada France Hawaii Telescope
CFI	*Canadian Foundation for Innovation*
CITA	*Canadian Institute for Theoretical Astrophysics*
CHIME	*Canadian Hydrogen Intensity Mapping Experiment*
CSA	Can*adian Space Agency*
DAO	*Dominion Astrophysical Observatory (Victoria)*
DRAO	*Dominion Radio Astrophysical Observatory (Penticton)*
EPO	*Education and Public Outreach*
HAARC	*Herzberg Astronomy and Astrophysics Research Centre*
HQP	*Highly Qualified Personnel*
IT	*Information Technology*
JCMT	James Clerk Maxwell Telescope
JWST	*James Webb Space Telescope*
LRP	*Long Range Plan for Canadian Astronomy*
LSST	*Large Synoptic Survey Telescope*
MSE	*Maunakea Spectroscopic Explorer*
ngVLA	Next Generation Very Large Array
NRC	National Research Council Canada
SETI	*Search for ExtraTerrestrial Intelligence*
SKA	*Square Kilometer Array*
SPICA	*Space Infrared Telescope for Cosmology and Astrophysics*
STEM	*Science, Technology, Engineering and Mathematics*
TMT	*Thirty Metre Telescope*
WFIRST	*Wide-Field Infrared Survey Telescope*