Report of the Ground-based Astronomy Committee

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1 World Observatories

1.1 TMT

The TMT is a thirty-meter optical-infrared telescope to be built on Mauna Kea. Full members of the international partnership are UC, Caltech, Canada, China, India, and Japan. The US, through NSF, is considering to join if such a telescope is the top-ranked priority in the upcoming US Decadal survey. Canada's contribution is currently close to a 15% share and include the enclosure and instrumentation work (including the adaptive optics system NFIRAOS).

Key science areas are fundamental physics and cosmology; early Universe, galaxy formation and the intergalactic medium; supermassive black holes; Milky Way and nearby galaxies; star, stellar physics and the interstellar medium; formation of stars and planets; exoplanets; our solar system; and time domain science. The first-light instruments are the Wide-Field Optical Spectrometer (WFOS; 0.31 – 1.0 μm) and the Infrared Imaging Spectrograph (IRIS; 0.84 – 2.4 μm), together with the Narrow Field InfraRed Adaptive Optics System (NFIRAOS). The TMT project is currently discussing the prioritization and planning of second generation instrumentation.

Construction began in October 2014 but was halted due to legal challenges. Due to the uncertain future of Mauna Kea as the building site for TMT, the TMT project considered alternative sites for TMT in 2016 (in Spain, Mexico, and two in Chile). On October 31st, 2016, the TMT International Observatory LLC (TIO) decided on the Observatorio del Roque de Los Muchachos (ORM), in La Palma, on the Canary Islands (Spain) as the alternate site for TMT. However, as of October 2018, the TMT has the legal right to restart constructions. As of May 2, 2019, construction has not yet restarted but has to restart before September 2019 due to various partner considerations.

We refer to the CATAC report for the LPR2020 panel for further details on the TMT.

1.2 SKA

The centimetre-wavelength Square Kilometre Array (SKA) was listed as the second priority in the 2010 LRP, with the plan that SKA construction funds would eventually supplant the TMT at the top as the latter would be built by the end of the decade. Both projects have been delayed well beyond the 2010 projections.

The SKA project as a whole has made substantial progress in the decade. The SKA Organization was formed in 2011 to steer design and pre-construction activities, and Canada is a member with input into governance. Headquarters were established at Jodrell Bank, UK, in 2015. The project has been phased into two stages, with Phase 1 (SKA1) currently finishing a set of Critical Design Reviews and construction start currently anticipated in mid-2021. SKA1 is intended to be 10% of the collecting area of the ultimate SKA2 telescope. The two original drivers for SKA1 were tests of fundamental physics with pulsars and black holes and the history of neutral hydrogen in the Universe, while the other science goals (galaxy evolution, cosmic magnetism, cosmic dawn, cradle of life, transients, etc.) now also form a set of High Priority Science Objectives that drive the SKA1 design. SKA1 was re-baselined in 2016/7 to account for increases in cost, with some, but not fatal, reduction in science capabilities.

The site decision in 2012 benefited both potential host countries, with South Africa hosting the SKA1-Mid dish-based component, building from the MeerKAT precursor, and Australia hosting the SKA1-Low aperture arrays (design still being finalized) and using the ASKAP precursor to investigate the potential of phased-array feeds in later versions of the higher-frequency dish component.

The various SKA1 subsystems have been developed by international consortia, with Canada (NRC with MDA) leading the Central Signal Processor (CSP) and achieving a coup by designing an improved SKA1-Mid correlator that meets performance requirements but with an estimated 20M Euro savings relative to the original design. Unfortunately the proposed Canadian composite dish technology was not selected for use, although Canada did develop low-noise amplifiers and digitisers for SKA1-Mid through the Dish Consortium.

A CFI grant to several Canadian universities (PIs Gaensler and Rosolowsky) is leading to the establishment of a radio data centre (CIRADA), which could be a prototype for a future Canadian SKA Regional (data) Centre.

Many Canadian scientists have joined and led various SKA Science Working Groups, and four of those working groups have been chaired by Canadians in the last five years. Canada has been represented on the Science and Engineering Advisory Committee by Spekkens since 2017, with Stairs taking over in mid-2019. A poll conducted in 2015 for the LRP Midterm Review indicated that roughly 30 Canadian researchers anticipated spending 25% or more of their time on SKA-related projects in the early science stages.

The mandate of the SKA Organisation is to oversee pre-construction activities, and Canada has a governance role in that process through its two positions on the Organisation's Board of Directors (Rupen and Spekkens are the current Board members, taking over in the last year from Fahlman and Gaensler). SKA governance during construction and operations lies with a treaty which will replace the SKA Organization by the SKA Observatory intergovernmental organization (IGO). Due to parliamentary logistical difficulties, Canada does not intend to sign the treaty in the immediate future, but will become an Associate Member through an accession process to be finalized by the IGO Council. This should still provide Canadian astronomers with reasonable access to the telescope, although the details are still being worked out. The nominal share for Canada stands at 6%, but funding has yet to be provided.

Canadian involvement in SKA1, SKA2, and other future large radio observatories (e.g. ngVLA) might best be separately evaluated and prioritized as they have very differing timescales and risks associated with them. Canadian involvement in SKA1 and SKA2 needs to be discussed as two completely different facilities. Presumably our involvement in SKA1 does not mean any special status for SKA2, which would presumably start taking shape in the 2030s at the very earliest.

1.3 ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) is a transformational observatory located in northern Chile on the 5000-m altitude Llano de Chajnantor plateau. It is composed of two distinctly operated interferometer arrays, the "12-m Array" of 50 antennas of 12-m diameter that can be positioned between tens and thousands of meters apart, and the "7-m Array" of 12 antennas of 7-m diameter that are fixed in a compact configuration. Four other antennas of 12-m diameter that are also located at fixed positions compose the "Total Power Array" (TPA) and these can be used in concert (but not as an interferometer) to acquire large-scale flux data that complement the interferometer array data. ALMA is a truly global observatory. Three regional partner communities operate it: North America (the U.S., Canada, and Taiwan), Europe (the ESO member states), and Asia (Japan, Taiwan, and South Korea), with further participation by the Republic of Chile.

ALMA is a unique facility, providing unprecedented sensitivities, resolutions, and frequency coverage at millimetre/submillimetre wavelengths. The last ten years (2010-2020) have seen ALMA move from its late construction stage, through early science (Cycles 0-6), to nearly steady-state operations (Cycle 7 and beyond). Over this period, ALMA has been an engine of astronomical discovery. It has already essentially met all its "Level One" science goals, which included the detection of CO or [CII] line emission from normal galaxies at $z = 3$, the detection of gas kinematics and tidal gaps in circumstellar disks at the distance of the nearest star-forming regions, and regular production of high precision images at $0.1''$ resolution. It has produced publications at rates similar to that of the Hubble Space Telescope, and last year it passed the milestone of 1000 papers published. It presently has the highest impact factor of a ground-based observatory worldwide.

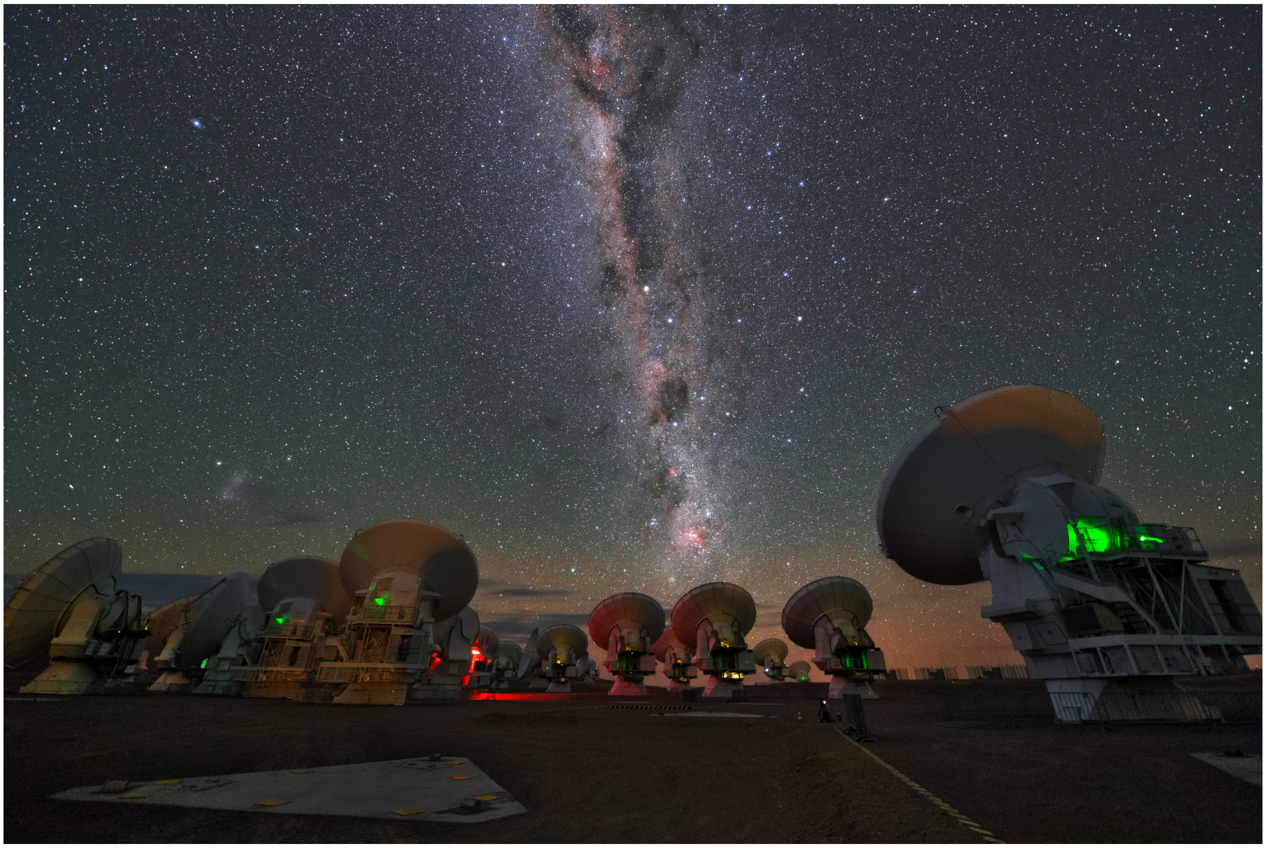

Figure 1: ALMA beneath the Milky Way. Credit: ESO/Y. Beletsky

Noting ALMA's potential for meaningful discovery, the 2000 panel for the Long Range Plan for Canadian Astronomy (LRP2000) recommended it as the highest priority for future Canadian involvement in a ground-based facility. Consequently, Canada officially joined the project in 2003, in partnership with the U.S. National Science Foundation (NSF). Canada's contributions to ALMA construction included the Band 3 receivers, a suite of 73 receivers of 86-116 GHz emission that were developed by NRC Herzberg in partnership with industry, one of the first four receiver bands available to the astronomical community. In addition, Canada provided indirect support to ALMA construction via an in-kind contribution to the U.S. National Radio Astronomy Observatory (NRAO) of the WIDAR correlator for NRAO's Jansky Very Large Array in New Mexico, U.S.A., also developed by NRC Herzberg and industrial partners. Canada further provided other software and financial contributions to the ALMA construction project.

North America (NA) provides 37.5% of the cost of ALMA operations, with Europe providing another 37.5% and Asia providing 25%. Each regional partner in turn receives the same share of observing time, after Chile, as host country, receives 10% of the total time available. Canada provides 7.25% of the North American cost of ALMA operations. Half of this commitment is made by in-kind contributions by NRC Herzberg for: i) support of North American ALMA users via a Victoria node of the North American ALMA Regional Centre (ARC), ii) maintenance and repair of the Band 3 receivers (as needed), and iii) archive software contributions by the Canadian Astronomy Data Centre (CADC). The other half of Canada's ALMA commitment is made by the Treasury Board of Canada as direct cash payments to NSF for operations in Chile.

After a commissioning and science verification phase in the early 2010s, an early form of ALMA, i.e., 16 antennas of the 12-m Array only with limited hours and a limited range of baseline lengths and receiver bands available, was made available to the community for best effort Early Science via a Cycle 0 call for proposals in 2011. Since then, ALMA has issued proposal calls nearly annually, with increased capabilities marking each successive Cycle. It most recently concluded its Cycle 7 call for proposals in April 2019, for which at least 43 of the 12-m Array antennas, at least 10 of the 7-m Array antennas, and at least 3 of the TPA antennas will be available for science, over a wide range of configurations and receiver bands. (Some restrictions on observing modes remain as new capabilities continue to be commissioned.) Some 4300 hours are expected to be available for science with the 12-m Array and 3000 hours are expected for the 7-m Array. In addition, a "supplemental call" for proposals to use only the 7-m Array-will be concluded in October 2019.

A single Proposal Review Committee (PRC) composed of sub-panels arranged by subject expertise judges all proposals. Indeed, Canadians have participated in the PRC for every ALMA Cycle so far. The PRC ranks and assigns grades to proposals according to scientific merit, where the grades define priority for completion. For example, ALMA projects graded "A" can be observed in the current and next Cycle to maximize the likelihood of completion. ALMA projects graded "B" are lower priority and will not be carried over to the next Cycle. Grade "C" projects are done on a best effort basis, given available conditions and RA range. Projects with lower grades are simply not scheduled. Though a nominal completion time is determined at the proposal stage, ALMA observations are conducted until pre-determined completion criteria are met, e.g., sensitivity or resolution, and the associated time used is charged to the relevant partner's share. Notably, under the terms of Canada's agreement with NSF, Canadians receive no fixed fraction of access within the North American share, and we effectively compete alongside our other NA partners for ALMA access.

Since ALMA has been available for community use, demand for its time has been impressive. For example, Cycle 0 alone attracted 919 proposals in total. Indeed, the number of submitted proposals has grown more or less steadily with each Cycle to 1839 in Cycle 6, the largest number of proposals received by any observatory in history. The recent Cycle 7 call resulted in 1773 proposals, just 3% fewer than Cycle 6. Given the very limited number of hours available, the oversubscription rate for the 12-m Array was highest in Cycle 0 at 8.6 for proposals from all partners. Though the numbers of proposals have increased since Cycle 0, the global oversubscription rate has declined to 4-5 in more recent Cycles as more observing hours became available. Since the 7-m Array itself became available for standalone observations around Cycle 5, its oversubscription rate has been around 4-5 as well.

Canadian demand for ALMA has been very high, but it is admittedly tricky to parse what constitutes such demand when Canadian projects have no fixed time allocation and there has been ample collaboration by Canadians with astronomers worldwide. For this report, Gerald Schieven of NRC Herzberg kindly shared the impressive job he has done tracking statistics for each Cycle. Canadians were PIs on 25 proposals for Cycle 0 and this number grew more or less steadily to 43-44 proposals for Cycles 6 and 7. The numbers of proposals on which Canadians were PIs OR co-Is, however, is much larger, starting at 86 for Cycle 0 and growing to 247 for Cycle 7. Taking the amount of nominal 12-m Array time requested by Canadian PIs and comparing that number to the amount of hours Canadians might "expect" in each Cycle given its 7.25% share of NA operation costs yields Canadian over-subscription rates of 11.7 for Cycle 0, 3-4 for Cycles 1-3, and 5-8 for Cycles 4-7. A similar exercise for the 7-m Array shows a more stochastic Canadian oversubscription rates of 11.3 for Cycle 5 (see below), 3.3 for Cycle 6, and 4.7 for Cycle 7. For context, there have been just under 30 unique Canadian PIs from ∼20 unique institutions across all Cycles so far, whereas the numbers of Canadians PIs or Co-Is increased from ∼50 in Cycles 0-1 to over 90 in Cycles 6-7.

Despite the high demand, Canadian success in ALMA time allocation has been very good. Taking the nominal hours allocated to Canadian PIs for higher-ranked Grade A and B projects on the 12-m Array compared to that allocated to North American PIs in total in each Cycle shows a peak of 10.2% in Cycle 0, declining to a minimum of 2.6% in Cycle 3 but bouncing back to ∼6-7% in Cycles 6-7. In comparison, Canadians have enjoyed even greater success on the standalone 7-m Array, with allocations of time for higher-ranked (A+B) projects of 51.9% in Cycle 5, 13.3% in Cycle 6, and 16.7% in Cycle 7. The Cycle 5 spike, however, was due to a Canadian (E. Rosolowsky) being co-PI of an ALMA Large Program that required a significant amount of 7-m Array time. Hence, Canada's allocations for its higher ranked projects appear consistent to first order with our 7.25% contributions to ALMA's NA operations costs.

Within its first decade, ALMA has made some startling discoveries. Though finding substructure in disks was one of its Level One goals, the detection of gaps in the disk of HL Tau (ALMA Partnership et al. 2016), found no less during the commissioning of longer baselines, was a watershed moment in studies of protoplanetary disks. Such substructures, as well as asymmetries and spiral patterns, have been now seen in several disks, including those of TW Hya (Andrews et al. 2016) and Oph IRS48 (van der Marel et al. 2013), among others (Andrews et al. 2018; Long et al. 2018). ALMA has also probed the continuum emission from the dust of high-redshift galaxies located in various "deep fields" (Karim et al. 2014; Hodge et al. 2013; Dunlop et al. 2017), as well as line emission from atomic and molecular gas from galaxies redshifted into the submillimetre/millimetre regime (Reichers et al. 2014; Walter et al. 2016). These data reveal the interplay between galactic gas and star formation rate across cosmic time. More recently, ALMA was a key component of the Event Horizon Telescope, a global network of submillimetre telescopes that imaged at the centre of the galaxy M87 the silhouette of a supermassive black hole against its surrounding accretion disk using very long-baseline interferometric techniques (Event Horizon Collaboration et al. 2019).

Canadians have shared in some of ALMA's greatest discoveries so far. Several have also led projects that have revealed important new insights. For example, Mann et al. (2014) showed the impact of intense ultraviolet radiation from the O star, θ^1C Ori, on the masses of nearby protoplanetary disks in the Trapezium Cluster. These data also included the first detection of rotation signatures from disks as distant as the Orion Molecular Cloud (Williams et al. 2015), allowing protostar masses to be directly estimated. Also, Hezaveh et al. (2013) detected strongly lensed galaxies, of which one, SPT0346-52 at z $\sim$ 5.7, was estimated to be an extraordinarily luminous and active star-forming galaxy. Furthermore, McNamara et al. (2014) described intense molecular outflow from the brightest galaxy of the Abell 1835 cluster that is driven by an expanding cavity blown by its AGN. As Canadians continue to use ALMA, including its archival data (e.g., see Wilson 2018; van der Marel et al. 2018), more exciting results are entering the literature.

Toward the next decade, ALMA will continue to evolve, with new capabilities and upgrades resulting from its ambitious Development Program. Canadians will likely contribute directly to this evolution and continue to make use of this unique facility. Development priorities for ALMA are addressed in a separate LRP2020 white paper led by Christine Wilson (McMaster).

2 International & National Facilities

2.1 CFHT

CFHT continues to provide high-quality and diverse observations to the Canadian community. CFHT is now functioning with an impressive five instruments in rotation: MegaCam, WIRCAM, ESPaDOnS, SITELLE, and SPIRou.

Since the 2015 midterm report, two new instruments were commissioned on CFHT:

- SITELLE is an optical imaging Fourier transform spectrometer (IFTS). SITELLE saw first light July 7th 2015 and has been offered for science observations since semester 2016A. The first publication from Science Verification data (SV) was published in August 2016. SITELLE continues to be well-requested in Canadian time from CanTAC and has an ongoing large program looking at nearby star forming galaxies (SIGNALS)

- SPIRou arrived at CFHT in January 2018 and was commissioned successful. SPIRou is a near-infrared spectropolarimeter and high-precision velocimeter working as a Guest Instrument for CFHT. The main science goals of SPIRou are the search and characterization of habitable exo-Earths around low-mass stars, and the study of the magnetic topology of young protostars as a tool for investigating star/planet formation mechanisms. SPIRou is currently (semester 2019B) one of the most requested instruments at CFHT. One large program is running on SPIRou, the SPIRou Legacy Survey (SLS).

Since the 2015 midterm report, two large program (LP) cycles were solicited. In the 2017 - 2019 LP cycle three programs were accepted:

- The Canada-France Imaging Survey (CFIS). CFIS is using 271 nights of MegaCAM time to map 1000s of square degrees in the u and r bands. CFIS is exploiting the unparalleled u-band sensitivity of MegaCAM, excellent r-band performance, and recovered image quality (IQ) of CFHT through two related components, enabling discoveries about structure formation from the Milky Way to high redshifts.

- VESTIGE: A Virgo Environmental Survey Tracing Ionised Gas Emission. VESTIGE is using 50 nights of MegaCAM time with a narrowband H-alpha filter. VESTIGE is the first deep blind H-alpha survey of a nearby cluster. The combination of data and simulations in VESTIGE will address a wide range of astrophysical questions: the star formation process in galaxies, the fate of the stripped gas in clusters, the dynamical structure of the nearest galaxy cluster, extragalactic planetary nebulae and the origin of the diffuse intracluster light, the ionised gas emission in the Milky Way, and the star formation activity of high-z line emitters.

- The CFHT Infrared Parallax Program: Mapping the Brown Dwarf-Exoplanet Connection. This program uses 60 nights with WIRCAM to obtain high-precision infrared astrometry of brown dwarfs in order to measure their fundamental parameters and to robustly test theoretical models of substellar evolution and ultracool atmospheres.

In the 2018 - 2022 LP cycle two program were accepted:

- The SPIRou Legacy Survey. The SLS is using 300 nights of SPIRou time to characterize exoplanets around M dwarfs. SLS is searching for Earth-like ones located at the right distance from their host stars to lie in the habitable zone

- The Star formation, Ionized Gas, and Nebular Abundances Legacy Survey (SIGNALS). SIGNALS is using 54 nights of SITELLE time. It will provide the largest, most complete and homogeneous database of spectroscopically and spatially resolved extragalactic HII regions ever assembled, at a mean spatial resolution of 20 pc. The main goals are to: 1) quantify the impact of the surrounding environment on the star formation process, 2) link feedback processes to the small-scale chemical enrichment and dynamics around star-forming regions, and 3) measure variations of the resolved star formation rate with respect to the indicators used for high redshift galaxies.

Several issues about CFHT's future remain to be resolved. This includes the Mauna Kea summit lease renewal which is being worked on by UH. Also, with MSE scheduled to replace CFHT, the future of the observatory will be determined by whether MSE moves forward as proposed. If MSE moves forward as planned, CFHT would be decommissioned in $\sim$ 2022.

2.2 MSE

The Maunakea Spectroscopic Explorer (MSE) is an ambitious redevelopment project to transform the CFHT 3.6-metre telescope into an 11-metre facility with a dedicated wide field multi-object spectrograph. MSE will lead the world in multi-object spectroscopy, with its unique capability to study up to 4,000 astronomical objects at once. Since the 2015 midterm report there has been significant development in the MSE project

- In 2016 MSE released a 300-page Detailed Science Case (DSC) which provided a detailed scientific reference for the project and featured some 180 co-authors. Both the DSC and a 10-page summary document are available on astro-ph.

- In 2017 successful conceptual design reviews were performed for numerous observatory sub-systems including the telescope structure (IDOM, Spain), enclosure (Empire Dynamic Systems, Canada), high-resolution spectrograph (NIAOT, China), fibre transmission system (NRC-HAA, Canada), fibre positioner system (three studies from USTC-China, CSIC-Spain, and AAO-Australia), top end assembly (GEPI and INSU-DT, France) and the low-to-moderate resolution spectrograph (CRAL, France).

- In January 2018 MSE underwent a successful Conceptual Design Review (CoDR). This placed it in good position to proceed with a Preliminary Design Phase (PDP) scheduled from 2018 - 2020
- In summer 2018 ACURA was asked to be the signatory for Canada on a Statement of Understanding setting out rules for the PDP. Canada should sign on as a PDP partner as the project progresses to show its support, in parallel with prioritization in the upcoming Long Range Plan.
- Also in 2018 NOAO and Texas A&M were granted observer status in the project to let them explore partnership options.
- In November 2018 MSE released its Project Book, which was a detailed engineering description of the new observatory. It summarized the technical status of MSE along with the science motivations and plan to progress the project forward. In total, the book is 160 pages in length with 125 contributors from the international MSE team. Approximately 10 of the contributors are from Canada.

Progress on the MSE PDP continues in several ways. Soon after the design review, a call was issued to the astronomical community to join the MSE's international science team, with the purpose of ”reaffirming“ the science case, before starting the Design Reference Survey (DRS) process. Since then, the size of the science team has more than tripled: there are currently 327 members from thirty countries. Nine different Science Working Groups (SWG) have been created to focus on different areas of the MSE science case. Each SWG has two co-leads. The SWGs are the primary groups responsible for the ongoing development of the MSE Science Case and the development of the DRS. A new version of the Detailed Science Case will be published at the start of 2019, and the DRS activities will start soon thereafter.

2.3 Gemini

The Gemini Observatory includes two 8.1-m telescopes that operate in the visible and near-infrared (NIR) regime in locations (Maunakea, Hawaii and Cerro Pachón, Chile) that provide access to the entire sky. One of unique features of Gemini Telescopes is that majority of the observations are carried out by staff members in queue-scheduled mode, providing flexibility in scheduling and thus more efficient use of observing time.

The Observatory is operated by a partnership of six countries: United States, Canada, Chile, Brazil, Argentina and Korea. The major change in governance occurred in the 2014–2015 period when the UK and Australia dropped out of partnership. Korea/Korea Astronomy and Space Science Institute (KASI) has become official partner (at 5% level) in January 2019. Canadian contribution to the Gemini Telescope funding is currently at 18.1% level.

In addition to the changes in partnership structure, Dr. Jennifer Lotz was appointed the new Director of the Observatory in October 2018. A world-renowned expert in galaxy morphology evolution, high-redshift universe, and gravitational lensing, Dr. Lotz previously held an associate astronomer position at the Space Telescope Science Institute (STScI). Dr. Lotz's appointment followed a one-year period when the Observatory was managed by Dr. Laura Ferrarese (NRC Herzberg) as the Interim Director. Dr. John Blakeslee from the Canadian Gemini Office was named Observatory's Chief Scientist in October 2017.

In the years following 2015 Mid-Term Review current Gemini instrumentation has been improved with:

- the upgrade of GMOS-N with red-sensitive Hamamatsu CCDs in 2017 (GMOS-S was upgraded in 2014);
- the new laser installed on Gemini Multi-Conjugate Adaptive Optics System (GeMS), which delivers a uniform, diffraction limited image quality in NIR wavelengths for Gemini South Adaptive Optics Imager (GSAOI) and Gemini South's NIR imaging spectrograph Flamingos-2;
- the implementation of the multi-objects spectroscopy mode for Flamingos-2.

The Observatory's next generation of instruments are being designed and built to fulfil the new role(s) of Gemini Telescopes beyond 2021, outlined in the Strategic Vision for the Gemini Observatory. Released at the end of 2016 by the Board of Directors, after open consultations with the Gemini Users community, the Strategic Vision recommendations include:

- allowing directions of the two telescopes to diverge;
- making the Observatory a premier facility for a) the follow-up of Large Synoptic Survey Telescope (LSST) targets, b) adaptive-optics enabled instruments (Gemini-N, Figure 2), and c) visitors instruments;
- retaining significant fraction of time for Principal Investigator-driven science.

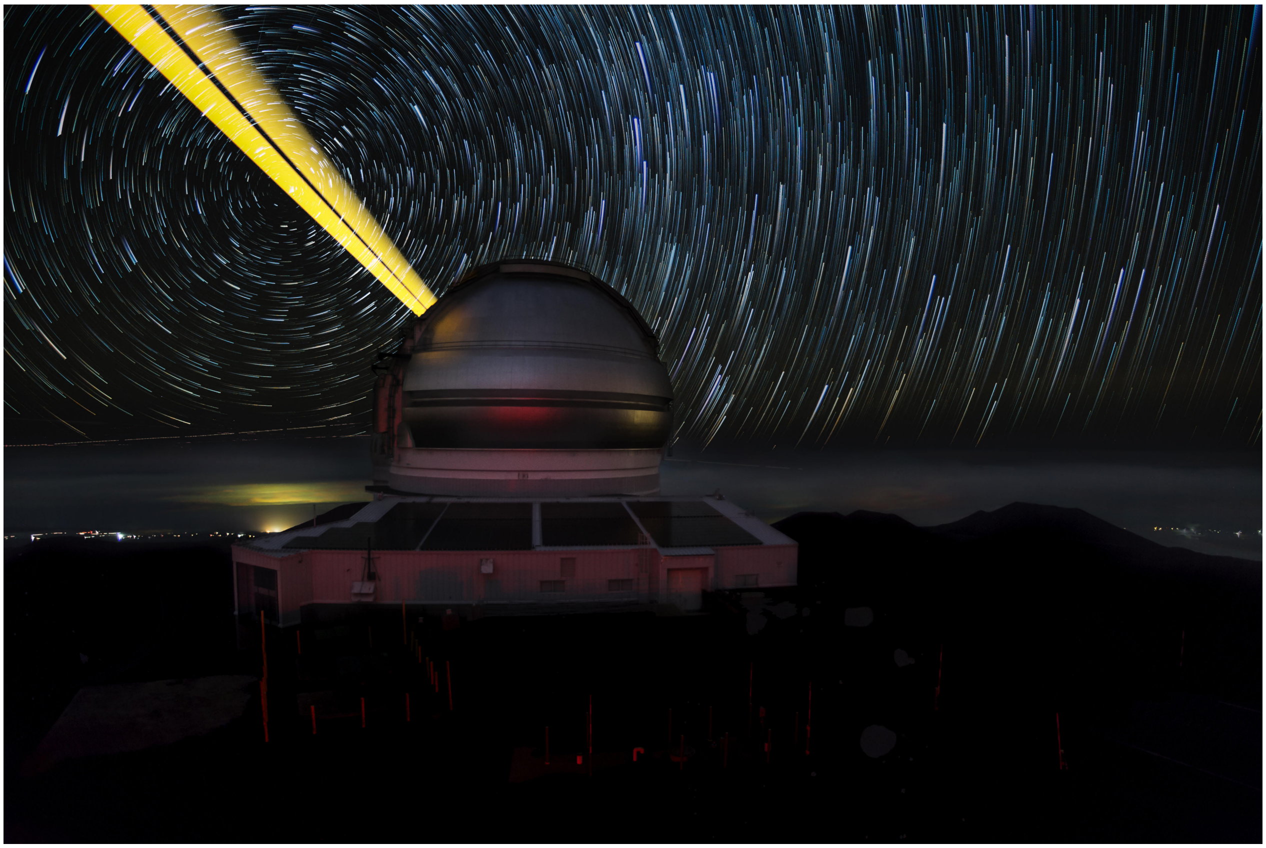

Figure 2: Gemini-N telescope during laser guide star operations (LGS) in 2016. This time lapse image consists of roughly 40 images. Credit: Gemini Observatory/AURA

Three facility-class instruments currently under development are Gemini High-resolution Optical SpecTrograph (GHOST), Spectrograph and Camera for Observations of Rapid Phenomena in the Infrared and Optical (SCORPIO), and Gemini Infrared Multi-Object Spectrograph (GIRMOS). In addition, funding from NSF has been secured for the development of a new-generation AO system for Gemini-N (GNAO).

GHOST will provide simultaneous wavelength coverage in the $363 - 950$ nm range, operating in two spectral resolution modes: standard ($R > 50,000$) and high ($R > 75,000$). The instrument will spatially sample each target over a field size of $1.2''$. In standard-resolution mode, GHOST will be able to observe two targets simultaneously over $7.5'$ (diameter) field-of-view, with radial velocity precision of 600 m/s over the full wavelength coverage. In high-resolution mode, GHOST will provide radial velocity precision of 10 m/s over the $430 - 750$ nm wavelength range. A broad range of science cases includes the radial-velocity confirmation of TESS planet candidates and the follow-up of GAIA targets. The instrument's Cassegrain unit, built at the Australian Astronomical Observatory, was successfully tested at Gemini-S in early 2018. The bench spectrograph is under construction at the NRC Herzberg.

SCORPIO, the Observatory's Gen3#4 instrument, is an 8-channel imager and spectrograph that will simultaneously observe in $grizYJHKs$ bands over a $3' \times 3'$ field-of-view (or a circular field-of-view with a $4.24'$ diameter). The instrument will obtain long-slit ($3'$) spectroscopy with a resolution of $R \sim 4,000$. Its spectroscopic and imagining capabilities make SCORPIO the optimal machine for the characterization of astronomical transients and thus for the efficient follow-up of such sources discovered in LSST's main survey and Deep Drilling Fields. A contract to design and build the instrument was awarded in March 2017 to the Southwest Research Institute in San Antonio, Texas. The project is currently in the critical design review stage; it is on schedule to be commissioned at the time of the LSST first light (2020).

GIRMOS is a precursor of the Multi-IFU imaging spectrometer (IRMOS), one of the second generation instruments designed for TMT. GIRMOS will carry out simultaneous spatially-resolved NIR spectroscopy of at least four objects within a $2'$ field-of-regard, taking the advantage of new AO system for Gemini-N, GNAO. The project, led by the Dunlap Institute, received CFI funding in October 2017. The instrument is currently in the critical design review stage; it is expected to become Gemini facility instrument by $\sim$ 2022.

Around 2014 the Observatory introduced two new ways to request observing time: the Large and Long and the Fast Turnaround programs. The Large and Long Program is designed for proposals requiring either a lot of observing time, or a limited amount of time spread over up to six semesters. In the 2014–2018 period 22 proposals have been awarded time through this program, two of which are led by Canadian astronomers (Drs. Kim Venn and Michael Balogh). Many more astronomers from Canada are Co-Is on successful Large and Long Proposals: 8 (36%) of these programs include at least one Co-I from a Canadian institution. The Fast Turnaround Program, with its monthly deadlines, is useful for proposals that require < 10 h on the sky and allows for quick data acquisition. In five years since the inauguration the program has gained popularity. For almost all partners (including Canada), in the last two years awarded time relative to requested time has been, on average, $\sim$ 50%.

Astronomers affiliated with Canadian universities and institutes have significantly contributed to the scientific output from Gemini Telescopes. In the period between 2010 and 2018 Canadian astronomers were first authors or co-authors on 22% of refereed publications that include data sets obtained with Gemini instruments. The number of citations for Gemini publications that include Canadian astronomers represents 33% of the total citation score for Gemini publications in this period. Major fraction of publications with Canadian contribution were written in collaboration with other Gemini partners (90%, 86% with USA-affiliated astronomers). More detailed analysis of Canada's publication performance using Gemini will be provided in the LRP2020 white paper "Canada's performance based on bibliometrics" by Dennis Crabtree (NRC Herzberg).

2.4 LSST

The Large Scale Synoptic Telescope (LSST) is an 8.4-m telescope under construction on Cerro Pachón in Chile. The LSST 3200 megapixel camera has a 3.5 degree field of view which will allow for deep, wide imaging of the sky. LSST will conduct a 10-year imaging survey of the sky starting in 2022. LSST's science goals include the study of dark matter and dark energy, the structure and formation of the Milky Way, time domain astrophysics, and mapping of the solar system. Adminstration of LSST has been combined with NOAO and Gemini into the NSF's National Center for Optical-Infrared Astronomy (NCOA).

LSST provides an opportunity for Canadian astronomy to build on its record of success in imaging surveys. Spectroscopic followup of LSST targets could be provided by facilities such as Gemini, MSE and TMT.

The University of Toronto has signed a memorandum of agreement with the Large Synoptic Survey Telescope Corporation (LSSTC) that provides access to LSST for a Canadian Consortium. The Consortium consists of a defined set of principal investigators (PI), who each have full access to LSST data, tools and working groups, along with up to four postdocs or students per PI. The signed memorandum provides for ten initial PIs across Canada (at an approximate cost of US$21500/year/PI for ten years), but allows the number of participants and associated payments to be increased at any time. The Dunlap Institute has committed to providing up to 50% funding for these first ten PIs. Sixteen Canadian faculty are currently planning to participate in LSST via membership in the Canadian LSST consortium. Six of these sixteen have secured full funding for their participation, while the other ten will be seeking a 50% subsidy on membership fees from the Dunlap Institute. Work continues on a legal agreement that would commit Canadian partner institutions to making their annual payments to the University of Toronto for the full ten years of the project, with U of T then making an overall annual payment to LSST. In addition, work is underway to set up a Canadian LSST Steering Committee to oversee the project.

For more information we refer to the White Paper: Canadian Participation in the LSST.

2.5 JCMT

The James Clerk Maxwell Telescope (JCMT) is a 15-m diameter submillimetre telescope situated on the summit of Mauna Kea, Hawaii, U.S.A. It has been in operation since 1987 and is still the world's largest single-dish submillimetre telescope. The JCMT had two flagship instruments over the past decade, SCUBA-2 and HARP. SCUBA-2 is a revolutionary large-format bolometric "camera" that allows fast mapping of continuum emission in the 850 μm and 450 μm bands simultaneously. SCUBA-2 itself was financed by the United Kingdom (UK) and Canadian universities at the 50% level each. In addition, two add-ons to SCUBA-2 produced entirely by Canadian universities were commissioned over the past decade: FTS-2, a Fourier Transform Spectrometer, and POL-2, a polarimeter. HARP is a unique 4×4 focal-plane array of heterodyne receivers that allows fast mapping of line emission across the 850 μm band that was built by the UK with a small contribution from NRC. In addition, JCMT continued availability of the older heterodyne receivers A3 and W for the 1.3 mm and 450 μm bands, respectively. All heterodyne receivers used the NRC-developed ACSIS backend that was made available in the late 2000s. In addition, the heterodyne Receiver B3 for the 850 μm band was modified by JCMT to allow interferometry with the nearby Submillimetre Array. As of September 2019, only SCUBA-2 and HARP are supported at the JCMT.

The last ten years saw the JCMT operate under two regimes. For the first half of the 2010s, the JCMT continued to be operated by the original partnership of the UK, Canada, and the Netherlands. In this partnership, the UK had a 55% share in JCMT, Canada had a 25% share, and the Netherlands had a 20% share. (As host, the University of Hawaii received 10% of JCMT time off the top.) NRC provided the Canadian support for JCMT operations through a combination of direct cash payments and in-kind contributions by staff at the Joint Astronomy Centre in Hilo and at NRC in Canada. In addition, NRC provided the JCMT data archive via the Canadian Astronomy Data Centre (CADC). In 2013, however, the Netherlands withdrew from the JCMT. The UK share went up to 75% but Canada's share remained at 25%. In March 2015, the United Kingdom and Canada finally ceased national support of the facility. Though the JCMT remained a robust and vital facility, the national resources required to operate it were needed by the original partners for other priorities, particularly ALMA. Indeed, the LRP2000 panel specifically recommended in its report that Canadian resources invested in JCMT be reprioritized to ALMA as needed.

JCMT was initially operated as a PI-driven facility, and Canada managed its 25% share via CanTAC, its own Telescope Allocation Committee. At the beginning of the past decade, however, half of JCMT time was devoted to the JCMT Legacy Survey (JLS), a collection of seven large programs, and the other half was devoted to smaller, PI-led programs. The JLS was defined in the mid-2000s as part of a JCMT community-wide response to the potential of then-new SCUBA-2 and HARP instruments. These programs, co-led by Canadians, included observations of deep cosmological fields (Geach et al. 2017), nearby galaxies (Wilson et al. 2009), the Galactic Plane (Moore et al. 2015), star-forming molecular clouds in the Gould Belt (Ward-Thompson et al. 2007), and debris disks (Holland et al. 2017), as well as an "all-sky" pilot survey (MacKenzie et al. 2011) and a spectral line survey (Plume et al. 2007). An international panel had previously reviewed the projects in the mid-2000s. In early 2012, the JLS projects were rescoped following the actual on-sky performance of SCUBA-2. The division of JLS projects to PI-led projects was also adjusted to 65%/35%, which increased to nearly 75%/25% by mid-2014, to maximize survey completion. The JLS projects ended when the initial partners ceased operating JCMT, with the rescoped observations largely completed. Notably, two Canadians, Gary Davis and Doug Johnstone, managed the JCMT over the last years of the original partnership, as Director (with 12 years service) and Associate Director (with 2 years service), respectively.

For the second half of the 2010s, JCMT ownership transferred from the UK to the University of Hawaii and JCMT operations were taken over by the East Asia Core Observatories Association (EACOA), a new international organization composed of Japan, Taiwan, South Korea, and China. (The organization has since morphed into the East Asian Observatory (EAO) and has expanded to include Thailand, Malaysia, Vietnam, and Indonesia.) As a part of this transition, NRC no longer provides operational funding to JCMT. Given the UK's and Canada's decades-long association with the JCMT, however, continued access to JCMT was maintained by coalitions of various universities in those countries, but at levels much less than previous. Led by Chris Wilson (McMaster), two years (2015-2017) of support were first obtained from direct contributions by six universities (McMaster, Alberta, Lethbridge, Waterloo, Western, and St. Mary's), at a total level of \$107K/year or $\sim$2% of total annual JCMT operations costs. Two further years (2017-2019) of support were then obtained via funding from the NSERC Research Tools and Instruments (RTI) program, as well as continued support by McMaster, Waterloo, and Alberta. Beyond these various contributions to support, the CADC continued to manage the JCMT archive. As of early 2019, however, no further Canadian direct funding avenues for JCMT operations have been found. Meanwhile, EAO and the University of Hawaii have agreed to a second five-year commitment to operate JCMT, over 2020-2025. EAO also has ambitious plans for new JCMT instrumentation, including a new wide-field 850-micron continuum instrument.

Scientific use of the JCMT in the EAO era resumed the initial 50-50 split between large programs and PI-driven smaller programs. These programs largely used the previous JCMT instrumentation (SCUBA-2, HARP) but several used POL-2, the polarimeter add-on to SCUBA-2 developed in Canada that was commissioned after the handover to EAO. In November 2015 and February 2017, seven and nine new large programs, respectively, were initiated, with some Canadian leadership. CADC management of the JCMT archive enabled Canadian participation in the new large programs. When university consortia or NSERC provided some support for JCMT operations, Canadians were also allowed to propose for a limited amount of PI time. In the new era, an international Telescope Allocation Committee, with one member per partner country, reviewed all proposals. Interestingly, 10% of JCMT time was allocated to the highest ranked proposals no matter their country of origin, technically allowing Canadians access to more JCMT time than their nominal contribution formally allowed if their proposals were excellent. Anecdotally, Canadians made good use of this allocation.

Canadians have been quite active in the new era of JCMT operations. Indeed, the BISTRO and BISTRO-2 (B-fields in Star-forming Region Observations) large programs (Canadian co-PI: Pierre Bastien, Montréal) have used POL-2 to map the magnetic field morphologies of star-forming clouds over much wider areas than previously possible, and have produced stunning images (e.g., Pattle et al. 2018). In addition, the JCMT Transients Survey (Canadian co-PI: Doug Johnstone, NRC) has demonstrated that protostellar sources can exhibit considerable variability over timescales of months (e.g., 10% of sources exhibiting variability of 10% or more over months to years so far; Johnstone et al. 2018).

Over the last ten years, Canadian demand for PI time has been quite strong, though it has notably declined in the past year. Towards the end of the original partnership era, oversubscription rates were high, e.g., 8.1 in semester 12B and 4.3 in semester 13A, in part due the decision to decrease the availability of such time in order to complete the JLS. In the EAO era, Canadian PI time was only $\sim$30 hours in total per semester, with roughly 2/3 given to proposers from the universities who contributed operational funds and roughly 1/3 available to other Canadian proposers. Given the very limited amount of access, demand was very high over this period, with oversubscription rates of $\sim$8 for proposers from the contributing universities and 3-4 for other Canadian proposers in semesters 16A-17A. In semester 18A, the division of Canadian PI time was eliminated with onset of the NSERC RTI funding, and the oversubscription rate was 6.3. In semesters 18B and 19A, however, demand was reduced, with oversubscription rates of only 1.7-1.8. For semesters 19B and 20A, there were no Canadian PI proposals allowed, due to an overallocation of Canadian PI time in semester 19A when the NSERC RTI funding ceased. Canadians, however, were eligible to lead or participate in new Large Programs that were solicited for semester 20A. Large Program membership will continue, and availability of a small amount of Canadian PI time may resume, as long as the CADC continues to manage the JCMT data archive.

Future potential Canadian participation in JCMT is described in a white paper about science with ground-based single-dish submillimetre-wave telescopes led by Scott Chapman (Dalhousie).

2.6 CCAT and CCAT-prime

The Cerro Chajnantor Atacama Telescope (CCAT) is a planned 25-m diameter submillimetre telescope to be situated atop Cerro Chajnantor, a peak of 5612 m altitude located above the Atacama desert plateau where ALMA resides. At that high altitude, the low amounts of precipitable water vapour allow the atmospheric windows at 350 μm and 200 μm to become available more frequently, allowing unparalleled access to such wavelengths from a ground-based facility. These wavelengths are near the SED peaks of submillimetre galaxies and protostellar sources, making CCAT very sensitive to emission from such objects. In addition, many high-excitation molecular lines and important redshifted atomic lines are found in those windows.

CCAT began in the 2000s as a partnership between Cornell University and Caltech, and expanded to include other universities/entities in the U.S. (Colorado, AUI), Germany (Köln, Bonn, MPIfR), Chile (Universidad de Chile), and Canada (Waterloo, UBC, Alberta, Calgary, Dalhousie, McGill, McMaster, Toronto, Western, and St. Mary's). The CCAT project began the past decade with a very strong endorsement from the U.S. Astro2010 Decadal Survey, emerging as the top-ranked mid-scale ground-based project. Regrettably, U.S. funding for construction of the 25-m CCAT via the National Science Foundation was declined in 2015 over lack of funds and Caltech, Colorado, and AUI exited the project. In response to the NSF decision, the Canadian Foundation for Innovation (CFI) declined to provide Canadian funding for CCAT.

By 2016, the project evolved into CCAT-prime (CCAT-p), a 6-m diameter survey-focused telescope at the high-altitude location slated for CCAT. CCAT-p has a "crossed Dragone" optical design, allowing high-throughput observations over a very wide field that can potentially enable tens of thousands of bolometers to be illuminated. The eight-degree wide field allows CCAT-p to have a very different set of science goals from the 25-m CCAT. Through a set of large Legacy-type survey programs, CCAT-p will probe large-scale structure, cluster velocities (constraining dark energy and neutrino masses), and galaxy and star formation.

Importantly, the more modest CCAT-p project can be constructed without NSF funding for the telescope itself, although funding is being sought from NSF for instrumentation. The total cost of CCAT-p construction and instrumentation is estimated to be ∼$50M. Cornell University was able to attract major funding from a private donor and is providing 50% of construction funds. The German universities will provide 30% of construction funds. These funds have allowed the construction of CCAT-p to begin. In November 2017, a contract for the manufacture of the CCAT-p telescope was awarded to Vertex Antennentechnik GmbH, with a goal of first light in late 2021. The Canadian CCAT team has already spent about $1M from a variety of sources on CCAT-p and are seeking approximately $6M of construction funding from CFI. In addition, $3M is being sought for Canadian contributions to build the 350 micron module for CCAT-p's prime-Cam instrument and develop its reduction pipeline software. For its contributions, Canada's share in CCAT-p will be 20%. Canada has two seats on the CCAT-p Board of Directors that are currently held by Michel Fich (Waterloo) and Norman Murray (CITA).

Future potential Canadian participation in CCAT and CCAT-p will be described in a white paper about science with ground-based single-dish submillimetre-wave telescopes led by Scott Chapman (Dalhousie).

2.7 ngVLA

The next generation Very Large Array (ngVLA) is a ∼ US$2B project to replace the current Jansky Very Large Array (VLA) with an array of 263 antennas operating from ∼ 1 to ∼ 116 GHz. The ngVLA will be a general-purpose, PI-drive telescope providing order-of-magnitude improvements in sensitivity, resolution, and instantaneous uv-coverage, with key science ranging from planetary system formation to galaxy evolution.

The observatory comprises three separate subarrays, which can be combined for the utmost in sensitivity and imaging performance. The *Main Array* consists of 214 × 18 m dishes, primarily populating the VLA site on the Plains of San Agustin in New Mexico, USA, but extending in a spiral pattern out to ∼ 500 km. The *Short Baseline Array* include 19 × 6 m dishes (four outfitted for single-dish use), is based at the VLA site, and provides sensitivity to emission on large angular scales. Finally, the *Long Baseline Array* has 10 stations comprising 3 × 18 m antennas each, spread across the US from Hawai'i to Puerto Rico, with one station at DRAO near Penticton, BC. This last subarray will replace the Very Long Baseline Array (VLBA) for imaging sources at very high angular resolution, but unlike the VLBA can be correlated in real time with all the other ngVLA dishes, providing a spatial dynamic range of more than a million to one.

The ngVLA is led by the US National Radio Astronomy Observatory (NRAO), although Canada has been actively involved since the earliest days in defining the scientific priorities, proposing technical solutions, and reviewing progress in both areas. Currently Canada has very active representatives on both of the key oversight committees, the ngVLA Scientific and Technical Advisory Councils (SAC and TAC, respectively); the latter is at present co-chaired by a Canadian. The ngVLA Science Book was published at the end of 2018, with more than 800 pages, 90 chapters, and numerous Canadian authors. This identified five key science goals:

1. unveiling the formation of solar system analogs on terrestrial scales;
2. probing the initial conditions for planetary systems and life with astrochemistry;
3. charting the assembly, structure, and evolution of galaxies from the first billion years to the present;
4. using pulsars in the Galactic Center to make a fundamental test of gravity;
5. understanding the formation and evolution of stellar and supermassive black holes in the era of multi-messenger astronomy.

These science goals have been translated into 'Level 0' requirements, recently reviewed and now in the process of being translated into true engineering requirements. A similar process has converted desiderata for operations, maintenance, land use, health and safety, and the like into a set of Level 0 stakeholder requirements, which just underwent a very positive review at the end of September. Together these two sets of requirements will be used to further refine the 1500-page reference design.

Funding for ngVLA must come primarily from the US National Science Foundation (NSF), though NRAO is hoping for international collboration at the $\sim 25\%$ level. NSF provided US$11M in late 2017 and US$4M in late 2019 for research and development work heading towards the Astro2020 US decadal survey. Assuming a good ranking from that panel, a proposal for construction funding could go to NSF as early as FY2021, leading to the beginning of construction in 2025, and completion of the full array by 2034. The construction cost is estimated as US$2.3B (2018 dollars), with steady-state operations (including archiving and the production of Science Ready Data Products [SRDPs]) being $\sim$ US$93M/year.

In addition to considerable scientific input, Canada has contributed the reference designs for two of the most important elements of the telescope: the dish and the correlator/beamformer. Both heavily leverage Canada's investment in SKA design, being based on NRC (HAA) work and composite dishes and special-purpose hardware for digital signal processing.

Numerous submissions of ngVLA white papers for the US Astro2020 Decadal Survey were received at the deadline of February 9, 2019, including 9 focused specifically on the ngVLA. The annual ngVLA conference this year was held in Charlottesville, VA on June 25-27, 2019, focusing on "Radio/Millimeter Astrophysical Frontiers in the Next Decade". The first international meeting on the ngVLA was held in September at NAOJ in Japan; the participants were remarkable both for their enthusiasm and for their youth, a happy sign for the future.

We also refer readers to the next generation VLA White Paper for the LRP2020 panel.

2.8 DRAO Facilities

2.8.1 Synthesis Telescope

The DRAO ST is capable of simultaneous observations at 1420MHz and 408MHz. It offers wide-field continuum polarimetry and neutral hydrogen spectroscopy at the former frequency (1' resolution over a 3-degree field), and continuum total intensity only at the latter (3' resolution over a 8-degree field). Telescope time is allocated via a competitive, peer-reviewed process, with deadlines at both equinoxes each year. Both short-term and long-term proposals are undertaken, with past projects ranging from targets of opportunity to surveys aimed at wide sky coverage or deep integrations. Although best-known for its work on Galactic ISM, in particular the Canadian Galactic Plane Survey (CGPS), the ST is also used for targets from solar system to nearby galaxies. Observing time on the ST continues to be fully subscribed, with projects for observers at Canadian universities - including many graduate and undergraduate students - and internationally.

A proposal for renewal of the ST came forward from DRAO in 2017. Three roles are envisaged for the telescope: it will be a forefront scientific instrument, a testbed for new radio astronomy technologies, and a training ground for graduate students in astronomy and in engineering. The rationale behind the telescope-as-a-testbed arose within Herzberg Astronomy and Astrophysics (HAA). HAA develops advanced radio astronomy technologies. Uptake of those technologies by the astronomical world succeeds when new concepts can be shown to work doing forefront science. The reinvisioned telescope will have nearly complete frequency coverage from 400-1800 MHz in Stokes I, Q, and U, with extensive and flexible spectral line zoom modes. This will enable a wide range of scientific applications to interstellar gas and magnetic fields in our own and nearby galaxies as well as precision characterization of cosmological foregrounds. The telescope will also demonstrate a two-octave single-pixel feed, a highly innovative correlator, and revolutionary digitization and clocking technology. The scientific and engineering development of the telescope will be a joint effort of DRAO, a national observatory, and university partners with heavy student involvement.

There has already been substantial progress on renewal, driven by University partners and their graduate students.

Xuan Du (Ph.D. candidate, Engineering, UBC Okanagan) has developed a wideband feed for the telescope to allow coverage of the band 400 to 1800 MHz. The design uses coaxial waveguides, in this case two such waveguides nested one inside the other. Each waveguide covers an octave band, 400 to 800 MHz for the central waveguide and 900 to 1800 MHz for the outer waveguide. The frequency range 800 to 900 MHz has been deliberately omitted as it is heavily occupied by cell phone traffic. The designed feed is compact. The frequency range can, in principle, be extended by further nesting of a third waveguide, also covering an octave of frequency, but such an expansion is not contemplated for this telescope.

Pamela Freeman (M.Sc. candidate, Physics and Astronomy, University of Calgary) is developing a prototype correlator for the Synthesis Telescope based on the technology developed by the University of Toronto for CHIME, coupled with analog-to-digital converters and associated FPGA processor (also a CHIME design, from McGill University). The work is funded by an NSERC Collaborative Research and Development grant led by the University of Toronto, and involving the University of Calgary, DRAO, and the companies AMD (Toronto) and CoolIT (Calgary). The prototype was successfully tested on the telescope in July and August 2019. DRAO is investigating in-house software development required to interface this correlator to existing reduction software, enabling the prototype demonstrated in this graduate student project to become the workhorse correlator for the telescope.

Professor Leonid Belostotski of the University of Calgary (Engineering) has a long-standing colaboration with DRAO and his group is a world leader in the design of low-noise amplifiers (LNAs) for radio astronomy. Amplifier designs emerging from this group have been tested on the existing Synthesis Telescope for several years. Thisara Katanunga (M.Sc. 2018) designed and built an LNA for the 400 to 800 MHz band with excellent performance. Ph.D. student Alexander Sheldon is developing a CMOS amplifier for the 900 to 1800 MHz band; it already has very good performance operating at room temperature, but cooling with small cryogenic refrigerators will be part of this work. All this work has strong relevance to the communications industry and the renewed ST as a testbed will be a valuable asset for this group.

DRAO staff have developed a telescope control system that is being incorporated into all DRAO telescopes. That advance will reach the Synthesis Telescope in 2020; it will improve current operations and will pave the way for the renewal described here.

We also refer to the DRAO Synthesis Telescope White Paper for the LRP2020 panel. Many thanks to Tom Landecker and Andrew Gray for providing this report.

2.8.2 26 m John A. Galt Telescope

The DRAO 26m was named the John A. Galt telescope in 2014 in honour of the DRAO's first employee and long-time director. Since that time, the Galt telescope has been actively engaged in the interferometric characterization of the polarized feed response of the CHIME telescope. Meanwhile, the telescope is nearing completion of a major upgrade including the installation of: modern spectral line and pulsar/FRB backends employing GPUs and a high-bandwidth FPGA signal-processing engine designed by the McGill Cosmology Instrumentation Lab; a customized MeerKAT L-band receiver fitted with NRC-developed low-noise amplifiers; optical fibers and helium lines; and the cryogenic infrastructure required to support helium-cooled receivers. For

L-band spectral-line observing, the upgrade will yield a 20-fold increase in bandwidth, 18,000-fold in spectral channels, and 125-fold in number of observable spectral lines across the band.

Many thanks to Tim Robishaw for providing this report.

2.9 CHIME

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) represents a new kind of radio telescope, relying heavily on computational power rather than expensive moving mechanical structures. It consist of 4 cylindrical telescopes covering an area of 80 m x 100 m, with 2048 receivers, and is located in the southwest quadrant of the Dominion Radio Astrophysical Observatory (DRAO) (see Figure 3). CHIME is primarily designed to map the intensity of neutral hydrogen in the Universe over the entire Northern sky between redshifts 0.8 and 2.5 (400 - 800 MHz). These data will produce the largest-volume survey of the Universe ever conducted. The sensitivity of the full CHIME telescope will allow it to characterize the baryon acoustic oscillation (BAO) scale and, in turn, measure the expansion history of the universe over the epoch when Dark Energy became the dominant constituent. The received signals are fed into a massive computing engine, based on Field Programmable Gate Arrays (FPGAs) and Graphical Processing Units (GPUs), which will form 1000 dual-polarized beams along the meridian. The telescope has no moving parts and the beams are swept across the sky by Earth rotation, so that the entire sky from equator to pole is mapped every 24 hours. With a collecting area of 8000 square metres, CHIME is the biggest radio telescope in North America and one of the biggest in the world. With 1000 beams on the sky CHIME has a very large field of view.

These facts prompted a Canadian group (from McGill, Toronto, and UBC, with DRAO and US partners) to request CFI funds (successfully) to add a second digital backend to search for Fast Radio Bursts (FRBs). FRBs are enigmatic events known only since 2007, single radio pulses that are so highly dispersed by intervening plasma that their origin is most likely extragalactic. CHIME has increased the detection rate of FRBs by a very large factor. In addition CHIME will make accurate and long-term measurments of pulsar timing, search for new pulsars, and study the magnetic field of the Milky Way by mapping the polarized sky.

Figure 3: The CHIME telescope located at the Dominion Radio Astrophysical Observatory, near Penticton, British Columbia.

The CHIME project is a collaboration between DRAO, UBC, University of Toronto, and McGill University, and is funded by the Canada Foundation for Innovation. CHIME was recognized outside of academia as it won the 2014 Annual Thompson Okanagan Kootenay Commercial Building Award (Oct 2014) for the Pathfinder telescope structure. CHIME was also highlighted in the 2015 Canadian Federal Budget. Construction of full CHIME was completed in 2017, culminating in a ceremony on September 7, 2017, in which the Minister of

Science, Kirsty Duncan, together with NRC president, Ian Stewart, lifted the last receiver into place and declared the telescope open. After the opening of CHIME the main commissioning of the telescope began. The Square Kilometre Array organization designated CHIME as an SKA Pathfinder in 2018. The design, construction, commissioning and analysis of CHIME also includes a large team of trainees. The project currently involves about 45 people in the Canadian astronomy community.

In the cosmology project, a long observing session began late in 2017 intended to provide a substantial body of data for trials of analysis methods. Data are moved to Compute Canada facilities for analysis, but this process is hampered by limited internet bandwidth into DRAO. Highly precise knowledge of CHIME beam shapes is required to reach the cosmology goals: CHIME beams are being measured by interferometry between CHIME and the 26 m John A. Galt Telescope at DRAO.

The pulsar backend is in steady use for pulsar timing, and is occasionally used for FRB work. New funding has been received to carry out a slow pulsar search, and the necessary equipment will be purchased in the near future.

In the FRB project, events must be identified in real time. The CHIME/FRB pipeline forms 1024 beams on the sky. Subsequent operations increase frequency resolution, flag radio-frequency interference, and de-disperse received signals. Routines for recognition of significant pulsed events follow, with reporting of relevant parameters, and baseband data around each event is stored. Known objects (e.g. pulsars) are recognized in this pipeline. The system is regularly detecting individual pulses from known pulsars on a few nodes of the processing pipeline with high signal-to-noise ratio. The bulk of the 128 computer nodes for the FRB pipeline were installed at the CHIME site in April and May 2018. A review of CHIME/FRB was held at DRAO in early May, focussing on science readiness. The first CHIME/FRB detections were announced in an astronomical telegram in late July 2018. The first major science results based on CHIME/FRB data have been announced at the 233rd AAS meeting in Seattle in January 2019 and two papers have been published in Nature later that month and CHIME was featured on the cover of Nature. Very active work is being done to understand amplitude calibration as well as gain variations with beam number and with frequency, all in the interests of placing credible errors on published results. The CHIME/FRB collaboration is now actively studying the construction of outriggers to permit precise localization of bursts through interferometric means. This project is called Canadian Hydrogen Observatory and Radio-transient Detector (CHORD). CHIME/FRB has received funding from the Moore Foundation to establish a network of outrigger stations with baselines from 100 km to several thousand km. The CHIME pathfinder is now being used to test prototype equipment for the CHORD project.

We also refer to the CHORD Cosmology and CHORD FRB White Papers for the LRP2020 panel.

3 Spectrum Management

3.1 Opening of New Spectrum Above 275 GHz

When the spectrum from 71-275 GHz was reorganized by the ITU, the radio astronomy community was ready, while the communications industry had not yet cracked the problem of achieving usable transmitter power levels at those frequencies. The result was a coup for radio astronomy. Studies for spectrum at even higher frequencies, into the far infrared, are now in progress. The communications industry has now developed usable transmitting devices so this promises to be a tougher fight. This will not just be a matter of establishing band requirements, but also, taking into the poor selectivity and linearity of current low-noise radio astronomy receiving systems at millimetre and submillimetre wavelengths, the assessment of coordination issues with active bands operators.

3.2 5G, Bluetooth and Other Mobile Devices

Interference issue in radio astronomy used to be largely a matter of dealing with individual interference sources, which were often contravening regulations on unwanted emissions. This is no longer the case. We are moving to a world of many mobile, low-power devices that are individually operating legally but can add up to an interference issue for radio astronomy. Typically these devices use spread-spectrum or similar modulation methods which are essentially unmitigatable without the encoding keys. The net result could be a general rise in the background noise level at the observatory. Spatial separation is the only current avoidance technique. This issue has been discussed in the spectrum management community for some time, but as yet nobody has any ideas. The advent of thousands of Low-Earth-Orbit (LEO) satellites to support 5G services are going to compound the problem. A sky full of satellites with their collective unwanted emissions being picked up through antenna sidelobes is discussed in Recommendation ITU-RA1513, but this issue will need to be revisited.

3.3 Opportunistic Observing

Having bands allocated to radio astronomical use is essential for the viability of our favourite science, but since we cannot grab spectrum for all radio astronomical observations ”opportunistic“ observing is of rapidly growing importance. If the interference level in a band not allocated to the radio astronomy service is low enough at a particular observatory, observations can be made in it. The CHIME radio telescope at DRAO is an excellent example. However, in cases where a substantial investment is being made in projects dependent on opportunistic observing, there needs to be an effort to keep the band usable for the intended duration of the experiment. With the current feeding frenzy by other services for frequency space, this cannot be taken for granted. To keep the project viable, the local and possibly national spectrum managers need to be consulted and kept in the loop. The International Radio Regulations provide no protection whatsoever for opportunistic radio astronomical observations.

3.4 A Canadian Radio Astronomy Representative

The above issues underline the need for a national representative to promote the needs of Canadian radio astronomers nationally - to protect our national facilities, and internationally - to ensure Canadian needs are taken into account in the formulation of new spectrum management regulations. With our substantial investment in offshore facilities, such as ALMA, representing Canadian needs at the international level is important. For the last few years Canada has had no such representative, which is a situation currently receiving attention.