The Journal of The Royal Astronomical Society of Canada

Journal

Le Journal de la Société royale d'astronomie du Canada

PROMOTING
ASTRONOMY
IN CANADA

April/avril 2019
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Inside this issue:

150 Years of Astronomical Imagery

Radio Astronomy at Queen's

New Horizons, A Poem

Witch's Brew

The Best of Monochrome.

Drawings, images in black and white, or narrow-band photography.

Adrian Aberdeen imaged the Horsehead Nebula using a Sky-Watcher Esprit 80-mm Telescope on a Celestron CGEM Mount using a ZWO ASI1600MM-COOL. He used a Baader 36-mm Hα Filter, Starizona Autofocuser and processed using Sequence Generator Pro, Pixinsight, and Photoshop. 119 x 120-sec sub exposures.

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Société Royale d'Astronomie du Canada

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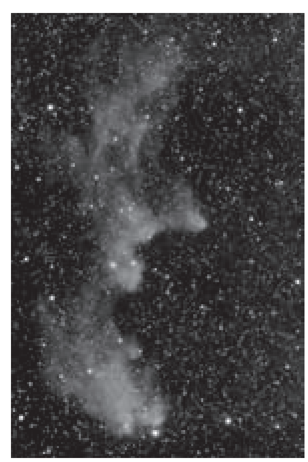

Klaus Brasch took this image of the Witch Head Nebula. It's a blend of several exposures taken with a TMB-92 refractor a couple of years ago and more recent images taken with an AP-155 at ƒ/5.2, with a Hutech modified Canon 6D and 6D Mark II, respectively, shooting at ISO 6400 and through an IDAS LPS-V4 filter. Cumulative exposure is about 30 minutes.

Journal

The *Journal* is a bi-monthly publication of The Royal Astronomical Society of Canada and is devoted to the advancement of astronomy and allied sciences. It contains articles on Canadian astronomers and current activities of the RASC and its Centres, research and review papers by professional and amateur astronomers, and articles of a historical, biographical, or educational nature of general interest to the astronomical community. All contributions are welcome, but the editors reserve the right to edit material prior to publication. Research papers are reviewed prior to publication, and professional astronomers with institutional affiliations are asked to pay publication charges of $100 per page. Such charges are waived for RASC members who do not have access to professional funds as well as for solicited articles. Manuscripts and other submitted material may be in English or French, and should be sent to the Editor-in-Chief.

Editor-in-Chief
Nicole Mortillaro
Email: editor@rasc.ca
Web site: www.rasc.ca
Telephone: 416-924-7973
Fax: 416-924-2911

Associate Editor, Research
Douglas Hube
Email: dhube@ualberta.ca

Associate Editor, General
Michael Attas
Email: attasm1@mymts.net

Assistant Editors
Michael Allen
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Production Manager
James Edgar
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Michelle Johns
Barry Jowett
Kim Leitch
Alida MacLeod

Design/Production
Michael Gatto, Grant Tomchuk
Email: gattotomatto@gmail.com,
granttomchuk@eastlink.ca

Advertising
Madison Chilvers
Email: mempub@rasc.ca

Printing
Cansel
www.cansel.ca

Her Excellency the Right Honourable **Julie Payette**, C.C., C.M.M., C.O.M., C.Q., C.D., Governor General of Canada, is the Viceregal Patron of the RASC.

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The Royal Astronomical Society of Canada
203 – 4920 Dundas St W
Toronto ON M9A 1B7, Canada

Email: nationaloffice@rasc.ca
Web site: www.rasc.ca
Telephone: 416-924-7973
Fax: 416-924-2911

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President's Corner

by Chris Gainor, Ph.D., Victoria Centre
(cgainor@shaw.ca)

A big reason I joined the RASC in my youth in the 1960s was the space race that culminated in astronauts flying to the vicinity of the Moon and finally landing on it. Thanks to my telescope and my membership in the RASC, I could follow the astronauts in more ways than simply watching TV or reading a magazine. And while the astronauts went no farther than the Moon, I could explore more distant reaches of the Universe with lots of help from my friends in the RASC.

Back in 1969, I belonged to the Edmonton Centre, and we held a Starnight event for the public in late April. Despite a late blast of winter weather that kept our instruments indoors, Starnight was still a success, thanks to the fact that we were showing the official NASA film of *Apollo 8*'s historic orbits of the Moon at a time when colour TV was a luxury, home video was still over the horizon, and few had imagined anything like YouTube.

Now, 50 years have gone by since that spring when we were looking forward to *Apollo 11*'s lunar landing in July 1969. While astronauts have been confined to low-Earth orbit since Apollo ended in 1972, NASA has dispatched a fleet of robotic spacecraft to the inner and outer reaches of our Solar System. When the *Hubble Space Telescope* with its amazing imaging abilities began operation in the 1990s, millions began to appreciate the wonders of the Universe that many of us RASCals already knew.

RASC will take a prominent part in this year's anniversary celebrations of the first human footsteps on another celestial body. Our 2019 General Assembly will take place at York University in Toronto, and our Northcott lecturer will be aerospace historian James Hansen, who wrote the biography of his friend, astronaut Neil Armstrong, that inspired the film *First Man*. I will be there to talk about the impressive but little-known role Canadians played in the success of Apollo.

This summer will also mark 25 years since Comet Shoemaker-Levy 9 struck Jupiter, and we will have David Levy at the GA to launch his new autobiography that is being published by the RASC. The GA will be held jointly with the annual spring

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meeting of the American Association of Variable Star Observers (AAVSO). We will have many AAVSO presentations on variable stars, and the RASC will present many public outreach activities for space explorers of all ages and skill levels.

In line with our decision to move GAs away from holiday weekends, this GA will take place the weekend of June 13 to 16. Since the GA last took place at York University in 2008, two subway stations have been built near the York campus, and facilities at the campus have been upgraded. This GA will be more accessible to more members than ever. Check out our GA website at rasc.ca/ga2019.

Although RASC's 150th anniversary is over, we have plenty to celebrate this year, and the General Assembly in Toronto will be a great place to look back at where we've been and look forward to new explorations of our Universe. ✶

News Notes / En Manchette

Compiled by Jay Anderson

Pan-STARRS Universe part 2

The Space Telescope Science Institute (STScI) in Baltimore, Maryland, in conjunction with the University of Hawai'i Institute for Astronomy (IfA), has released the second edition of data from Pan-STARRS—the Panoramic Survey Telescope & Rapid Response System—the world's largest digital sky survey. This second release contains over 1.6 petabytes of data (a petabyte is one million gigabytes), making it the largest volume of astronomical information ever released. The amount of imaging data is equivalent to 30,000 times the total text content of Wikipedia.

The Pan-STARRS observatory consists of a 1.8-metre telescope equipped with a 1.4-billion-pixel digital camera, located at the summit of Haleakalā, on Maui. Conceived and developed by the IfA, it embarked on a digital survey of the sky in visible and near-infrared light in May 2010. Pan-STARRS was the first survey to observe the entire sky visible from Hawai'i multiple times in many colours of light. One of the survey's goals was to identify moving, transient, and variable objects, including asteroids that could potentially threaten the Earth. The survey took approximately four years to complete, scanning the sky 12 times in five filters. This second data release provides, for the first time, access to all of the individual exposures at each epoch of time. This will allow astronomers and public users of the archive to search the full survey for high-energy explosive events in the cosmos, discover moving objects in our own Solar System, and explore the time domain of the Universe.

Dr. Heather Flewelling, a researcher at the IfA, and a key designer of the PS1 database, stated that "Pan-STARRS DR2 represents a vast quantity of astronomical data, with many great discoveries already unveiled. These discoveries just barely scratch the surface of what is possible, however, and the astronomy community will now be able to dig deep, mine the data, and find the astronomical treasures within that we have not even begun to imagine."

The four years of data comprise three billion separate sources, including stars, galaxies, and various other objects. This research program was undertaken by the PS1 Science Consortium—a collaboration among 10 research institutions in four countries, with support from NASA and the National Science Foundation (NSF). Consortium observations for the sky survey were completed in April 2014. The initial Pan-STARRS public data release occurred in

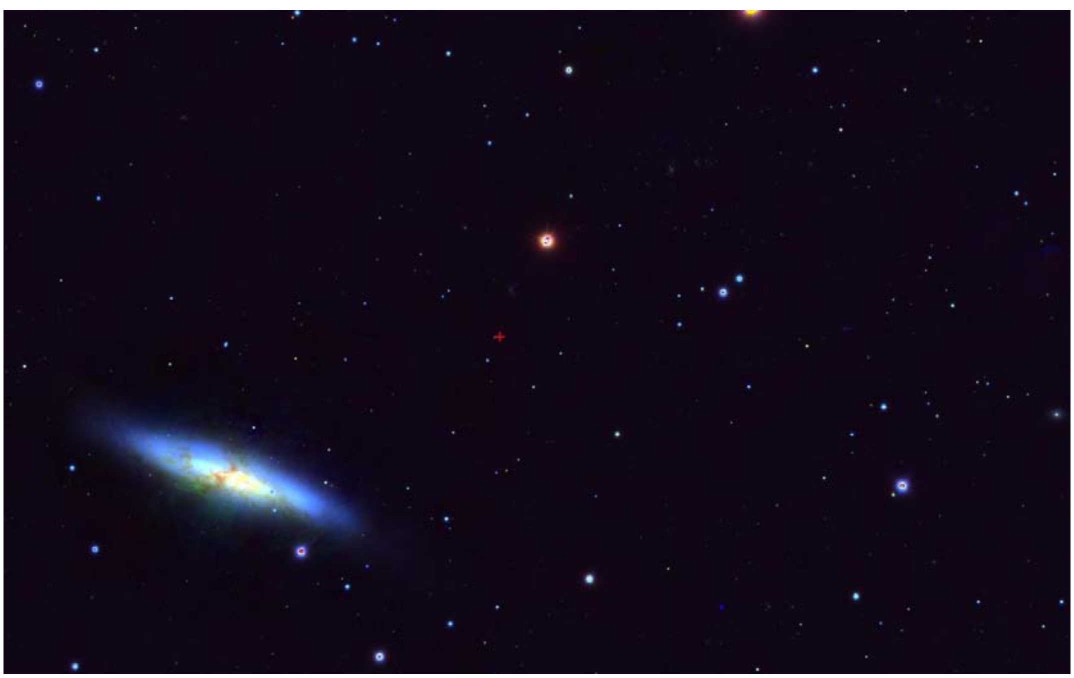


Figure 1 — An image of the galaxy Messier 82 (M82) downloaded from the Pan-STARRS archive. This is a low-resolution colour download of an RGB set. Image: STScI Image Cutout Service (https://outerspace.stsci.edu/display/PANSTARRS/PS1+Image+Cutout+Service).

December 2016, but included only the combined data and not the individual exposures at each epoch of time.

"The Pan-STARRS1 Survey allows anyone access to millions of images and catalogues containing precision measurements of billions of stars, galaxies, and moving objects," said Dr. Ken Chambers, Director of the Pan-STARRS Observatories. "While searching for Near Earth Objects, Pan-STARRS has made many discoveries from 'Oumuamua passing through our Solar System to lonely planets between the stars; it has mapped the dust in three dimensions in our galaxy and found new streams of stars; and it has found new kinds of exploding stars and distant quasars in the early Universe. We hope people will discover all kinds of things we missed in this incredibly large and rich dataset."

The Space Telescope Science Institute hosts the storage hardware, the computers that handle the database queries, and the user-friendly interfaces to access the data. The survey data resides in the Mikulski Archive for Space Telescopes (MAST), which serves as NASA's repository for all of its optical and ultraviolet-light observations, some of which date to the early 1970s. The Pan-STARRS data can be accessed through https://panstarrs.stsci.edu/.

Compiled with material provided by the ESA/Hubble Information Center

A tiny member of the outer Solar System

Kilometre-sized Kuiper Belt objects (KBO) are expected to be no brighter than 29th magnitude, beyond the detection capabilities of even 10-metre telescopes. Nevertheless, Japanese astronomers have detected a 1.3-km-radius object at the edge of the Solar System using a pair of 11-inch (28 cm) Celestron Schmidt Astrographs. They did it by observing a brief 1/4-second occultation of a 12th magnitude star as the Kuiper Belt object passed in front of the star.

Edgeworth-Kuiper Belt objects with radii from one kilometre to several kilometres have been predicted to exist for more than 70 years, but they are too distant, small, and dim for even world-leading telescopes to observe directly. To overcome this limitation, a research team led by Ko Arimatsu at the National Astronomical Observatory of Japan monitored over 2000 stars in the field of the Celestron telescopes for over 60 hours. The Organized Autotelescopes for Serendipitous Event Survey (OASES) team placed the two small telescopes on the roof of the Miyako open-air school on Miyako Island, Miyakojimashi, Okinawa Prefecture, Japan.

Images were collected at a rate of 15.4 frames per second using an exposure of 65.0 ms through a ZWO CMOS camera and a focal reducer to reduce the focal ratio to $f/1.58$. Two telescope detectors were used to distinguish actual events from chance variations in atmospheric transparency; they were separated by 39 and 53 m respectively in two observation runs. Each run

Figure 2 — An artist's impression of the newly discovered KBO at the edges of the Solar System. Image: Ko Arimatsu.

acquired 26,400 time-sequential images and the photometric analysis totalled 3.39 billion measurements. The analysis software searched for consecutive, simultaneous brightness drops in the two telescopes.

The Edgeworth-Kuiper Belt is a collection of small celestial bodies located beyond Neptune's orbit, the most famous of which is Pluto. These small objects are believed to be remnants left over from the formation of the Solar System. While small bodies like asteroids in the inner Solar System have been altered by solar radiation, collisions, and the gravity of the planets over time, objects in the cold, dark, lonely Edgeworth-Kuiper Belt preserve the pristine conditions of the early years of our Solar System.

Previous surveys of main-belt asteroids established that the expected occultation rate of the closer Solar System populations is 1000 times less than for Edgeworth-Kuiper Belt Objects and so a KBO is the object most likely to have caused the detected occultation. This single detection also suggests that kilometre-sized KBOs are more numerous than previously thought, perhaps as many as 550,000 per square degree on the sky. This result supports models where planetesimals first grow slowly into "kilometre-sized objects before runaway growth causes them to merge into planets."

Arimatsu explains: "This is a real victory for little projects. Our team had less than 0.3 percent of the budget of large international projects. We didn't even have enough money to build a second dome to protect our second telescope! Yet we still managed to make a discovery that is impossible for the big projects. Now that we know our system works, we will investigate the Edgeworth-Kuiper Belt in more detail. We also have our sights set on the still-undiscovered Oort Cloud out beyond that."

Compiled in part with material provided by the National Institutes of Natural Sciences and Kobe University.

Bovines in Space

Astronomers in a team led by Northwestern University believe they have witnessed the birth of a black hole or a neutron star after detecting a spectacularly bright object that erupted in the constellation Hercules on June 16 last summer. The outburst, dubbed AT2018cow, was detected by telescopes of the Asteroid Terrestrial-impact Last Alert System (ATLAS) on Haleakala and Mauna Loa. "The Cow," as it was nicknamed, appeared in a galaxy identified as CGCG 137-068, 200 million light-years away, where it suddenly flared up and then vanished almost as quickly.

With the help of the W.M. Keck Observatory on Mauna Kea, Hawaii, and the University of Hawaii Institute for Astronomy's ATLAS twin telescopes, a multi-institutional team led by astronomers in Northwestern University now has evidence that they likely captured the exact moment a star collapsed to form a compact object, such as a black hole or neutron star. The stellar debris, approaching and swirling around the object's event horizon, caused the remarkably bright glow.

"Based on its X-ray and UV emission, 'The Cow' may appear to have been caused by a black hole devouring a white dwarf. But further observations of other wavelengths across the spectrum led to our interpretation that 'The Cow' is actually the formation of an accreting black hole or neutron star," said lead author Raffaella Margutti, assistant professor of physics and astronomy at Northwestern University. "We know from theory that black holes and neutron stars form when a star dies, but we've never seen them right after they are born. Never."

The event captured immediate international interest and left astronomers scratching their heads. "We thought it must be a supernova," Margutti said. "But what we observed challenged our current notions of stellar death."

For one, the anomaly was unnaturally bright—10 to 100 times brighter than a typical supernova. It also flared up and disappeared much faster than other known star explosions, with particles flying at 30,000 kilometres per second (10 percent of the speed of light). Within just 16 days, the object had already emitted most of its power. In a Universe where some phenomena last for millions and billions of years, two weeks amounts to the blink of an eye.

"We knew right away that this source went from inactive to peak luminosity within just a few days," said co-author Ryan Chornock, assistant physics and astronomy professor at Ohio University. "That was enough to get everybody excited because it was so unusual and, by astronomical standards, it was very close by."

Using Northwestern's access to Keck Observatory's twin telescopes, Margutti's team took a closer look at the object's makeup with the Low Resolution Imaging Spectrometer (LRIS) on the Keck I telescope as well as the DEep Imaging and Multi-Object Spectrograph (DEIMOS) on Keck II.

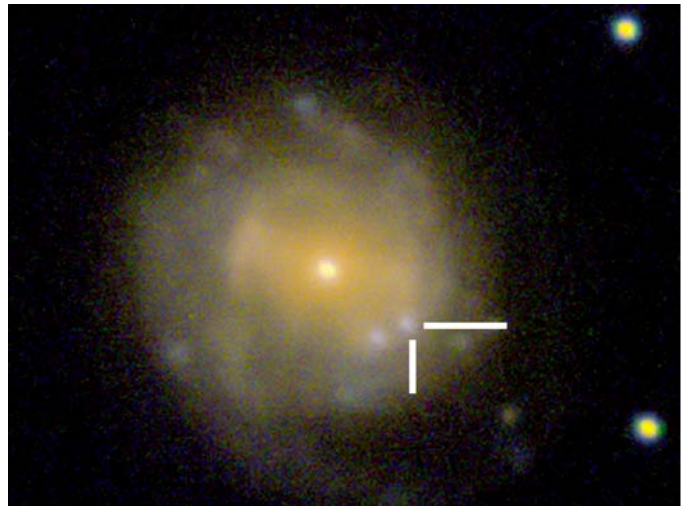


Figure 3 — An image of AT2018cow and its host galaxy obtained on 2018 August 17 using W. M. Keck Observatory's instrument, the DEep Imaging and Multi-Object Spectrograph (DEIMOS). CREDIT: R. Margutti/W. M. Keck Observatory/ Sloan Digital Sky Survey

"Keck was instrumental in determining the chemical composition and geometry of AT2018cow," said co-author Nathan Roth, a postdoctoral fellow at the University of Maryland. "Keck's unique niche is its capability to monitor the late-time behaviour of The Cow. This can be difficult; as more time passes after the event, the fainter it becomes. But with Keck's late-time spectroscopy, we were able to pierce through the 'interiors' of the explosion. This revealed AT2018cow's red-shifted spectral features very nicely."

"The Cow is a great example of a type of observation that's becoming critical in astronomy: rapid response to transient events," says Keck Observatory Chief Scientist John O'Meara. "Looking forward, we are implementing new observational policies and telescope instrumentation that allow us to be as quick on the sky and to the science as we can."

When Margutti and her team examined The Cow's chemical composition, they found clear evidence of hydrogen and helium, which excluded models of compact objects merging, like those that produce gravitational waves.

"It took us a while for us to realize what we were looking at, I would say months," said co-author Brian Metzger, associate physics professor at Columbia University. "We tried several possibilities and were forced to go back to the drawing board multiple times. We were finally able to interpret the results, thanks to the hard work of our incredibly dedicated team."

Astronomers have traditionally studied stellar deaths in the optical wavelength, which uses telescopes to capture visible light. Margutti's team, on the other hand, used a more comprehensive approach. After ATLAS spotted the object, the team quickly conducted follow-up observations using multiple observatories to analyze The Cow in different wavelengths.

The researchers viewed the object in hard X-rays using NASA's Nuclear Spectroscopic Telescope Array (NuSTAR) and the European Space Agency's (ESA) INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), in soft X-rays (which are 10 times more powerful than normal X-rays) using ESA's X-ray Multi-Mirror Mission (XMM-Newton), and in radio waves using National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA).

This enabled them to continue studying the anomaly long after its initial visible brightness faded.

Margutti attributes The Cow's relative nakedness to potentially unraveling this intergalactic mystery. Although stars might collapse into black holes all the time, the large amount of material around newly born black holes blocks astronomers' vision. Fortunately, about 10 times less ejecta swirled around The Cow compared to a typical stellar explosion. The lack of material allowed astronomers to peer straight through to the object's "central engine," which revealed itself as a probable black hole or neutron star.

"A 'lightbulb' was sitting deep inside the ejecta of the explosion," Margutti said. "It would have been hard to see this in a normal stellar explosion. But The Cow had very little ejecta mass, which allowed us to view the central engine's radiation directly."

Margutti's team doesn't have the last word, yet. A second team of astronomers identified the mystery flash as signs of a black hole swallowing a passing white-dwarf star. If this idea is correct, the black hole must be very large in order to create a debris cloud so quickly and its place in the outskirts of a galaxy would be very unusual. The final story has yet to be written on the Cow.

Compiled in part with material provided by the W.M. Keck Observatory.

Say Hi to the new neighbour

Astronomers using the NASA/ESA *Hubble Space Telescope* to study some of the oldest and faintest stars in the globular cluster NGC 6752 have made an unexpected finding lurking in the background of the image. They discovered a dwarf galaxy in our cosmic backyard, only 30 million light-years away.

The new galaxy was discovered in exceptionally deep HST images to study white-dwarf stars within NGC 6752's cluster.

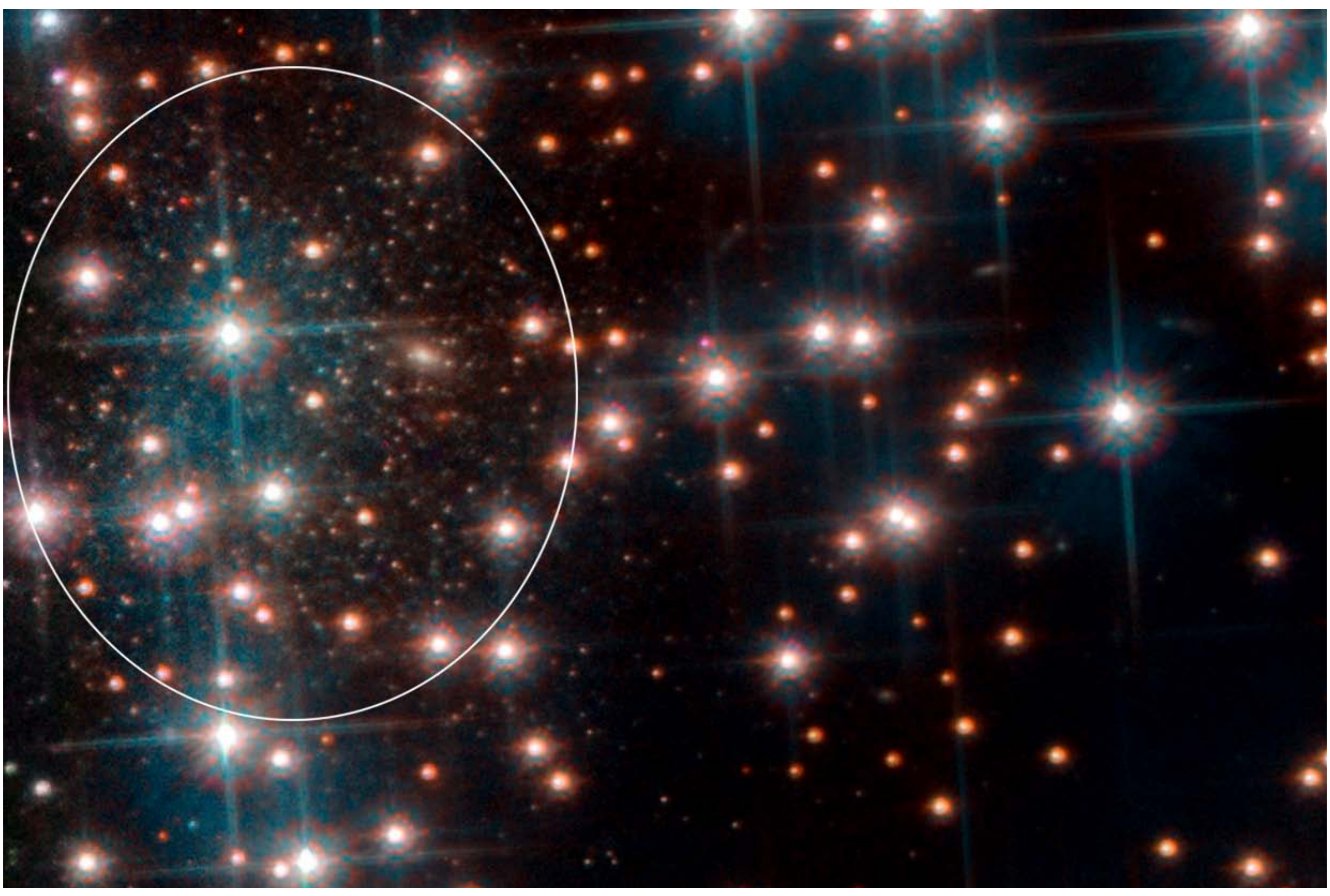


Figure 4 — This image, taken with Hubble's *Advanced Camera for Surveys shows a part the globular cluster NGC 6752. Behind the bright stars of the cluster a denser collection of faint stars is visible—a previously unknown dwarf spheroidal galaxy. This galaxy, nicknamed Bedin 1, is about 30 million light-years from Earth. Image: ESA/Hubble, NASA, Bedin et al.*

The aim of their observations was to use these stars to measure the age of the globular cluster, but in the process they spotted a compact collection of stars in the outer fringes of the image. After a careful analysis of their brightnesses and temperatures, the astronomers concluded that these stars did not belong to the cluster—which is part of the Milky Way—but rather they are millions of light-years more distant.

The newly discovered cosmic neighbour, nicknamed Bedin 1, is a modestly sized, elongated galaxy. It measures only around 3000 light-years at its greatest extent—a fraction of the size of the Milky Way. Not only is it tiny, it is also incredibly faint, near the 30-magnitude limit of the image. These properties led astronomers to classify it as a dwarf spheroidal galaxy.

Dwarf spheroidal galaxies are defined by their small size, low-luminosity, lack of dust and old stellar populations. Thirty-six galaxies of this type are already known to exist in the Local Group of Galaxies, 22 of which are satellite galaxies of the Milky Way.

While dwarf spheroidal galaxies are not uncommon, Bedin 1 has some notable features. Not only is it one of just a few dwarf spheroidals that have a well-established distance but it is also extremely isolated. It lies about 30 million light-years from the Milky Way and 2 million light-years from the nearest plausible large galaxy host, NGC 6744. This makes it possibly the most isolated small dwarf galaxy discovered to date. Benin 1 appears to have had a relatively quiet star-formation history with little production of metals (elements other than hydrogen and helium) and appears to have little or no younger stars; its chemical evolution is similar to a globular cluster.

From the properties of its stars, astronomers were able to infer that the galaxy is around 13 billion years old—nearly as old as the Universe itself. Because of its isolation—which resulted in hardly any interaction with other galaxies—and its age, Bedin 1 is the astronomical equivalent of a living fossil from the early Universe. The astronomers conclude that this system likely formed more than 10 Gy ago in a "single" burst, and likely experienced no additional star formation since its formation. The reasonably well-determined distance of this system makes it one of the best candidates for a relatively isolated dwarf spheroidal galaxy.

The discovery of Bedin 1 was a truly serendipitous find. Very few *Hubble* images allow such faint objects to be seen, and they cover only a small area of the sky. Future telescopes with a large field of view, such as the WFIRST telescope, will have cameras covering a much larger area of the sky and may find many more of these galactic neighbours. ✶

Compiled in part with material provided by ESA/Hubble.

Feature Articles / Articles de fond

Science and Art: 150 Years of Astronomical Imagery

by Clark Muir (Kitchener-Waterloo Centre)
cmuir10@rogers.com

As part of the 2018 sesquicentennial celebration of the RASC, the Kitchener-Waterloo Centre held an art exhibit at the Homer Watson House & Gallery. The gallery in Kitchener, Ontario, served as the home of the acclaimed Canadian artist in 1881.

The exhibit's theme was to combine works from the RASC archives with modern photographs, digital images, and sketches from current and past members of the Kitchener-Waterloo Centre. The pieces on display therefore go back to 1868, the year of the founding of the Toronto Astronomical Club (predecessor of the RASC) all the way to 2018.

The exhibit commenced on 2018 September 9 through to October 21. During the run, several open-house events were held. They included a "Doors Open" experience that allowed about 300 people to see the exhibition. There was also a "Meet the Artist" event that gave attendees a chance to learn how the images were photographed or sketched. The grand opening proved popular with those within the local arts community and supporters of the gallery. In total, more than 4,000 people saw the exhibit!

With one notable exception, all of the selected works were photographed and later professionally printed and displayed in poster-size frames. In total, 35 framed prints were hung throughout the gallery along with a basic description of each piece. Local photographer and RASC member Jeff Dawkins displayed a few of his spectacular nighttime landscape prints in an adjoining room to accompany the RASC exhibit.

An attempt was made to have as many different types of celestial objects and phenomena featured as possible, both from the modern examples and from our humble beginnings. This proved more difficult than initially thought. The myriad of different types of celestial targets were simply too many to provide examples of all of them.

Included among the content was the original painting of the Great Meteor Procession of 1913 by RASC member and professional artist Gustav Hahn (1866–1962). This exceptional painting was on display alongside the copy that appeared in a *JRASC* article from May 1913 by C.A. Chant. Gustav Hahn and Homer Watson (1855–1936) were contemporaries and clearly had a mutual respect for each other. Their cordial correspondence (also displayed in the exhibit) gives evidence of this relationship along with both mens' standing within the Canadian arts scene.

The gallery staff, led by curator Faith Hieblinger, skilfully nuanced the exhibit from one room to the other. Watson had for a time painted landscapes under a full Moon regularly. A

Figure 1 — The "Watson Gallery" room is shown during the grand opening of the exhibit. (All photos by the author)

Figure 2 — Total solar eclipse is recorded by RASC members from 1896 and 2018.

couple of Watson's paintings featuring Moon-lit landscapes were displayed in a separate space accompanied with the Hahn original painting and some of our RASC prints from the same era. A display table featuring some of the sketching tools that would have been used by artists from the late 19th century was also featured in this space.

This exhibit allowed viewers to compare the styles and techniques in sketching and photography of similar events and objects over RASC's 150 years. One example is the total solar eclipse experience. Displayed next to each other was the print of the 1896 August 9 total solar eclipse sketch from Norway by Honorary Member Mary Proctor and the 2017 August 21 totality photograph taken from Wyoming by former K-W Centre President Jeff Collinson.

On another wall within the gallery, three prints all exhibit the image of Jupiter. The earliest was a sketch by A.F. Miller from 1885. This was placed adjacent to one of Klaus Brasch's sketches from 1960. Finally, a digital image by Darryl Archer from mid-2010s completed the trio. The three images of Jupiter, each from a different century, emphasize that although the technology changes, the fascination we have with the planet doesn't.

The result was an excellent introduction for the public at large to recognize the continued passion for capturing the night sky by ordinary people who live within their

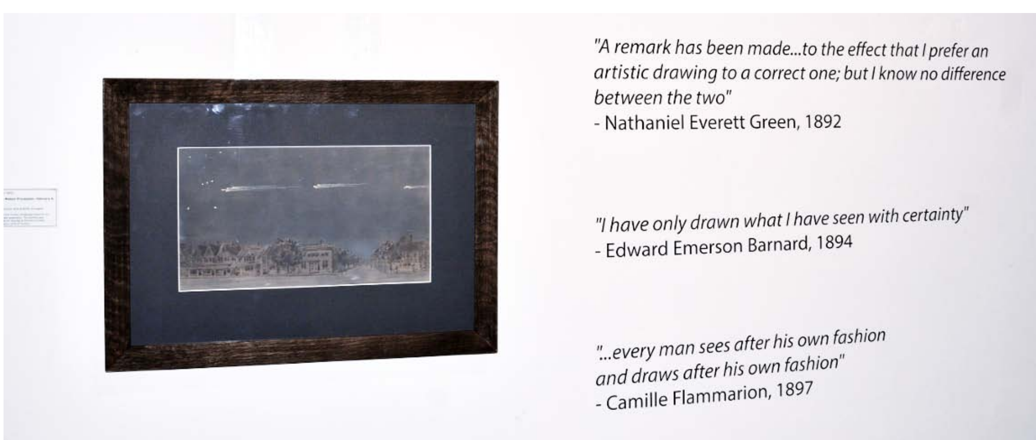


Figure 3 — Gustav Hahn's "Great Meteoric Display" painting is highlighted with quotes by various astronomical artists from late 19th century.

Figure 4 — Title of exhibit is shown above two prints of Comet Hyakutake.

community. Furthermore, it suggests to them that spectacular images of astronomical targets are not the sole domain of world-class observatories or orbiting telescopes. It was also a rare opportunity for RASC members and other keen amateurs to see these images displayed in large print form.

A piece used for promotion of the event was based on the awareness that Homer Watson himself was best known for his landscape paintings. An outstanding contribution by Matt Quinn was therefore selected. His night landscape was displayed over the fireplace of the main exhibition room. We would later learn that a different image of Quinn's was one of two selected to grace stamps commemorating RASC's 150th anniversary with Canada Post.

For several decades now, the Homer Watson House and Gallery has a long tradition of showcasing local artistic talent in their temporary exhibits. It was a privilege to have RASC members' astronomical works featured at the gallery, whether they be photographers, sketchers, or painters. ✶

Figure 5 — Homer Watson House and Gallery front entrance.

Endnotes

1 Printing was generously provided by Innovative Printing, Millbank Ontario.

2 Graciously on loan from the University of Toronto UTARMS.

3 A hand-written letter by Hahn was sent to Watson for his 80th birthday dated 1935 January 15.

4 In the 1920s, Homer Watson's interest in the Moon was spiritual, which at the time was fashionable.

5 This stamp was formally released at the 2018 RASC GA in Calgary, Alberta.

Pentodes, Power Patterns, Pliers, and Parsecs: Pioneering Radio Astronomy at Queen's University

by D. Routledge, professor emeritus, University of Alberta (dr2@ualberta.ca), R. Butler, formerly Communications Research Centre, Shirley's Bay, Ottawa (randnb5344@gmail.com), and W.H. McCutcheon, professor emeritus, University of British Columbia (mccutche@phas.ubc.ca)

"There is a tide in the affairs of men," Shakespeare said, "which, taken at the flood, leads on to fortune." What follows is the story of how Queen's University's Physics Department attempted to catch such a tide in the 1950s, at the moment when astronomy was expanding into the electromagnetic spectrum beyond the visual window.

First Radio Telescopes and Observations

In early March 1958, in a hayfield south of the hamlet of Westbrook west of Kingston, two antennae made of aluminum tubing stared upward into the Milky Way (see Figure 1). Inside a hut midway between them, a pen connected to the output of a sensitive receiver jittered across a chart, scribing a ragged red line. Together, the antennas and receiver constituted the first of several radio telescopes that would be built—primarily by graduate students—during the next decade and a half in that hayfield, the nascent Queen's Radio Observatory (QRO).

The two Yagi antennas, aimed to centre on Cassiopeia as it transited, were absorbing faint radio power at six metres wavelength. Thousands of times weaker than required by TV sets, the voltages they fed to the central receiver nevertheless interacted, producing an interference pattern—a joint reception pattern of north-south pancake-shaped beams when seen from a distant object in the sky—through which the Galaxy would sweep as the Earth rotated. The multitude of beams, the radio analogue of the optical interference pattern in a double-slit experiment, formed a radio-wavelength "fringe" pattern. This reception pattern resembled a peacock's tail on display.

Extending across several cycles of the oscillatory fringe pattern, the broad smear of radio emission from the Milky Way could not affect the receiver. Why, then, was this pen tracing out interference fringes?

Precision interferometry at Cambridge had recently pinpointed a small-diameter radio powerhouse in Cassiopeia—it had to be small or interferometers would not see it—blasting out power across the radio spectrum. What sort of bizarre object was this? And how far away? Next door? Distant but inside our own galaxy like M1, the Crab Nebula? Or hundreds of millions of light-years from us like the faint galaxy—no, two galaxies, apparently, colliding—recently identified as another strong radio source, in Cygnus?

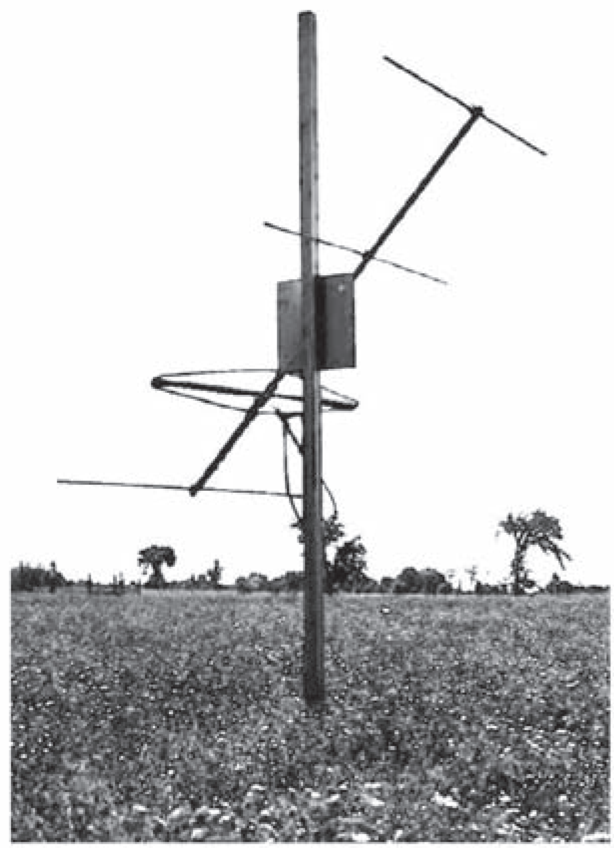


Figure 1 – Half of Queen's University's first radio telescope at Westbrook in 1958—one of two Yagi antennas comprising Arnold Matthews' east-west interferometer for recording scintillations of Cas A at a wavelength of six metres. The three metal rods (one "reflector" dipole and two "director" dipoles) are three metres long. The diamond shape (a dipole "folded" to raise its impedance) is connected by coaxial cable to the receiver in a central hut. The loop of cable hanging down (a "balun") prevents currents from flowing on the outside of the cable and disturbing the shape of the Yagi's reception beam (its "power pattern").

Most optical telescopes pointed at that spot in Cassiopeia would reveal nothing spectacular. However, the Palomar 200 inch (in 1958 the world's largest) had detected faint red wisps of nebulosity. Astonishingly, these wisps were moving, racing through space at up to 7,400 km per second. Comparing their transverse and line-of-sight motions, the distance of those wisps had to be 3,400 parsecs—one parsec being 3.26 light-years.

Radio interferometery at Manchester, meanwhile, had shown this brightly radiating object (labelled Cassiopeia A) to be a shell, four arcminutes wide and thus four parsecs in diameter. It might be an exploded star, a supernova remnant like the Crab Nebula but younger—a mere 350 years old.

However insignificant Cas A appeared at optical wavelengths—because of obscuration in what most people took to be a vacuum, the interstellar medium—to radio telescopes, this "radio star" came booming in, weaker only than the nearby Sun. Why should such an optically underwhelming object transmit powerful radio waves?

An explanation by a Soviet astrophysicist, Ioseph Shklovsky, had emerged: electrons hurtling through the interstellar medium at nearly the speed of light could be deflected into spiral trajectories by weak magnetic fields. This produced "synchrotron" radiation. His theory had been validated in observations of the Crab Nebula when both its radio and optical emission had been found to be partially linearly polarized. Synchrotron radiation could be the mechanism lighting up Cas A as well.

The pen at QRO continued to jitter across the chart, the fringes decreasing in amplitude after Cas A's transit an hour before midnight. In the afternoon, a young man arrived to check the interferometer and tend the chart recorder. This was Arnold Matthews, the first of a dozen-and-a-half graduate students in the Physics Department who would build and operate radio telescopes at QRO (see Table 1). He had been attending classes in the morning and this was his experiment, conceived by his thesis supervisor, Dr. George A. Harrower[1] but implemented according to his own calculations and by his own handiwork.

After examining the chart, Matthews might have decided that everything was running well and all he had to do was replenish the ink and paper in the recorder. If not, he had to trouble-shoot the problem and if possible, repair it on the spot. Perhaps calculations—done by slide rule of course—would show that something required modification. If so, and the work could be performed in the field, he would open his tool box and reach for pliers, a wrench, soldering gun, electrical tape, hacksaw, screwdriver, and replace a connector, shorten

Table I — Theses in Queen's U. Physics Department Based on Work at QRO and ARO, 1958-72

NAME	DEG	SUP	YR	SUBJECT
Matthews	**M**	**GAH**	**58**	**Period spectrum of radio star scintillations**
Hogg	**M**	**GAH**	**59**	**Short-lived solar radio bursts in the range 88-128 Mc/s**
Ryan	**D**	**GAH**	**59**	**Scintillation of four radio sources at upper transit**
Black	**M**	**GAH**	**61**	**Scintillations of radio stars related to earth's magnetic field**
MacDougall	**M**	**GAH**	**61**	**Upper atmospheric irregularities by radio star scintillations**
Srivastava	**M**	**GAH**	**62**	**Spectrum analysis of radio star scintillations**
Gibbons	**M**	**GAH**	**62**	**Scattering elements for the 146 Mc/s reflection array**
Kronberg	**M**	**GAH**	**63**	**Variable-spacing interferometer for radio astronomy**
Sandqvist	**M**	**GAH**	**63**	**Sidelobes of a synthetic aperture**
MacDougall	**D**	**GAH**	**63**	**Ionospheric Irregularities by Radio Star Scintillations**
McCutcheon	**M**	**GAH**	**64**	**Design and construction of the random reflection array**
Butler	**M**	**GAH**	**65**	**Theoretical and experimental investigation of reflection arrays**
Gregory	**M**	**GAH**	**65**	**Phase-switching receiver for variable-spacing interferometer**
Hesse	**M**	**GAH**	**65**	**Preparation for a sky survey with variable-spacing interferometer**
Routledge	**M**	**VAH**	**66**	**Radio polarimeter for galactic continuum**
Potter	M	VAH	67	Observations of small diameter radio sources
Blackwell	**M**	**VAH**	**67**	**Long baseline interferometer**
Miller	M	VAH	69	Galactic background at centimeter wavelengths
Routledge	D	VAH	69	Radio observations of the galactic plane
De Kock	**M**	**VAH**	**70**	**Commissioning a 60 foot radio telescope**
MacDonell	M	AHB	71	Microwave spectra and variability of radio sources
Guindon	M	AHB	71	Radio spectra of sources in 1400 MHz catalogue [Observed at Green Bank]
Butler	D	VAH	71	Observations of selected galactic radio sources
Bradford	D	VAH	71	Spectra of type III solar radio bursts detected by Alouette I
Retallack	**M**	**VAH**	**72**	**Radio pulses from direction of galactic centre**
Woodsworth	M	VAH	72	Observations of radio stars at 2.8 cm

Legend: M—M.Sc.; D:—Ph.D.; GAH—George A. Harrower; VAH—Victor A. Hughes; AHB—Alan H. Bridle. Bold indicates research was carried out at Westbrook; Italics: research required ARO 46-m observations. Graduate students working in theoretical astrophysics are not included here.

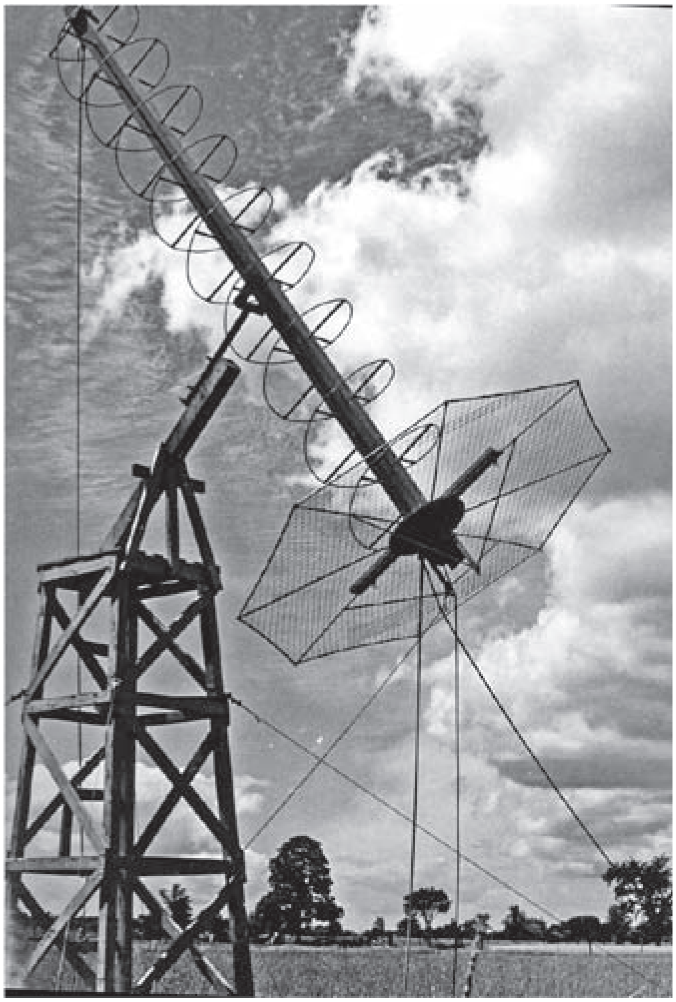


Figure 2 — David E. Hogg's MSc project—studying transient bursts of radio noise from the Sun by scanning repetitively in wavelength from 3.4m to 2.3m at 5-second intervals. The antenna is an equatorially mounted 9-turn helix of length 6m, with a reflector of diameter 3m. The receiver output is recorded directly from an oscilloscope screen by a camera.

a cable, adjust an antenna pointing, replace a vacuum tube, re-solder a connection, or whatever he deemed necessary. This was hands-on training in self-reliance and experimental science. He was the experimenter, answerable to no users' committee, no time allocation committee, no head of engineering. When in doubt, he could confer with Harrower, but ultimately this telescope was his to design and his to operate, and the data would be his to analyze while writing his M.Sc. thesis. At the oral examination, he would be the one standing alone in front of the examining committee, defending every word and number in that thesis, and "just losing weight," as P.G. Wodehouse would put it.

The chart in his hands now, though, showed a far from smoothly oscillating fringe pattern. The fringes were torn by irregular excursions, showing variations in the power incoming from Cas A. Far from making Matthews frown, however, that irregularity was essential, for he wished to study not the supernova remnant itself, but the jaggedness of the recording, the time structure of the irregular variations in radio power—in other words, the way that Cas A "scintillated."

How the incoming waves could vary so rapidly in intensity was the question. An object four parsecs in diameter could not flicker like a candle—no coordinating signal could cross it in less than 13 years. These fluctuations could not be intrinsic to the source but must be imposed during propagation of the waves through the intervening space. Most of the variation, in fact, was already known to occur in the last few hundred kilometres, caused by distortion of the wavefront by irregularities in the Earth's own ionosphere.

Ionospheric physics was, in fact, a primary area of Harrower's expertise. For two years he had been collaborating with T.R. Hartz of the Defence Research Telecommunications Establishment (DRTE) in Ottawa, analyzing radio-source scintillations and ionospheric data.

Despite sitting near a city of more than 50,000, QRO did not experience appreciable man-made interference. Runways left behind after WWII lay four kilometres to the southeast, used sporadically by the Kingston Flying Club. Two TV stations served the area—channel 7 at 1.7m wavelength and channel 11 at 1.5m. Cell phones lay decades in the future. In March of 1958, only four satellites had ever been launched into orbit. *Sputnik I* had already burned up. *Sputnik II* and *III*, massive but now derelict, still orbited; both would burn up in April. *Explorer I*, tiny but the one spacecraft still functioning, transmitted only milliwatts at 2.8m wavelength. Not being in a polar orbit, it could not pass overhead at QRO. (In four years' time, Canada would enter the space age with the launch of *Alouette I*, designed and built in Ottawa and intended to probe the ionosphere from the "top side" at wavelengths from 25m to 300m.) In the broadcast bands, CKWS, CKLC, and CFRC transmitted at 312m, 217m, and 201m (AM) and at 3.11m, 3.03m, and 3.26m (FM). QRO had plenty of empty spectrum for future radio telescopes to use.

In 1958, the field of radio astronomy was burgeoning, as scientists and astronomers worldwide rushed to peer through the new long-wave window into the Universe. A dozen octaves wide—compared with the single octave of wavelengths spanned by human vision—the radio window was already revealing bizarre and unanticipated phenomena. At the end of July, 159 astronomers and radio scientists would convene in Paris to present more than a hundred papers in radio astronomy.

Queen's University was catching the radio tide on the rise—by the time Matthews shut down his scintillation telescope to write his thesis, another was already on the air. This telescope tracked the most powerful radio source in the sky—an immense ball of roiling ionized gas, a cauldron of thermonuclear reactions, origin of a seething atmosphere laced by writhing magnetic fields, site of powerful eruptions and storms, unpredictable and only 500 light-seconds from us: the Sun.

David Hogg's solar radio telescope used a single antenna, mounted equatorially for tracking the Sun (see Figure 2). His thesis supervisor was again George Harrower. Unlike ionospheric scintillation, the phenomenon under investigation this time—transient solar radio bursts—was intrinsic to the source, not the propagation path… or was it? At the Paris Symposium on Radio Astronomy that would commence in a month, out of 107 scientific papers by scientists from 12 countries—including A.E. Covington from the National Research Council (NRC) in Ottawa—40 percent would be on solar radio phenomena and attempts to understand the physics behind them. Of those, over half would include observations or analyses of "radio bursts" that shifted in wavelength as if beams or clumps of charged particles were speeding through the coronal plasma, perhaps in the grip of tortured magnetic fields. The radio waves the particles launched would then have to propagate through an inhomogeneous magnetized plasma—the corona itself—to reach the Earth.

In Hogg's three months of observations from QRO, he recorded several radio bursts from the Sun, using a highly modified commercial receiver. He scanned from 88 to 128 MHz by motorizing the frequency tuning of the receiver. With a camera mounted to view the screen of an oscilloscope, he synchronized the oscilloscope's horizontal sweep with the tuning sweep of the receiver. The instantaneous spot brightness showed the solar radio power reaching the antenna. With this he photographed many transients, from which he selected ten to study their frequency drift with time.

Matthews' and Hogg's telescopes were examples of special-purpose instruments built on very low budgets. Nor would these be the last of this type to be built at QRO (see Table 1). John Black, for example, built and operated two interferometers for his M.Sc. scintillation work, so as to monitor Cas A continuously, as well as Cygnus A, the Crab Nebula, and Virgo A (M87) as they rose, transited, and set.

Elsewhere, however, by the summer of 1958 huge multi-purpose radio telescopes were being designed, funded, and constructed. A 26-m steerable paraboloid would be operating at Penticton in B.C. by 1960, a 64-m steerable paraboloid would see first light at Parkes in Australia in 1961, and a 91-m meridian-transit paraboloid would come into service at Green Bank in West Virginia in 1962. But, of course, in Britain, in 1957 the world had seen the first giant telescope lumber into action, at the time of *Sputnik I*. This massive telescope—it required bearings from WWI battleship gun turrets—had instantly become an icon, the 76-m steerable paraboloid south of Manchester at Jodrell Bank.

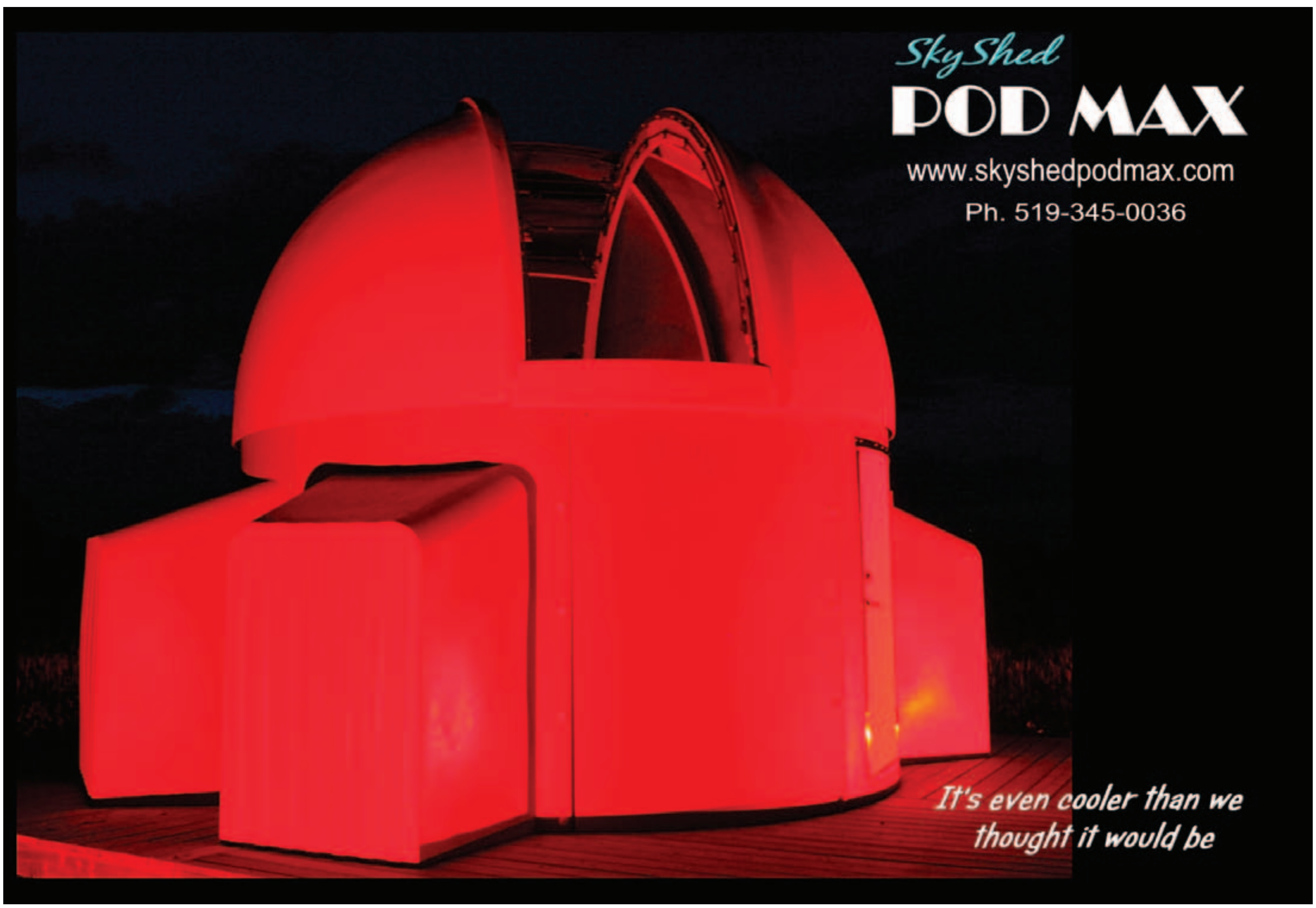


Figure 3 — The reflection-array telescope for 2-m wavelength in 1964. The two-element Yagis are reflecting elements mounted on 5-m poles for height adjustment. Through the door of the small hut can be seen the rack of receiver electronics. At 53-m height, the tower (base visible here) is an aviation hazard and has to be painted in red and white bands, besides carrying a red light at the top.

The cost of such general-purpose instruments was shocking, however. Including cost overruns, expenditure on the Jodrell Bank telescope had risen to £700,000. (In 2019 terms, that is $11,000,000 CAD.) How, Harrower asked himself, could researchers at individual universities compete?

To answer that, he first pinpointed the fundamental difficulty with radio astronomy at the time—that good angular resolution (that is, imaging with good detail) requires antenna structures hundreds or thousands of wavelengths wide. The human eye, for example, can resolve a single arcminute because a pupil of 2mm diameter is 4000 wavelengths wide at 500 nanometre wavelength. To achieve the same resolution at two metres would still take a telescope aperture 4000 wavelengths across, but that is eight kilometres. Even the Jodrell Bank telescope spanned only 38 wavelengths at two metres, so its images would contain detail no finer than 1.7 degrees. Its gigantic collecting area of over 2000 m^2 would be largely unneeded for imaging the radio sky at 2-m wavelength—the faint sources it detected would be lost in the huge, fuzzy blobs that were the strong sources. Though excellent at centimetre wavelengths, e.g. the atomic hydrogen spectral line at λ21cm, its 76-m diameter was inadequate for imaging at metre wavelengths, where the tonnes of steel forming the dish surface and backup structure were mainly wasted.

And thus, was born, in about 1960, Harrower's idea of the porous reflecting array—an inexpensive technique for metre wavelengths of achieving the same angular resolution as a complete paraboloid, but without unnecessary collecting area. He would use a large number of individually small reflecting elements just above ground level, distributed throughout a circular area so that incoming radio waves would be reflected from them to a focal point above. The heights of the reflecting elements would be adjusted to mimic the paraboloidal surface of an actual dish, minus an integral number of wavelengths near the "rim" to keep all elements near the ground. By placing the reflectors at random within the area of the circle, sidelobes (unwanted responses at large angles from the main beam) could be kept low. The density of elements—the porosity—within the circle would determine the effective area. This idea produced three M.Sc. theses (see Table 1). Michael Gibbons optimized and tested the reflecting elements, settling on Yagi antennas with short-circuited terminals. Richard Butler calculated the expected power pattern of the array and compared that against measurements on a scale model at 9cm wavelength. William McCutcheon constructed a full-size array at 2-m wavelength at QRO, and made further computations of the power pattern.

The full-scale reflection-array telescope at QRO consisted of 100 two-element Yagi antennas within a 120-metre diameter circle. (See Figure 3.) Cables carried signals from the "feed" at the top of the tower to the receiver in a small hut at the base. The feed consisted of a pair of crossed dipoles so the "background" power received directly from the sky could be subtracted from that reflected from the Yagis.

The new telescope would have a beam width of two degrees. Steering the beam, however, would require repositioning all 100 reflecting elements, so that tracking an object was impossible, and even using it over a range of declinations as a transit instrument would be physically arduous. Furthermore, it was found that achieving adequate collecting area (sensitivity) required more elements than first envisaged. The concept was not pursued further.

The Moving Tee

Undeterred, Harrower still desired angular resolution competitive with behemoth single-dish telescopes, but without their superfluous collecting area and immense steel backup structure. He realized that with a new technique called "aperture synthesis," detailed images of the radio sky could now be made—using angle iron, wire mesh, cable, etc., plus student expertise and labour—for a tiny fraction of the cost.

Besides providing a new look at the sky, an aperture synthesis telescope could address a question of high importance at the time: at a given wavelength, how many radio sources can be counted of given strength or brighter? This was the "source count" issue, important for cosmology and a bone of contention between Martin Ryle's Cambridge group and Bernard Mills's Australian group. The Cambridge source counts—from sky surveys made with interferometers—appeared to be systematically higher than those from Sydney, with the Sydney group alleging that a fraction of the Cambridge "sources" were actually duplicates, sources being counted more than once as they appeared in successive interference fringes.

Why should Queen's not contribute to this debate, Harrower asked himself, and perhaps even help settle the disagreement with independent data from a new telescope at QRO?

Philipp Kronberg, an M.Sc. student, undertook design and construction of a synthesis telescope, supervised by Harrower. An operating wavelength of two metres was selected—more precisely, 2.05 metres, in the radio amateur "two metre" band, to take advantage of commercial components such as frequency-heterodyning "mixers." And why not do better than even the world's biggest single dish at that wavelength, with a beam of one degree at QRO?

The project got underway in 1961. What, then, was this new technique of "aperture synthesis"?

Briefly put, synthesis imaging is a way to produce a sharp reception beam with a pair of cheap antennas, computing power, and tenacity instead of a huge steerable paraboloid.

The enemy of ever-larger single-dish telescopes is gravity. Not only does the moving tonnage become gigantic, but the mirror sags away from the desired parabolic shape. Also, how it deforms depends on the direction of pointing. The cost goes up typically as the cube of the diameter, and the sounds of collapsing budgets and buckling steel echo across the years. The foundations had been poured, for example, for a steerable 183-m dish at Sugar Grove in West Virginia before sanity prevailed in 1962 and the project died.

To achieve sharp angular detail, a telescope still has to be many wavelengths across, however. How to solve the conundrum?

Enter Jean Baptiste Joseph Fourier, born the son of a tailor in France in 1768. Analyzing how heat flowed through an object—this was the era of steam engines—he made a stunning mathematical discovery: you can build up ("synthesize") nearly any mathematical profile—a city skyline, for instance—out of simple sine-wave oscillations of different rates ("frequencies" with their corresponding wavelengths), strengths ("amplitudes"), and timings ("phases"). And conversely, you can disassemble nearly any profile into such sine-wave oscillations. Fourier was awarded the rank of baron.

To demonstrate the power of Fourier synthesis, suppose we add together waves of increasing frequency having the amplitudes shown in Figure 4(a). The result is the waveform in Figure 4(b), a pair of rectangular humps. As we see, summing higher and higher harmonics of the fundamental frequency, the less crude the rectangles become, i.e. the sharper the detail portrayed.

However, the shapes of astronomical objects are profiles in

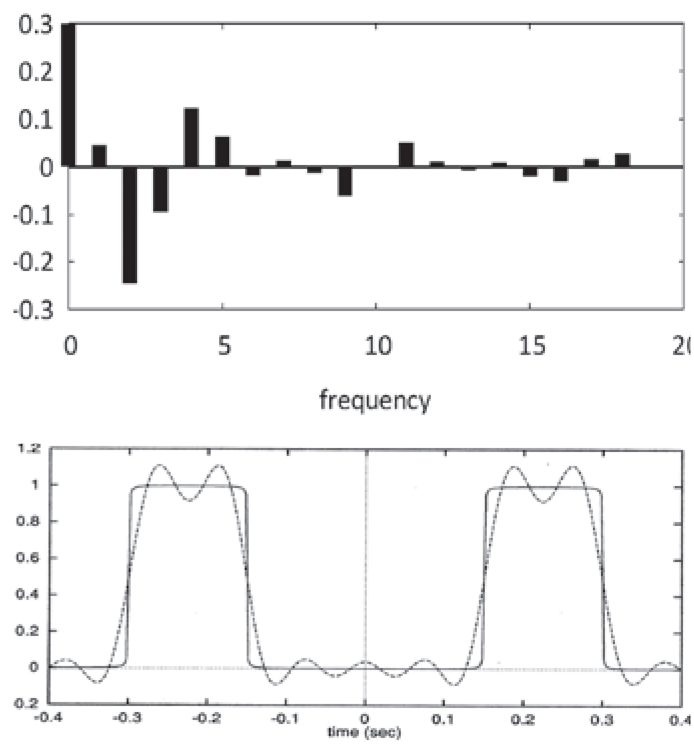


Figure 4(a) — Amplitudes of sine-wave oscillations used to build up the double-hump shape below.

Figure 4(b) — Double-hump shape synthesized by adding sine-wave components with amplitudes shown in Fig.4(a) above. The dotted line is the sum of seven harmonics, while the solid line is the sum of five hundred. This resembles the brightness profile along Cygnus A.

terms of angle across the sky, not time. Therefore, instead of oscillations in *time* we imagine instead oscillations in *angle*. Variation along the time axis becomes variation with angular position across the object, and in place of the word "frequency" we use "spatial frequency." The process in Figure 4 becomes synthesis of an image in one dimension.

But how to know what amplitudes to use—as in Figure 4(a)—at the various spatial frequencies? Surprisingly, we have already seen an instrument for measuring the amplitudes of sine-wave components of objects in the sky. This instrument picks up only one spatial frequency at a time, and it consists of two cheap antennas, plus amplifiers and some cable to carry the incoming signals to a receiver. There they combine and interfere, which is why it is called an interferometer.

The larger the number of wavelengths between the antennas, the more rapidly the interference fringes oscillate with angle. Therefore, lengthening the antenna spacing (baseline) day by day will pick out successively higher spatial frequencies from the brightness profile across the object. Day by day we record the amplitudes—and phases—of the oscillating output (the fringes on the chart), *assuming* that the object in the sky does not change from day to day.

When we have enough recordings, we can add oscillations together of the required amplitudes, keeping the phases correct. Result: an image of the object as in Figure 4(b), containing detail as sharp as the fastest oscillation (highest spatial frequency) used in the summation.

Using this technique, in fact, by the late 1950s the radio source Cygnus A had been found—amazingly and inexplicably—to be double, with a brightness profile along its length something like Figure 4(b). The interferometer measurements—performed at 2.4m wavelength by working westward from Jodrell Bank with transportable antennas—were reported at the 1958 Paris Symposium[2]. Cygnus A looked like a dumbbell, which defied explanation.

One-dimensional profiles were useful, but detailed two-dimensional images would be actual radio *pictures*. (These would one day reveal that far from being unique, Cygnus A was the prototype double radio source; there are thousands of extragalactic sources like it, even more distant, all incorporating beams of relativistic particles powered by massive black holes.)

Two-dimensional synthesis had already been achieved, by Ryle's group at Cambridge, with first results in 1957 by Blythe—sky maps with a 2.2° "pencil beam"[3]. Sharper images—0.8° resolution—at the same wavelength came three years later from a second Cambridge synthesis telescope[4]. This was progress—to achieve 0.8° at 7.9m, a single-dish telescope would have to be two-thirds of a kilometre in diameter.

Figure 5 shows the fundamental concepts of two-dimensional synthesis. The performance of a large rectangular aperture could be achieved with a cross, or more efficiently with a "tee," or more efficiently yet with just two antennas, placed at locations that would form a tee if one had extreme patience.

At QRO—as at Cambridge—the compromise approach would be taken, with the long east-west arm of the tee being constructed as a "corner reflector" (see Figure 6), but the half-length north-south arm being formed with a shorter, moveable, corner reflector. And patience.

At the time, "two solitudes" existed in astronomy—optical and radio—with little communication between the two. Radio astronomy, the small brash upstart, consisted of radio

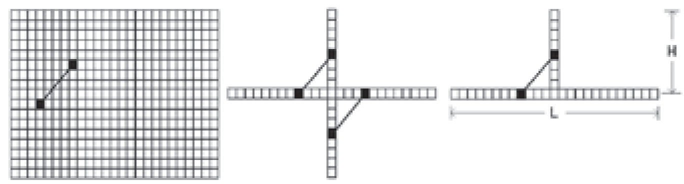


Figure 5 — From filled aperture to tee in three conceptual steps. In the rectangular aperture at left, the spacing (length and orientation) between two elements is usually not unique—in fact there is large redundancy for most spacings. In the cross, two linear antenna arrays are built and the two output voltages are multiplied together in the receiver. This product of two fan beams gives a pencil beam of the same sharpness as would the rectangular aperture. In the tee at right, even the small redundancy in the cross has been removed. The tee produces the same sharp pencil beam as the cross. In the extreme, even the linear arrays do not need to be physically constructed—two small antennas can be moved day by day to occupy positions forming a tee. In the QRO "moving tee" telescope, the long east-west arm (L = 117m) was constructed, but a smaller moveable antenna was used to form the north-south arm (60 positions over length H = 62m). The pencil beam of the QRO telescope was therefore the same as if the complete aperture of size L X 2H, i.e. 117m X 124m, had been built.

Figure 6 — The long E-W fixed arm of the 2m "moving-tee" synthesis telescope, under construction in 1962. The beginnings of the moving element are visible to the left. Professor George Harrower stands, while Philipp Kronberg climbs on the 60-degree corner reflector. Kronberg is holding one of the 96 end-to-end folded dipoles that together form a "line feed" for the corner reflector. The sides of the reflector are wire mesh, which acts as a mirror for radio waves. With mirrors 60° to each other, 5 images appear. The real line feed plus its five images act together as an array of long antennas, increasing the sensitivity of the telescope to incoming waves.

engineering, receivers and antennas, soldering irons and pliers, and boring flux-density measurements and power-law spectra plotted on logarithmic axes. Optical astronomy, meanwhile, "real" astronomy, dealt with stellar atmospheres, photometry and spectroscopy and orbital parameters of binary stars, photographic plates, evolutionary plots of stellar magnitudes and temperatures and linewidths, *photos* of planetary nebulae, and so on. In other words, the two groups studied different objects, with different instruments and techniques, and worked at different angular scales. Optical images had arcsecond resolution and usually showed a field of view of a few arcminutes, while radio "contour maps" showed at best half-degree resolution, and covered several degrees of sky. To optical astronomers' eyes, these were just line drawings of blobs. The fuzziness of these radio maps would remain radio astronomy's biggest problem until aperture synthesis techniques were invented and then implemented in hardware and software, whereupon radio images would rapidly become as sharp and detailed as optical images had long been—sometimes much sharper with very-long-baseline interferometry (VLBI)—and radio astronomers would become more and more accepted by optical astronomers.

Harrower had seen that Queen's was positioned to build a world-rank telescope at metre wavelengths. Aperture synthesis could provide good angular resolution at low cost, without superfluous collecting area, and produce sharper images at 2-m wavelength than those being produced elsewhere. He had every reason to believe that this goal was within reach.

Producing an image by Fourier synthesis required adding together many days' observations. At Cambridge, Ryle said later, if the digital computer had not been invented when it was, his group would have been forced to invent it themselves to accomplish this step. The observations recorded on charts had first to be digitized (punched onto cards or paper tape), then used as input for a program to perform the two-dimensional Fourier summation.

At Queen's, the university's computer was an IBM 1620, recently installed in Ellis Hall. This machine had core memory (RAM) storing 20,000 base-ten digits (expandable to 60,000), and a processor clock speed of 2 MHz. Even the fastest instruction took 10 microseconds. Input was done on punched cards.

Kronberg would write a program in FORTRAN to accomplish the Fourier summation. This program (the "source" deck of cards) had to be fed into the input hopper for the compilation step and then a new set of cards (the "object deck," which the machine punched out in machine language) had to be fed in, followed by the data cards, in the execution step. The output appeared—eventually—on punched cards. The astronomer could now write the output numbers (the brightness of the radio sky point by point) in a two-dimensional array representing the sky and draw contours by hand.

Figure 6 shows the 2-m "moving tee" under construction at QRO. By September 1963, Kronberg had produced a first-try

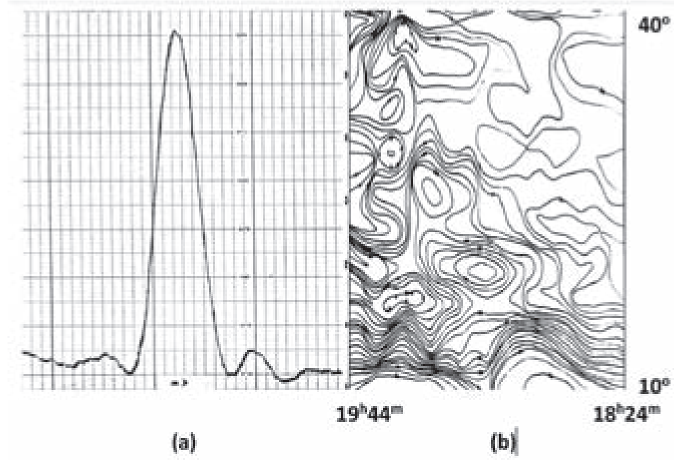


Figure 7 — (a) Chart recording at 2 metres by Hesse, as Cas A transits through the NS fan beam power pattern of the long arm of the moving-tee telescope. Chart speed is one large division per 15 minutes; hence the fan beam is 1° EW at half maximum. Sidelobes are visible on each side, of about 5%.

(b) Combining interferometer outputs from many days' observations in a Fourier summation, a pencil beam forms. Thirty degrees in declination of Kronberg's 1963 map is shown. Closed contours indicate individual sources, and broad emission from the Milky Way dominates the south and east.

contour map of a strip of the sky 1^h20^m wide in right ascension and 40° high in declination, with resolution 1° EW × 3.5° NS (see Figure 7(b)).

When Kronberg defended his thesis in 1963 and departed for Britain to continue his studies, he rightly believed he had accomplished a gargantuan task, and foresaw that subsequent students would accomplish a complete sky survey at 2-m wavelength. As usual in science, however, the new instrument required tweaking before final data-gathering could commence. The fringe records must not be contaminated by phantom sources—the response of the telescope to radio sources in the sidelobes. And indeed, there might be sidelobes.

Aage Sandqvist checked on sidelobes—and solutions—for his M.Sc., under Harrower's supervision. He developed probes for measuring currents, including their phases, along the linear array of dipoles that formed the line feed of the long corner reflector. He concluded that the array needed to be "tapered" ("apodized" in optical terms) to reduce sidelobes.

If an antenna is used for transmitting, its power pattern has the same shape that its reception pattern would have if a receiver replaced the transmitter. In transmitting terms, the network of "twin-lead" transmission line connecting the 96 dipoles to form the line feed was providing equal currents to all dipoles. In antenna jargon, the linear array had a "uniform taper" (no apodization). Theory and experience predicted this would produce strong sidelobes. When receiving, these could indeed pick up sources, "aliasing" them into the receiver output as indistinguishable from sources transiting the main beam—duplicates contaminating the data.

After studying various tapers, and methods of achieving them, Sandqvist decided to group the dipoles in sets of four, and add resistors to reduce the signals from the dipoles progressively toward the ends of the array. Time had elapsed since Kronberg's departure, and the feed now exhibited a taper worse than uniform, i.e. higher at the ends than the centre—possibly the first signs in the new telescope of that ceaseless degradation affecting all instruments exposed to the relentless effects of weather. (In the Kingston area, rain freezes, and snow melts and then freezes again, over and over, and these events are particularly troublesome—solder joints and metal pieces suffer continual breakages.)

Sandqvist applied a "Gaussian" (bell-shaped) taper along the feed array and found that the long arm by itself produced a fan beam 1.14° wide, with sidelobes no higher than 0.25 percent of the main beam.

The next students to work on this telescope were Helmut Hesse and Philip Gregory, again doing M.Sc. projects supervised by Harrower. Uncertainties in the performance of the receiver had arisen, as well as the necessity of calibrating it. Also, a modification could halve the number of days required for a survey. And again, the feeder system for the long corner reflector was giving trouble.

Gregory undertook to improve the receiver. This multiplied the voltage output of the long arm by that of the movable element and had to record the ever-changing complex product (the fringes from a north-south interferometer), in both amplitude and phase. Equivalently, it could record the real and imaginary parts, and this was what it had been built to do. Before Gregory, however, recording real and imaginary parts had taken two days' observations, the second being performed with an extra quarter-wave cable connected between the movable antenna and the receiver. Gregory twinned the receiver channels to measure both simultaneously.

The receiver now consisted of a pair of (ideally) identical receivers. Gregory established the bandwidths of these and ascertained how the bandwidths affected the accuracy of the output fringes. Devising tests of several receiver parameters, he then quantified the performance of the receiver. He concluded that the new receiver system was capable of detecting at least as many celestial radio sources as the telescope could resolve.

Hesse found that the flexible twin-lead transmission lines used to connect the dipoles feeding the corner reflectors were not standing up to the rugged environment at QRO. Grouping dipoles in sets of twelve along the long arm, he rebuilt the feeder system using coaxial cable where possible, as more robust and weatherproof, and incorporating baluns and impedance transformers where necessary. A scan with the improved feeder system is shown in Figure 7(a).

Hesse also designed and built a receiver calibration system. In preparation for the finally-imminent sky survey, he then wrote a new program for Fourier synthesis on the IBM 1620. This program, parts of which were in machine code and parts in FORTRAN, implemented the just-published Cooley-Tukey algorithm for Fast Fourier Transforms.

Gregory and Hesse submitted their theses and defended them. Sadly, these would be the last theses involving the 2-m (146 MHz) moving-tee. As they left to continue their astronomical careers elsewhere, the telescope stood at last truly ready—for the moment—for its sky survey.

However, a major change had already occurred in the physics radio astronomy group.

New Leadership

At this point the breadth of interest in radio astronomy at Queen's should be made clear. George Harrower had joined the Physics Department in 1955 and launched Queen's into the field of radio astronomy as early as any university in Canada by establishing QRO in 1956. This was never a single-handed endeavour, however—he was collaborating closely with academic staff in other departments—Allie Vibert Douglas in Mathematics and Astronomy, John E. Hogarth in Mathematics, and Robin M. Chisholm in Electrical Engineering.

Chisholm brought expertise in antenna research and signal processing, including the new technique of aperture synthesis. He had spent some time in New South Wales, at the

Commonwealth Scientific and Industrial Research Organisation (CSIRO) radio astronomy field station at Fleurs. There, Mills's group had pioneered the cross-type telescope, one of which produced a 0.8° pencil beam at 3.5-m wavelength. Now Chisholm was keeping his research links with Fleurs strong, travelling there often. By 1958 he and Harrower were designing a 3-km-baseline "compound interferometer" for 3.5-m, which would synthesize a reception beam under 5 arcminutes wide. This was extremely ambitious, and the telescope would be the largest in the world. For tests they chose a tee configuration but scaled down in wavelength by a factor of ten for cost and practicality. The test-bed instrument would be a tee of two dipole arrays, with the bar of the "T" running north-south. Each scaled-down array would be 47-m long. By 1962, the Electrical Engineering Department had begun construction of this 35-cm tee at QRO.

The north-south arm was to be steerable in declination. However, difficulties with impedance changes arose, and the elements were changed to "long Yagis" with 40 directors, made of aluminum tubing. Even then the proposed electrical steering system remained intractable. The east-west array had been built, however, and produced a fan beam along the meridian. This array—actually a pair of E-W arrays mounted together—was tiltable to different declinations. It can be seen in Figures 8 and 10.

By now, however, the original compound interferometer project was far behind competitors and was abandoned. While it failed to yield astronomical measurements, the project had produced at least 11 M.Sc. degrees in Electrical Engineering for receiver and antenna design. Chisholm had also become deeply involved in what would become the world's first successful VLBI project, and Electrical Engineering bequeathed the 35-cm antennas and receiver to Physics.

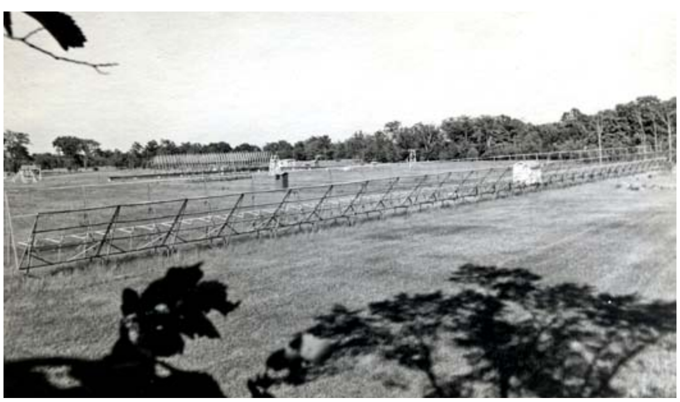


Figure 8 — Queen's Radio Observatory viewed from the South, in 1965. The long E-W fixed arm of the 2m-wavelength moving-tee synthesis telescope is in the foreground, with the white hut containing its receiver behind it. In the background to the North sit the 35cm-wavelength twin arrays built by the Electrical Engineering Department and transferred to the Physics Department. The rail-mounted movable element of the moving-tee is faintly visible between the long corner reflector and the 35cm twin arrays. Both corner reflectors of the moving-tee are tiltable in declination.

George Harrower, meanwhile, had come to a crossroads in his career. Queen's had offered him the position of Dean of Science, and he had elected to take it.

A successor had been found, fortunately, to take the helm of the radio astronomy group in the Physics Department. This was Victor A. Hughes, who arrived from England in September 1963, having done wartime work in telecommunications, graduate work in radio astronomy with Bernard Lovell at the University of Manchester, then radio and space research with James Stanley Hey at Malvern.

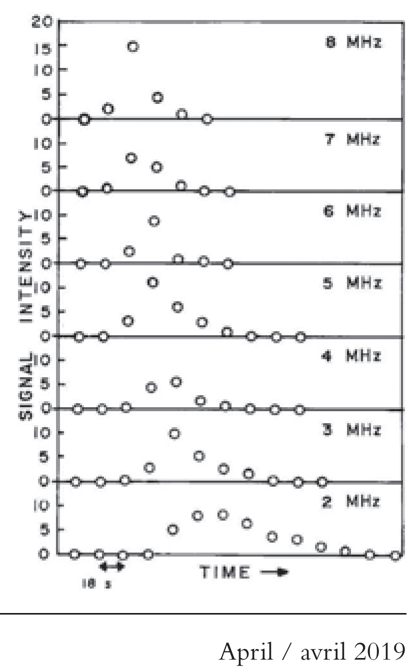
Having been part of the "pioneering" age of radio astronomical invention and discovery in England, Hughes was very happy to see the roll-up-your-sleeves-and-build-it tradition being inculcated in radio astronomers of the next generation at Queen's. He was pleased to continue the collaboration with Electrical Engineering, and assisted Harrower in supervising Gregory and Hesse in their work at Westbrook.

After Hesse and Gregory defended their theses and departed, however, the 2-m moving-tee telescope entered a period of decay, including some vandalism, without being used for the "clean" sky survey it was capable of. Nonetheless, QRO would soon see another active period, involving other telescopes and arrays.

In 1964, Hughes obtained recordings of observations—including solar radio bursts—made with the *Alouette* satellite. These came from T.R. Hartz of DRTE in Ottawa. Henry Bradford, a new Ph.D. student, used these to study "Type III" solar radio bursts (see Figure 9) in one of the first radio astronomy projects at Queen's not involving QRO—a sign of things to come.

Hughes also saw potential in the now-surplus 35-cm -wavelength twin arrays at QRO and the two-channel correlation receiver which had been designed—and modified by successive Electrical Engineering graduate students—to be used with it. Why not use these, he asked himself, to measure

Figure 9 — Alouette I observations of a type III solar burst. Radio intensity has been sampled (dots) every 18 seconds by the swept-frequency receiver carried by the satellite. The burst arrives later at lower frequencies (longer wavelengths). Ground-based radio telescopes often miss parts of these bursts because of ionospheric reflection at long wavelengths.



the polarization of the radiation arriving from the galaxy that surrounds us?

By this time, radio emission from the interstellar medium, separate from discrete sources within it, had been explained as the interaction of relativistic electrons with the pervading galactic magnetic field—synchrotron radiation. As with the Crab Nebula, the emission should be partially linearly polarized and therefore mapping the polarization should reveal the distribution and orientation of the magnetic field throughout the galaxy's spiral arms.

A new M.Sc. student supervised by Hughes, David Routledge, arrived in 1964 and took on the task of reconditioning and adapting the 35-cm receiver for this project. Hughes had brought an interesting concept with him: by slightly offsetting the frequency-heterodyning "local oscillators" in the two channels of the receiver, the position angle of the system's maximum sensitivity to linear polarization could be made to rotate on the sky. The 35cm twin arrays consisted of 80 long Yagis each, with the two sets orthogonally polarized. Each array produced a fan beam along the meridian, of E-W width 0.7 degree. It would be as if the stationary 35-cm arrays behaved like a single spinning antenna, so that a polarized signal from the sky produced a slowly oscillating receiver output, which could be measured.

This instrument did work, in the sense that the system, with its completely rebuilt receiver, did allow measurement of the polarization of test antenna transmissions. However, spurious polarization resulting from collimation errors between the two arrays (even after laborious reconditioning and adjustment) and—once again—sidelobes, foretold major difficulties in measuring galactic polarization using these arrays. The twin 35-cm arrays joined the ranks of retired telescopes at QRO.

The receiver, however, would see use in another incarnation. In 1966 Hughes obtained an 18-metre paraboloidal dish antenna from the Defence Research Board, where it had been used fastened to a tower. At QRO it was resurfaced, and a new M.Sc. student, Daniel de Kock, took on the task of designing a fully steerable alt-azimuth mount and indication system, and installing the dish on a wheeled triangular structure riding on rails (see Figure 10). The new telescope, commissioned in 1969 with a dual-polarized feed, used the 35-cm receiver from the polarization project and produced a beam 1.4° in width.

A subsequent M.Sc. student, Donald Retallack, used this paraboloid—with a new 35-cm receiver—to search the galactic centre, looking for pulses coinciding with gravitational wave pulses then being reported by Joseph Weber from his mass-interferometric detector in Maryland. Pulse timing data provided by Weber covering months of radio observing at QRO showed no timing coincidences had occurred, and his reported detections were later discovered to be artifacts of his data analysis. Nevertheless, the QRO paraboloid did detect pulsed radio emissions from the galactic centre and gave their positions[5].

Figure 10 — The QRO 18-m dish on E-W rails in 1969. Plans for a second dish to form an interferometer were never implemented. In the background to the East sit the twin arrays for 35-cm wavelength built by the Electrical Engineering Department.

Technicians

Although much of the work at QRO and in the Physics radio astronomy lab was performed by graduate students, those students relied on the group's technicians. During the era 1957–1972, the group employed three in sequence, but never more than two at one time. These knowledgeable, hard-working, versatile repositories of experience and paragons of patience were Don Cooper, Joel Tarback, and Bob Baran. Tarback in particular laboured many weeks per year outdoors at QRO. In Hesse's thesis, for example, he says, "Research technician J. Tarback helped this project inestimably with his wide knowledge and the spirit with which he went about his work, and thus deserves special thanks." Tarback also carried out much of the heavy task of reconditioning the twin 35-cm arrays both mechanically and electrically, and single-handedly installed a new double-layer wire mesh surface on the surplus 18-m dish.

Vacuum-Tube Receivers

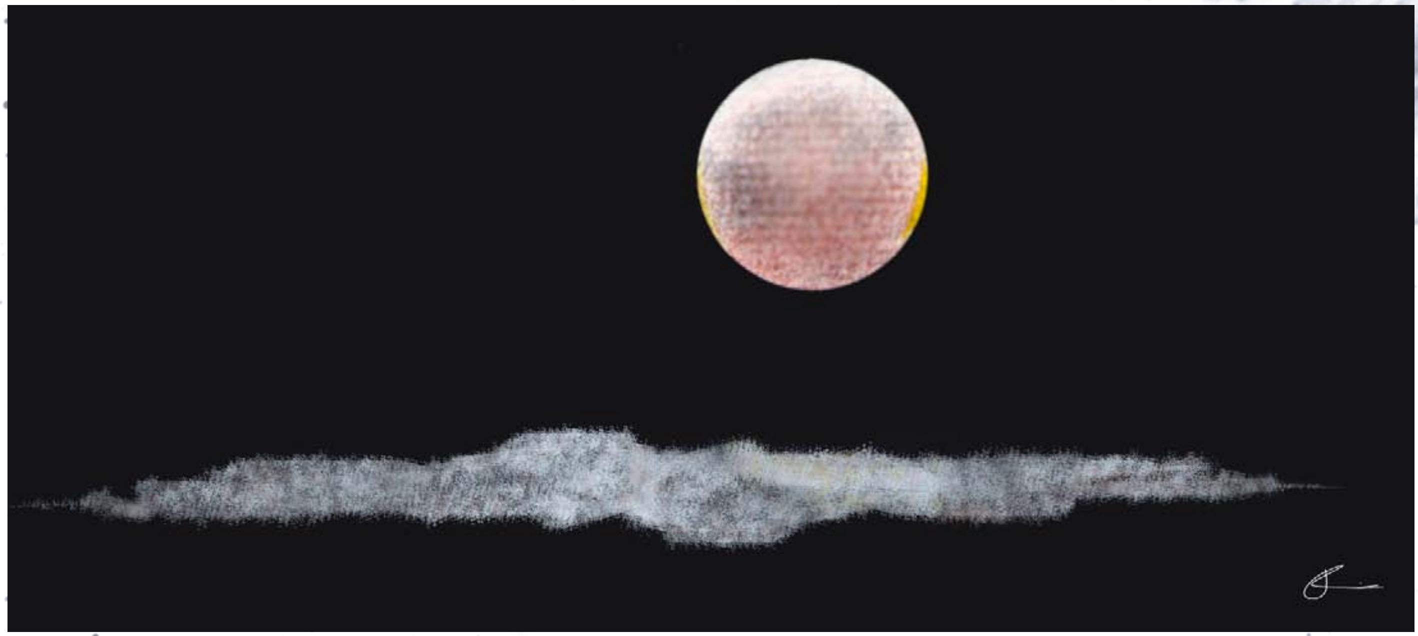
One well-intentioned graduate student working at QRO assembled the components of his receiver near his antennas for tests, but as evening approached realized that he had no weather-proof enclosure. Seeing rain clouds forming but

Continues on page 68

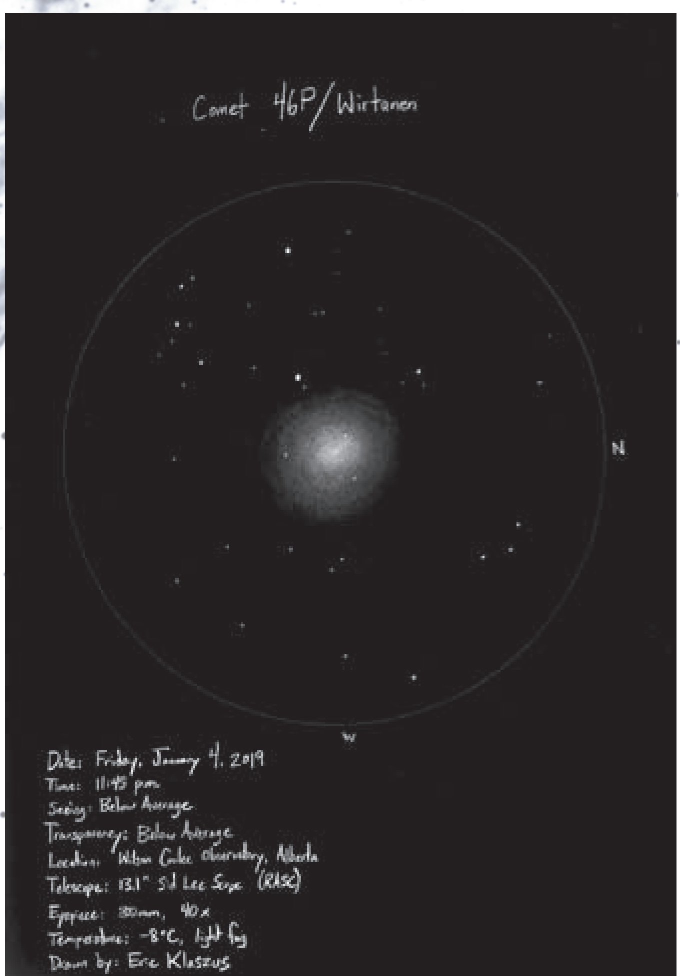
Pen & Pixel

The beautiful and familiar M81. This image was taken by Andre Paquette using a Planewave CDK 12.5″ and U16M on a Celestron CGE Pro mount. It is an RGB image composed of 17 x 20-minute subs.

On January 20, people across Canada were treated to a total lunar eclipse. RASC historian Randall Rosenfeld sketched the event at 23:50 EST, from downtown Toronto in somewhat chilly conditions (−19 °C), saying "the gusts of wind were somewhat bracing." He sketched this naked-eye using coloured pencils on textured paper, processed in Photoshop.



Ron Brecher imaged M33 from his SkyShed in Guelph using his Sky-Watcher Esprit 150 f/7 refractor, QHY 16200-A camera, Optolong Hα, L, R, G, and B filters, Paramount MX. He acquired it using TheSkyX, unguided and focused manually using a Bahtinov mask. All pre-processing and processing was done in PixInsight. No Moon for L, moderate moonlight for Hα and RGB, average transparency and fair to average seeing. Data acquired 2018 November 4 through 2019 January 13. 75 x 5m L, 24 x 5 m R, G, and B, and 7 x 10 m Hα (Total = 13hr 25m)



Ken Klaszus sketched Comet 46P/Wirtanen using a pencil on white paper. After scanning, the image was inverted into the negative using Photoshop.

Continued from page 65

wishing to run his telescope overnight, he borrowed an unused waterproof "cabinet" he spied. This was a refrigerator that at one time had been used in the main observatory hut but was no longer functioning. Acting responsibly, he moved the components of his receiver—many of them commercial units on loan from Electrical Engineering—into the refrigerator. Giving his receiver a final tweak for the night's observations, he closed his new cabinet and departed.

Returning in the morning, he found the receiver still running. However, he had forgotten about the First Law of Thermodynamics: "Energy can be transformed from one form to another, but can be neither created nor destroyed." As the temperature in the ex-refrigerator rose higher and higher overnight, plastic components in several electronic units had melted, including dials and light jewels. These had also obeyed the Law of Gravitation by drooling down the front panels.

Vacuum tubes did all the things transistors do now, but with a fundamental difference: they dissipated thousands of times more heat—a few Watts each. Packing even hundreds together—let alone millions—to build an integrated circuit would produce spontaneous combustion.

With three electrodes in the glass envelope—in addition to the filament that heated the cathode—the basic vacuum tube was the triode. The pentode (five electrodes plus filament) offered improved characteristics for some applications.

The montage in Figure 11 shows McCutcheon's receiver for 2 metres, and one of the four cabinets of the 35-cm two-channel polarization receiver. In the 35-cm receiver, the first cabinet contained two parametric amplifiers (adjusted for identical gain and bandwidth by postdoctoral fellow Carson Stewart) that were "pumped" by 3-cm microwaves from a special vacuum tube—a "klystron"—beneath which sat its own massive vacuum-tube power supply. The fourth cabinet contained only such power supplies, each incorporating several high-power vacuum tubes. In the 35-cm-receiver cabinet shown in Figure 11, 29 vacuum tubes reside inside cylindrical metal sheaths. Keeping receiver huts warm, even in winter, was never a problem.

New Academic Staff

The "supervisor" column in Table I reflects the transition of thesis supervision from Harrower to Hughes that occurred in 1964–1965.

Following Hughes's arrival, additional academic staff began to be added to the group. The first was theoretical astrophysicist Richard N. Henriksen from the University of Manchester, in 1965, bringing expertise in magnetic effects in astrophysics. In 1966, Alan H. Bridle also joined the group, from Ryle's group at Cambridge.

Bringing knowledge of decametre-wavelength astronomy and the broad-scale galactic synchrotron radiation, Bridle instituted a weekly "literature review" in which all graduate students were expected to take part. Each was assigned two or more specific subjects of responsibility, spanning current astronomical papers in the international journals. Topics that Bridle assigned included the enigmatic quasi-stellar radio sources (discovered 1963) including the question of whether their redshift was cosmological, the ongoing discovery (since 1962) of extrasolar X-ray sources using rocket-borne instruments, discoveries (1963 onward) of radio spectral-line emission—including maser amplification—from interstellar molecules, and (1965 onward) the cosmic microwave background radiation and implications regarding the Big Bang.

Each week each student would present a précis of a significant paper in each of his assigned areas. Beyond the advantage of keeping everyone abreast of developments in astronomy, this was excellent training for presenting papers concisely and clearly at scientific conferences. Penetrating questions were to be expected. Soon academic staff members, including from other areas of physics and other departments on

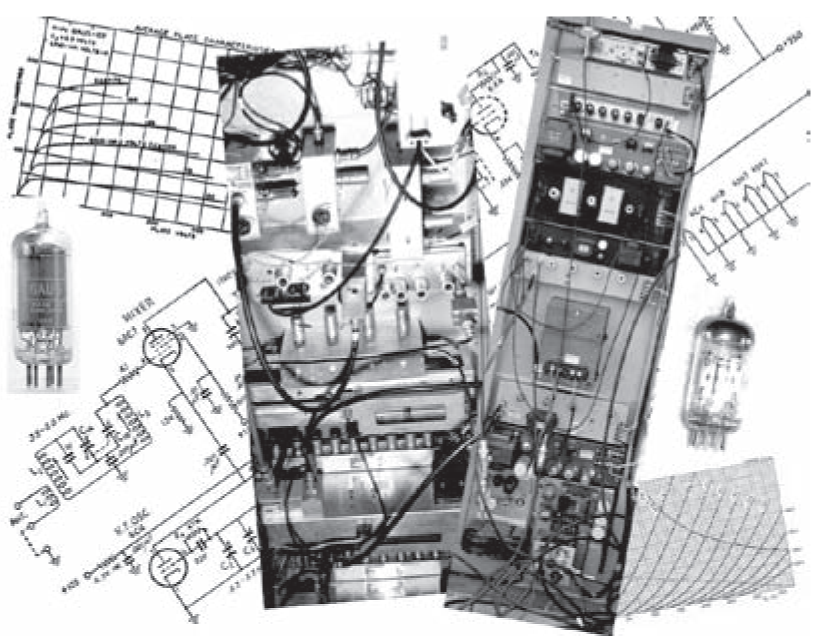


Figure 11 — A vacuum-tube montage showing the rack containing McCutcheon's receiver for the 2-m reflection-array telescope in the rack on the right, and one of the four cabinets of the 35-cm two-channel polarization receiver on the left. At far left is a pentode, and at far right is a triode. Racks are taller than a person, and cabinets are shoulder height. In the background appear anode current-voltage curves, and the schematic diagram for a shortwave receiver. Connections to its five vacuum-tube filaments appear at right.

campus, were attending the group's literature review sessions as well.

One topic assigned for the review was decametric-wavelength astronomy, advancing in Tasmania, California, Ukraine, and especially Canada, with construction of a huge synthesis tee for 13.5-m wavelength[6] and another for 30m wavelength[7] at the Dominion Radio Astrophysical Observatory (DRAO) at Penticton. Both these telescopes had begun observations by 1965. Bridle, in fact, had already worked with the DRAO 30m-wavelength telescope, acquiring data for radio-source spectra[8].

In 1967, came the jaw-dropping discovery by Ryle's group at Cambridge—made not with their increasingly powerful cm-wavelength synthesis telescopes but with a wire-and-cable-and-wooden-posts antenna array for 3.5-m built largely by graduate students—of the unforeseen phenomenon of pulsars. These would lead to better understanding of supernova remnants and the interstellar medium, and brought neutron stars, enormous magnetic fields, and interstellar radio beams into daily discussions.

Figure 12 — The 46-m ARO telescope and at left the control building, at ARO in 1968. Receivers are available at three wavelengths, offering increasingly sharp pencil beams: 9-cm (9′), 4.5-cm (4.2′), and 2.8-cm (2.7′). When commissioned, this is the third-largest fully steerable telescope in the world, after Jodrell Bank and Parkes. Receivers may be mounted at both the prime focus and Gregorian focus.

Michael J. Kesteven arrived from Sydney, Australia, in 1968, with expertise in decimetre-wave observations of supernova remnants and in aperture synthesis. Wai-Yin Chau—a second theoretical astrophysicist—joined in 1969, bringing knowledge of general relativity and neutron stars.

Through the interval 1957–1972, postdoctoral fellows also joined the group and raised its activity level for various periods of time. These included Carson Stewart, Arthur E. Niell, Paul A. Feldman, Henry M. Bradford, Melvin R. Viner, and Andrew W. Woodsworth. These also augmented the audience at the literature review sessions, adding to the trepidation of the student presenters.

Second Major Change: Algonquin Radio Observatory

In 1966, 230 km north of Kingston at a radio-quiet site on Lake Traverse in Algonquin Park—henceforth known as Algonquin Radio Observatory (ARO)—a magnificent radio telescope saw first light. (See Figure 12.)

This 46-m telescope would be maintained by NRC electronics technicians and engineers. Observers would not be required to bring a pair of pliers or soldering iron near it. Designed by world-calibre radio engineers including NRC's own radio astronomers, it was intended for their use plus that of university astronomers and their students.

The effect on Hughes's radio astronomy group at Queen's was profound. As Table I shows, activity at QRO dwindled as students began choosing thesis projects based on observing programs at ARO, rather than construction projects.

The contrast between QRO and ARO could not have been stronger. QRO was "hands-on," which meant bringing tool boxes and whatever instrumentation might be required. ARO, conversely, was "don't touch." The observer had responsibility for changing paper in the chart recorder, setting the speed of the chart recorder, and setting the receiver-output filter preceding the chart recorder. Scanning or slewing or stowing the telescope remained strictly the domain of the operator, who sat at a control console before a set of digital displays and dials as intimidating to students as those of a nuclear power station.

Servicing the telescope and its receivers, e.g. riding the cherry picker to the prime focus with a dewar of liquid nitrogen, was likewise the domain of NRC technicians. Planning a night's observations, however—including pointing calibrations, focal position calibrations, flux-density calibrations, etc., and of course scan positions, directions, and speeds—was the responsibility of the student. If a calibration source set in the west before the telescope could slew to it, he had his own poor planning to blame. If atmospheric conditions deteriorated and he had not prepared fall-back observations at a

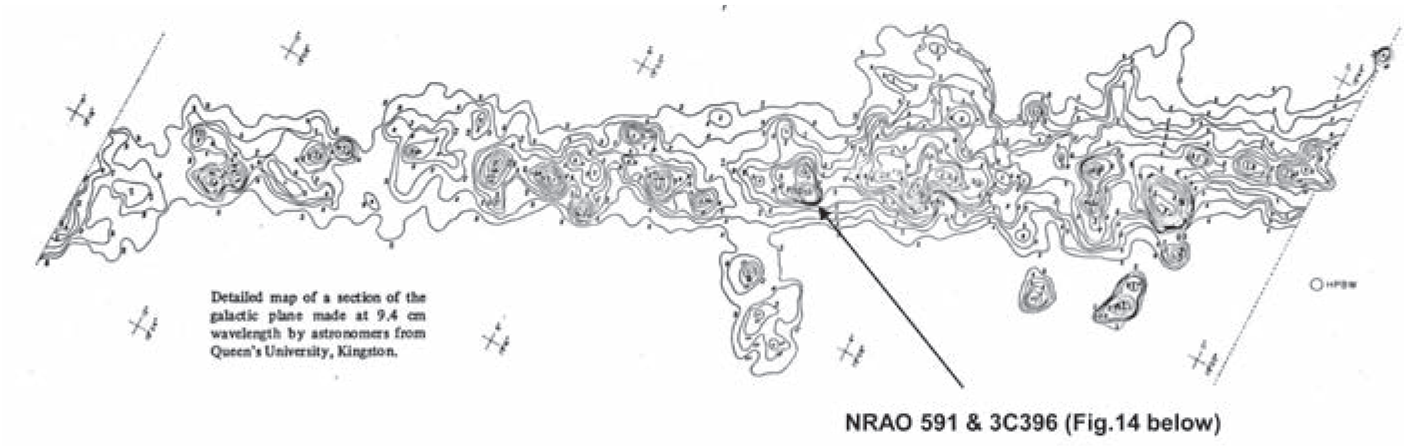


Figure 13 — Radio emisssion from 15 degrees of the Milky Way in Aquila observed by Routledge in 1968 using the ARO 46-m at 9-cm wavelength. The angular resolution (width of the pencil-beam power pattern) is 9′. Knots of closed contours reveal individual sources embedded in the broad-scale emission from the galaxy's interstellar medium. This image was made by scanning the single beam of the telescope across the survey area like a single-pixel camera, and recording the power received point by point.

longer wavelength, likewise. Luckily, NRC astronomers (Bryan Andrew, Norman Broten, Carman Costain, Lloyd Higgs, Tom Legg, John MacLeod, Wilfred Medd, and Christopher Purton) were establishing effective calibration and correction procedures (e.g. focal-position adjustment with zenith angle) and observing strategies, and Queen's students benefitted immediately from these.

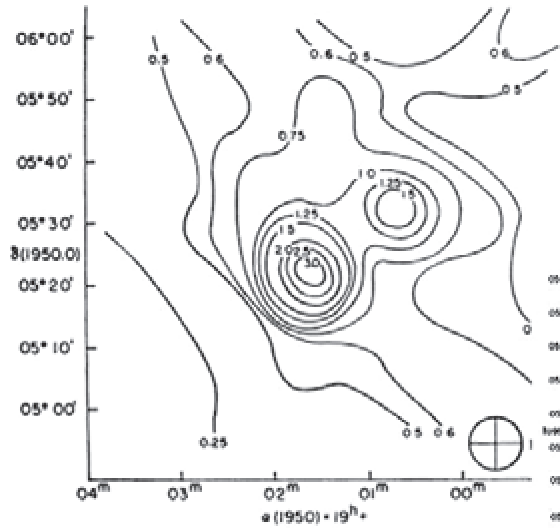
Built on an alt-azimuth mount, the telescope converted to and from equatorial coordinates for the digital control console, but without using a digital computer. An analogue device—an equatorial telescope—emitted a beam of light tracked by photoelectric sensors attached to the rear surface of the 46-m reflector. With arcsecond accuracy, analogue feedback control systems and powerful motors drove the 800-tonne telescope to the right ascension and declination requested by the operator and scanned precisely as commanded.

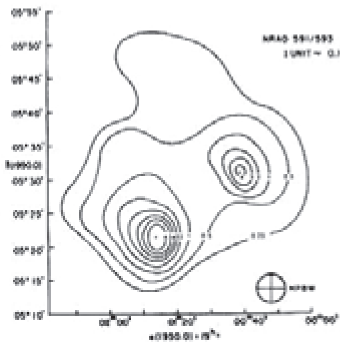
In 1968, tragically, the brilliant career of Robin M. Chisholm of the Electrical Engineering Department was cut short when he passed away in October. This occurred after the Canadian effort to achieve the world's first VLBI, of which he had been part, had succeeded. Fringes had first been achieved on quasars at 67-cm wavelength between the new ARO 46-m and the DRAO 26-m in May 1967[9]. Chisholm and the Electrical Engineering radio astronomy group had cooperated closely with the Physics radio astronomy group since Chisholm's arrival at Queen's, and his loss was felt deeply by both groups.

Examples of results from ARO that began appearing in student theses and in international journals are shown in Figures 13 and 14. The contours are drawn by hand.

At centimetre wavelengths, the radiation from the Milky Way and individual sources within its interstellar medium consists of a blend of "thermal" emission from ionized gas, and "nonthermal" synchrotron emission. Observations with the ARO 46-m at multiple wavelengths immediately began separating sources from the background, and thermal emission from nonthermal. The ionized gas is generally optically thin (translucent) but in spots may be optically thick (opaque). From their radio spectra, some sources were deduced to be HII regions like M8 (the Lagoon Nebula), consisting of gas ionized by young stars within them. Others were found to be synchrotron emitters, often supernova remnants like Cas A or M1.

A major problem in radio astronomy had from the beginning been the determination of distances to many radio sources. Fortuitously, however, a partial solution became available at just this time, for objects within our Milky Way Galaxy. As Queen's students began returning from ARO with observations to analyze, a spectral-line survey of λ21-cm atomic hydrogen (HI) emission along the galactic plane became available. This had been compiled using the 91-m meridian-transit telescope at Green Bank[10]. Because the galaxy rotates like water swirling around a drain rather than as a rigid disk, HI located at a given distance on the line of sight between





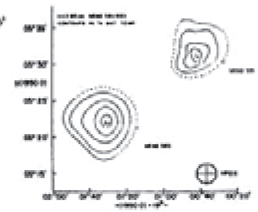


Figure 14 — Radio sources NRAO 591 and 3C396 imaged by Butler with the ARO 46-m telescope at three wavelengths. As observing wavelength decreases from 9-cm, through 4.5-cm, to 2.8-cm, the resolution becomes sharper—see circles showing beam size—and the brightness of broad-scale galactic emission also decreases. This is the pair of sources marked in Figure 13.

an object and the telescope ought to absorb radio power from that object at a calculable line-of-sight velocity. Using the Doppler effect, that could be converted to a redshift or blueshift, and hence a precise wavelength. Conversely, by measuring its line-of-sight velocity, the distance to that concentration of HI could be deduced, giving a minimum distance to the object behind it.

Distance estimates to some brighter sources observed at ARO therefore became possible using the recently published Schmidt model of galactic rotation, the Doppler effect, and trigonometry. With plausible distances, furthermore, suddenly the physical phenomena occurring within radio sources also became accessible.

An example of a pair of sources positioned—was it by chance, or because of physical proximity?—on nearly the same line of sight is shown in Figure 14. The HI "absorption profile" toward 3C396 (the stronger, south-following source) showed that it lies a huge distance from the Sun—certainly no closer than 7,800 parsecs. (The weaker source, HII region NRAO 591, was later shown to be at least as distant, likely 14,000 pc from the Sun[11].)

Observations in the new radio window were therefore opening new possibilities in galactic astronomy. The region shown in Figures 13 and 14, after all, lay within the Serpens-Aquila Rift, an area of sky notorious for high visual extinction. Even in the red, optical dimming in the direction of 3C396 exceeds 25 magnitudes[12]. Yet observations and calculations by Queen's students were not only revealing the existence of unseen objects lying beyond much of that absorbing material but allowing some of their physical parameters to be deduced—e.g. for HII regions their ionization density, emission measure, and mass, as well as estimates of their exciting stars.

Last Work at QRO

In Table I, the transition in 1964–1965 from Harrower's thesis supervision to Hughes's supervision is sharp, whereas the migration from QRO to ARO is more gradual. Students of Hughes (VAH) and Bridle (AHB) carried out their research observations primarily at ARO, not QRO. The likelihood of a student's thesis work being publishable in scientific journals had become much higher using NRC's world-class 46-metre telescope than battling the unrelenting forces of weather and deterioration at QRO to perfect build-it-yourself apparatus in hopes of obtaining the same quality of data.

In Table I, hands-on projects undertaken at QRO are shown in bold font. After Harrower's last thesis students graduate in 1965, such entries become sparse. Thesis research in the radio astronomy group has switched to ARO.

The last thesis written on work at QRO, on observations with the 18-m steerable paraboloid (Figure 10), was by Retallack, in 1972.

Thus ended an era.

Conclusion

The authors were students in the Queen's University Physics Department's radio astronomy group during the decade and a half discussed here. We feel privileged and grateful to have had the chance to take part in the expansion of astronomy into the radio portion of the electromagnetic spectrum—an event that will occur only once in the advance of science—and to help catch the tide of discovery this would yield. ✶

Acknowledgements

We thank our fellow students in the Physics radio astronomy group—Henry Bradford, Philip Gregory, Helmut Hesse, David Hogg, Philipp Kronberg, and Aage Sandqvist—for permission to quote from their theses. Alan Bridle very kindly commented on the text, adding useful information. We also gratefully acknowledge the efficient and indispensable help of the Queen's University archivist, Paul Banfield, and his staff.

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New Horizons

Rick Stankiewicz, New Years Day, 2019

An old year ends with missions
complete,

We all look forward to new horizons.

New Year, new beginnings,
new threats to defeat,

We all look forward to new horizons.

New perspectives, new knowledge,
new missions conceived,

We all look forward to new horizons.

New dreams, new hopes, new views of
our world perceived,

We all look forward to new horizons.

New strength, new courage, new hope
not lost,

We all look forward to new horizons.

New discoveries, new challenges, new
success at all cost,

We all look forward to new horizons.

New visions, new futures, new goals
replete,

We all look forward to new horizons.

A new year starts with missions to
complete,

We all look forward to New Horizons.

NASA/JHUAPL/SWRI

The Magic of March 23 and the Power of *Apollo 8*

By David Levy, Kingston and Montréal Centres

For those of us who were alive back then, where were you on Christmas Eve, in the year 1968? I remember exactly where I was: sitting in front of my family's television, we were watching a surreal scene. There was a camera peering through a triangular-shaped window on a spacecraft called *Apollo 8*, out of which was a view of mountains, plains, and craters. And at the bottom of the screen were the words, "Live from the Moon." I have a feeling that most of you, if you were living then, were watching too. The *Apollo 8* Christmas Eve broadcast was the most watched television program in the world up to that time. The announcer on our station, Walter Cronkite, was not saying much. Occasionally he would update us as to what part of the Moon the spacecraft was looking at, but most of the time, the view on the screen said it all. And it was magical.

The year 1968 was a terrible year for the most part. In April, Martin Luther King was murdered outside his hotel room in Memphis, and just two months later in Los Angeles, Senator Robert Kennedy was assassinated. And two months after that, the Democratic National Convention disintegrated into a riot on the streets of Chicago, with "The whole world watching." That November, Richard Nixon won a close national election. Then came Christmas Eve.

Apollo 8 was not intended to head for the Moon. The Saturn V rocket, as tall as a 36-storey building, had never flown with humans aboard. The NASA picture that accompanies this article, in fact, shows Wernher von Braun, the man who designed the Saturn V, utterly dwarfed by five engines so large that one could set up housekeeping in each of them. (The other picture is astronaut Bill Anders' epochal "Earthrise.") The Saturn V's unmanned test flights had been beset by several minor problems, and the Lunar Module, which was intended to land two astronauts on the Moon and return them to the Command Module, was not yet ready for flight testing. But in August 1968, George Low, Manager of the Apollo Spacecraft Program office, came up with an ingenious idea: NASA could fly a manned Saturn V with only the Command module. If the launch was successful, it could then proceed to orbit the Moon.

After some debate and a lot of tense moments, *Apollo 8* launched on the winter solstice, 1968 December 21. About two hours later, a simple message was radioed: "Apollo 8: You are go for TLI." After the trans-lunar injection, *Apollo 8*—with Frank Borman, Jim Lovell, and Bill Anders—was on its way

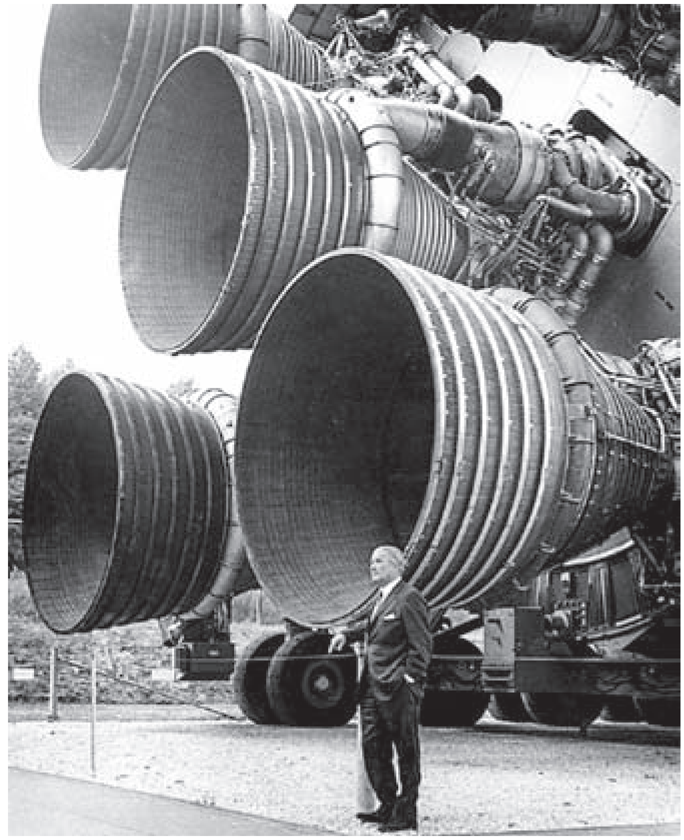

Figure 1 — Werner von Braun standing in front of a Saturn V, with its five F1 engines big enough to be small houses.

to a Christmas Eve rendezvous with the Moon. There was nothing left to do but travel and wait.

For me, by far the most memorable part was the astronauts' Christmas Eve message: "We are now approaching lunar sunrise, and for all the people back on Earth, the crew of *Apollo 8* has a message that we would like to send to you."

Then each astronaut read from the book of Genesis. Our family was spellbound as we listened to these words. But it was the ending that really turned the year 1968 from one of tragedy to one of promise and hope: "And from the crew of *Apollo 8*, we close with good night, good luck, a Merry Christmas—and God bless all of you, all of you on the good Earth."

An extraordinary date

In 1963, while living as a patient at the Jewish National Home for Asthmatic Children in Denver, I strolled outside on the evening of March 23 to observe the evening sky. The sky was brilliant and clear that evening so long ago as I set up my small first telescope, Echo, and proceeded to sketch a portion of the Milky Way as it shone in the sky over Denver. It was a silly and immature project of no particular value whatsoever, but it was important to me, and it resulted in a small chart of the winter Milky Way.

Figure 1 — Earthrise by Bill Anders (courtesy NASA).

Over many years, the particular date of March 23 has brought many treasured memories to my personal life and my skywatching life. Late in 1988, I began studying the behaviour of TV Corvi, a certain variable star that had been discovered in 1931 by Clyde Tombaugh, the same person who discovered Pluto. On the evening of 1990 March 23, TV Corvi erupted again like a nova, brightening from fainter than magnitude 19 to magnitude 12, an increase of almost 250 times in brightness in just a few hours. Even though it has gone through outbursts of energy many times since then, one of those outbursts also took place on another March 23.

All these events paled in contrast to what happened next. On 1993 March 23, Gene and Carolyn Shoemaker and I, while observing from Palomar Observatory, took the two photographs of a region of sky that led to our discovery of Comet Shoemaker-Levy 9. Sixteen months later, the 21-odd pieces of that tidally disrupted comet collided with Jupiter, the largest planet in our Solar System, in what is now regarded as the mightiest collision ever witnessed by humanity. This event captured the attention, and the imagination, of the world, and was directly responsible for inspiring many people to become interested in the breathtaking majesty and behaviour of the Universe.

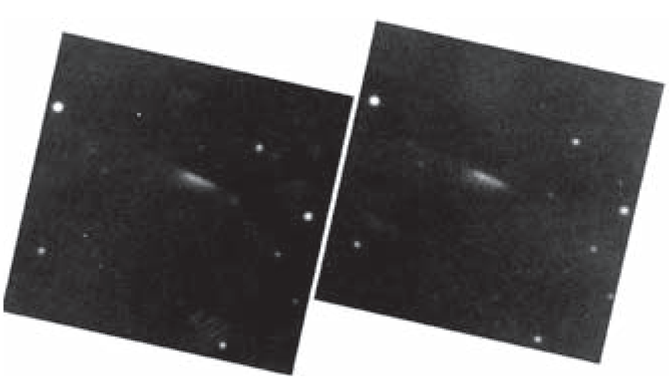

Figure 3 — The discovery images of Comet Shoemaker-Levy 9, taken on 1993 March 23, by Gene Shoemaker and David Levy.

The fact that my youthful map of the Milky Way, a new variable star, and one of the most interesting comets in the history of science (according to scientists around the world), all began on March 23, left a most lasting impression on me regarding that special date. In the non-astronomical parts of my own life, on 1992 March 23, I typed a postcard to Wendee Wallach, a teacher in Las Cruces, New Mexico. It was my not-very-romantic way of asking her out on a date. At the time it was just a coincidence that the letter was written on that particular date. But five years later, it was not a surprise, therefore, that Wendee and I were married on 1997 March 23.

There is a special reason that March 23 recurs in this way. The various astronomical happenings associated with this date comprise not just a single part of astronomy, like a planet, a comet, or a star that suddenly changes in brightness, but almost the whole gamut of what can happen in the sky, from a comet that collides with a planet, to a unique variable star, and on to the vast expanse of our galaxy across the night, and how all these things relate to the happiest parts of my personal life. The date reminds me once again of how exciting and unexpected the night sky can be. ✶

David H. Levy is arguably one of the most enthusiastic and famous amateur astronomers of our time. Although he has never taken a class in astronomy, he has written more than three dozen books, has written for three astronomy magazines, and has appeared on television programs featured on the Discovery and the Science channels. Among David's accomplishments are 23 comet discoveries, the most famous being Shoemaker-Levy 9 that collided with Jupiter in 1994, a few hundred shared asteroid discoveries, an Emmy for the documentary Three Minutes to Impact, *five honorary doctorates in science, and a Ph.D. that combines astronomy and English Literature. Currently, he is the editor of the web magazine* Sky's Up!, *has a monthly column, "Skyward," in the local* Vail Voice *paper and in other publications. David continues to hunt for comets and asteroids, and he lectures worldwide. David was President of the National Sharing the Sky Foundation, which tries to inspire people young and old to enjoy the night sky.*

Binary Universe

More Than a Clock

by Blake Nancarrow, Toronto Centre
(blaken@computer-ease.com)

Preview

I bombarded you in December 2018 with an ostentation of apps for determining local sidereal time (LST). Often after researching apps I remove them, but there was one I kept as it looked rather interesting. I'm talking about Astro Clock or Astro Clock Widget (ACW) provided by Erratic Labs, version 0.0.96-RC3. There are a few apps with similar names.

I mentioned that ACW is choc-a-block with information including Sun and Moon rise, transit and set times, twilight times, along with all the planet rise, meridian-crossing, and set times. I also relayed it came with a home-screen widget.

Let's do a deeper dive now.

Data Galore

When you open up Astro Clock proper (we'll talk about the widget later), you'll see a rather long list. In Figure 1, I stitched together all the panels.

Figure 1 — The complete list of information panels in the Astro Clock Widget app.

The Sky

Below the title bar, the first element shows the sky. In Figure 1, you can see the Sun against a blue background, simulating a daytime apparition. After sunset, not surprisingly, it shows a darkened sky (Figure 2).

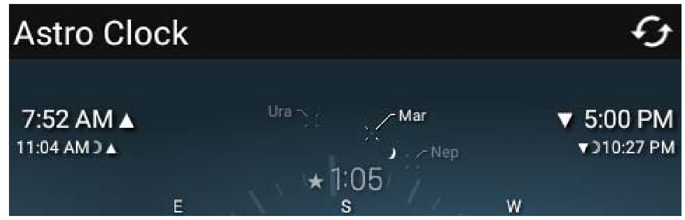

Figure 2 — The night-sky panel with sidereal time, some planets, and the Moon marked.

If you look closely, you'll see planet locations are marked above the compass cardinal points. The Moon is shown with the appropriate phase. This tells you what planets are visible and how much moonlight you may have to contend with. In the advanced settings, you can force the planets to be displayed even in daylight and choose whether to use their full names or abbreviations.

The times on the left and right edges are for the Sun and Moon rise and set times respectively.

The sky panel shows your location, the current date, and the time by default. I turned off these options to unclutter the sky display. I also want to keep tabs on the sidereal time, so I set the advanced option accordingly. That's the 1:05 value beside the star.

Seeking

Immediately below the sky panel is the Seek Bar with buttons and a slider.

The button with the clock icon hints that if you drag the slider it will change the time in the day. You can interactively roll back to midnight or sunrise or move ahead to sunset or late night. It's neat for previewing upcoming events or figuring out what you saw. Tap the time button to switch to calendar mode then drag to the date of interest. The chevron left and right buttons permit small jumps. It's easy to get back to "now" using the circular arrow button.

While you're changing to different dates and times, the sky display adjusts along with the panels below. They reflect what's going on with the Sun, Moon, and planets as you land at a date/time.

The final button, the triangle, is a recent addition. It exposes the animation bar, which lets you zip through a period of time, say from sunset to sunrise. If you're clever you can show the analemma.

Use the calendar button to jump to a particular distant date.

You are Here

The next panel is obvious. Your place on the third rock from the Sun is shown. Location detection is automatic and ACW supports different methods, such as internet and the Global Positioning Satellite system. For automatically detected locations, it seems it can derive the elevation.

The triangle button here is odd. When tapped, it brings up a Google Map for the designated location. I thought I could use this to visually choose a new spot, but it doesn't seem to work that way. I use the settings panel to get to a particular location.

You can shut down the automatic mode and indicate a custom location. Sadly, ACW does not save location profiles.

Our Star

The Sun panel is next. Lots of detail again, notably the rise time on the left and the set time on the right. The transit time, when the Sun will cross the meridian, is denoted with the up arrow in the middle.

Just below the times are degree values. For the rise and set columns, the azimuth direction is shown. Note the east and west designations. At the transit time, when the Sun culminates, the elevation above the horizon is highlighted. Total daylight time appears. I like the final row of values showing the advance or decrease in time for the next day. The +21s in Figure 1 tells us the Sun rose 21 seconds earlier and will set 1 minute later.

Luna

The panel for our natural satellite contains all the information you'd expect. Once again, the large numbers catch our attention: rise, transit, and set.

The graphical display illustrates the correct phase. To the right is the phase in percentage and the elongation angle (the angle between Moon and Sun measured eastward). You'll see handy references for the next full and new phases.

Gold and Blue

The next section is not just for astronomers. Photographers may find this information helpful. The "golden hour" is emphasized, the period when the Sun is low and light is warm. The "blue hour" is noted too, shortly after the Sun has set as everything takes on a cool, soft-blue tone.

The table shows the times for the lighting transitions with the coloured bar in the middle as a helpful visual aid. All this is based on your location and the date, of course.

Bar Graph

Evocative of many astronomy planning applications, the Twilight Bar panel shows a time scale with coloured blocks representing daylight, rise/set periods, and twilight. Inserted within the time scale is a bar for the Moon combining the lighting effects of the Sun and Moon.

Now we know how long it will be dark. In this example, the rise/set row shows yesterday's times, from 9:30 p.m. to 7:51 a.m. and then tonight's from 10:30 p.m. to the same time. This demonstrates how the Moon is infiltrating the evening. Full darkness starts at 11:11 p.m. when the Moon is below the horizon and runs until 6:08 a.m., the beginning of astronomical twilight. For the astrophotographer, that's seven hours of imaging time for faint fuzzies.

Wanderers

The final panel is for the Solar System. We see the rise, transit, and set times for each body along with the magnitude. Finally, the percentage column indicates the illuminated phase of the planet. It's subtle but the orbs on the left show phase.

Dark Mode

Since my December quick peek, ACW has been updated and now includes a night mode (Figure 3). Yes!

Figure 3 — Dark mode in Astro Clock Widget app can switch on automatically.

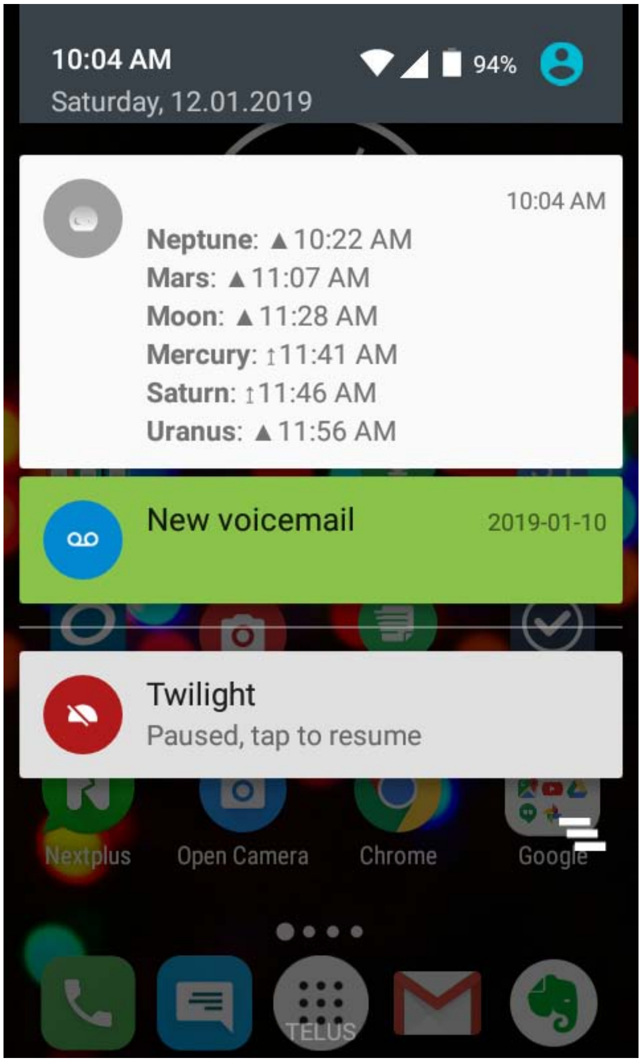

Figure 4 — Notifications from Astro Clock Widget showing a parade of planets.

This can be activated within the settings screen or quickly with the star-like button in the main interface. Dark mode can be forced on or off or made to activate automatically. That's clever.

Astro Clock Widget provides a dynamic display for the Android home screen to let you quickly check for planets or sidereal time.

Is your address correct?
Are you moving?

If you are planning to move, or your address is incorrect on the label of your Journal, *please contact the office immediately. By changing your address in advance, you will continue to receive all issues of* SkyNews *and the* Observer's Handbook.

(416) 924-7973
www.rasc.ca/contact

The 4x1 size widget is essentially the sky element we see in the app proper simulating the view south with the planets and Moon and rise/set times. There are specific settings for the widget such as transparency, scaling, and map-projection method. I tried resizing the widget, but it does not work correctly.

Alerts

Finally, ACW will issue notifications (Figure 4). You will see alerts in advance for Sun, Moon, and planets. All notifications are adjustable. By default, they are silent, but you can add audio effects.

More info

There is no onboard help that I can see, no user guide, nor information on the developer's website. I had to wing it to figure out some settings and to learn what some of the data was telling me. There is a page in Google+ Communities (but who knows how long that service will last). Author Luca Rubino is active with periodic updates. He told me will consider adding meteor shower alerts.

I quite like Astro Clock Widget. Is a very interesting app for people interested in *the numbers*. I like how it keeps me informed of Solar System events and twilight times. It's handy to know the Moon phase and which planets are visible. It's almost one-stop shopping.

Links

Download:
https://play.google.com/store/apps/details?id=it.lucarubino.astroclockwidget

Google+:
https://plus.google.com/communities/112166830352097257621

Bits and Bytes

The authors of Emerald Chronometer corrected me on their app: it does *not* run on Apple Watch. To clarify, they have versions that run on iPhones and iPads as well as a version that runs on Google Wear OS (previously called Android Wear) watch devices. I apologize for any confusion. ✶

Blake's interest in astronomy waxed and waned for a number of years but joining the RASC in 2007 changed all that. He volunteers in education and public outreach, supervises at the Toronto Centre Carr Astronomical Observatory, sits on the David Dunlap Observatory committee, and is a member of the national observing committee. In daylight, Blake works in the IT industry.

Observing Tips

406 Asteroids Over 60 Years

by Hugues H. Lacombe

[Note from Chris Beckett, RASC Committee Member: This month I begin my role as an Observing column editor for JRASC. I inherit the position from my long-time friend and mentor, Dave Chapman, who will remain a sounding board. Hugues Lacombe has been kind to send an article for my first month, an appropriate contributor, since Hugues and I go back to our time on the Observing Committee where he provided us with much needed guidance and support. Hugues also has many inspiring observing projects, I hope you enjoy his asteroid quest as much as I do.]

I recently observed my 400th asteroid. My very good friend Patrice Scattolin used to ask me why I was observing such uninteresting objects. What drove me on this quest? Light pollution and the *Observer's Handbook*. Here's what happened.

I became an amateur astronomer back in 1959, and I joined the RASC in 1964 or 1965. I've been a member on and off ever since. I began observing with a 3-inch cardboard-tube Edmund Scientific reflector. Then I graduated to an 8-inch Celestron SCT. That was back in 1979. But I didn't do much observing then because of work pressures.

When I retired in 2002, I joined the Centre francophone de Montréal (CfdeM). That's when I got into visual observing big time, or so I wished.

Because I'm a rather systematic type of person, I first completed the Explore the Universe program. I knew enough then to almost do it eyes closed. Then I tackled the Messier list. I couldn't do it all from my backyard in Montréal because of light pollution. So, I began making use of the CfdeM observing site in St-Valérien.

Back home in Montréal I could, of course, observe naked-eye planets and the Moon easily enough. But I wanted to do more, in spite of light pollution. That's when the Ephemerides for the Brightest Minor Planets in the *Observer's Handbook* caught my attention. As well, I began observing the brighter variable stars, another area of interest to this day.

By the end of 2007, I had chalked up 24 asteroids with my old C-8, using charts printed from Coelix, a computer-based planetarium program (*Observer's Handbook* 2019, p. 10), available in French and English.

A major highlight of that year: observing my first Earth-crossing asteroid, 2006 VV2, on 2007 March 30 (see picture of log book).

For a number of years, my wife and I had planned to move out to the country. In 2004, we had bought a small plot of land in Baie-Saint-Paul, in the Charlevoix region. Of note, this is inside the Charlevoix impact crater (*Observer's Handbook* 2019, p. 261), probably one of the few inhabited craters on Earth. In 2008, we had our house built. The following year the observatory was up, equipped with a C14.

Figure 1 — Hugues Lacombe and his 14-inch Celestron SCT in his Baie-Saint-Paul observatory

With my new toy, I first focused on the deep sky, completing the Finest NGC observing program and beginning the Herschel 400 list. I completed the latter in February 2014.

While progressing on these lists, I kept running into other asteroids. The numbers slowly grew. In particular I began looking for asteroids that were close together in the sky that I could see simultaneously through the eyepiece. I also enjoyed watching asteroids passing by deep-sky objects. I make it a practice every month of checking when such events occur.

Halfway through 2010, I noticed that I had almost bagged 100 asteroids. The adrenaline turned on, and in no time, I was up to that number. Then I was back to my normal routine, picking up an extra asteroid here, another one there. History repeats itself. As I drew close to the 200-asteroids mark, I got into another observing frenzy and quickly reached that goal in 2012.

At this time, I noticed that among the 200 asteroids, I had observed all numbered asteroid from (1) Ceres to (100) Hecate, save 9. That's when I began looking for specific asteroids, those that were missing to complete the "1 to 100" set.

Fast forward. I reached that objective and then went on to bag a total of 300 asteroids by 2015. Afterwards, and I'm still working on this challenge, I set upon observing all asteroids numbered from 1 to 200. It's working towards this goal that I reached the 400 mark (406 asteroids to this date).

But I have now reached a sort of observational ceiling. I am missing the following four objects to complete the list of asteroids numbered from 1 to 200: (132) Aethra (mag. 15.0), (143) Adria (mag. 14.6) in Scorpio (will be mag. 14.1 and reachable next summer in Aquila), (157) Dejanira (mag. 17.2), and (193) Ambrosia (mag. 16.0)

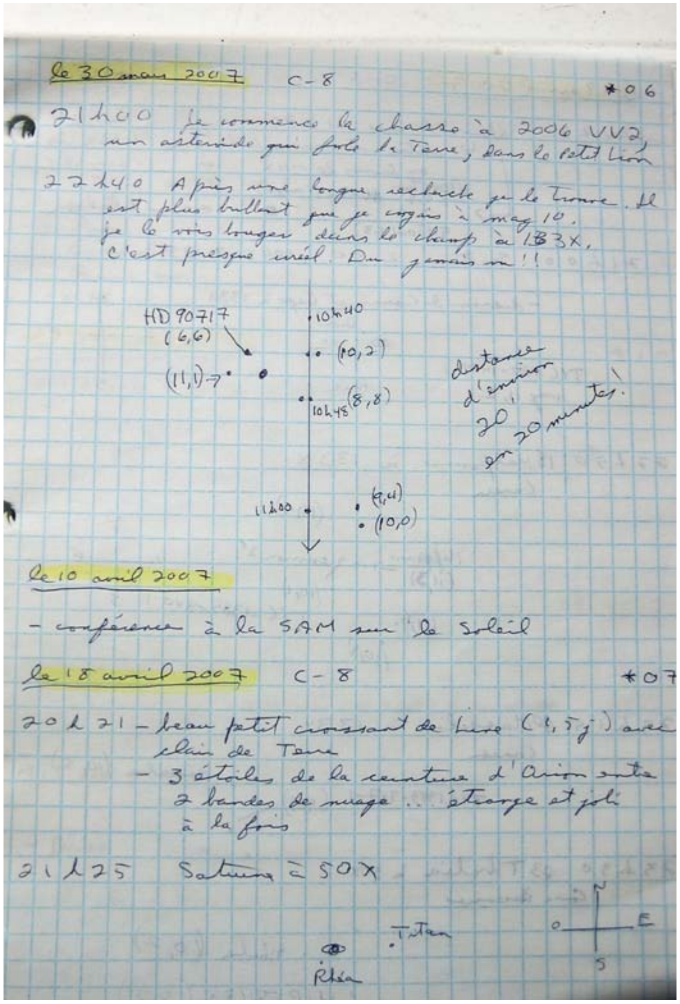

Figure 2 —The author's observing log from 2007 March 30.

These four are presently either too faint or not well positioned in the sky for me to catch them with my C14. I have to wait for their orbital position to improve before I can hope to see them.

I'm in no rush. In the meantime, I will continue to pick up higher-numbered asteroids from time to time as I pursue other interests. So far I have observed more than 1,400 lunar craters and over 1000 non-Solar System objects, and there is no end in sight. But then I'm in awe when I see others pursuing the Herschel 2500 list! Wow!

Hugues Lacombe is a former President of CfdeM and of the RASC Observing Committee. In 2008 he received the "Observer of the year" award from his fellow Québec visual observers.

Observing Tips

406 astéroïdes en 60 ans

Par Hugues Lacombe

J'ai récemment observé mon 400e astéroïde. Mon bon ami de longue date, Patrice Scattolin, m'a déjà demandé pourquoi j'observais des objets si inintéressants! Ce qui m'a lancé dans une telle direction? La pollution lumineuse et le *Observer's Handbook*. Voici comment ça s'est passé.

J'ai fait mes débuts en astronomie amateur en 1959 et je me suis joint à la SRAC vers 1964-65. Je suis membre de façon intermittente depuis. J'ai commencé à faire de l'observation avec un télescope réflecteur de trois pouces, avec tube en carton, d'Edmund Scientific. Puis j'ai amélioré mon sort avec un télescope schmidt-cassegrain de 8 pouces, de Celestron. C'était en 1979. Mais à l'époque mon travail me laissait peu de temps pour faire de l'observation.

Quand j'ai pris ma retraite en 2002, je me suis joint au Centre francophone de la SRAC / Société d'astronomie de Montréal. C'est à partir de ce moment que je me suis lancé dans l'observation visuelle du ciel de façon sérieuse, du moins c'était mon souhait.

Parce que je travaille de façon systématique, j'ai débuté avec le programme « Explorez l'Univers ». Je connaissais déjà suffisamment le ciel pour compléter ce programme presque les yeux fermés. Puis je me suis attaqué à la liste des objets Messier. À cause de la pollution lumineuse à Montréal, je ne pouvais la compléter de ma cour arrière. Je me suis donc mis à fréquenter le terrain d'observation du club à St-Valérien.

De Montréal il m'était facile, bien sûr, d'observer les planètes visibles à l'œil nu ainsi que la Lune. Mais je voulais en faire davantage, malgré la pollution lumineuse. C'est alors que je me suis intéressé aux éphémérides des planètes mineures brillantes, dans le *Observer's Handbook*. C'est également à cette époque que j'ai commencé à observer les étoiles variables les plus brillantes, un sujet qui pour moi demeure d'intérêt à ce jour.

Vers la fin de 2007 j'avais repéré 24 astéroïdes avec mon vieux C-8, me servant du logiciel de planétarium Coelix (*Observer's Handbook 2019*, p. 10) pour imprimer des cartes appropriées.

Un fait saillant de l'année 2007 : l'observation de mon premier géocroiseur, 2006 VV2, le 30 mars (voir photo du cahier d'observation).

Depuis longtemps mon épouse et moi avions pensé nous installer à la campagne. En 2004 on s'est acheté un terrain à Baie-Saint-Paul, dans la région de Charlevoix, à l'intérieur du cratère éponyme (*Observer's Handbook*, p. 261), probablement l'un des seuls cratères habités sur la planète. En 2008 on s'est fait construire. L'année suivante l'observatoire était érigé, avec un télescope C-14.

Avec mon nouveau jouet, je me suis concentré sur les objets du ciel profond, complétant la liste « *Finest NGC* » et amorçant la liste « *Herschel 400* » que j'ai terminée en février 2014.

Tout en avançant dans l'observation des objets qui composent ces listes, je continuais à voir d'autres astéroïdes. Le nombre d'astéroïdes observés croissait lentement. Je me suis mis à m'intéresser aux astéroïdes qui étaient près l'un de l'autre dans le ciel et que je pouvais voir simultanément à l'oculaire. J'aimais aussi observer les astéroïdes qui étaient proches des objets du ciel profond. Chaque mois je vérifie les occasions d'en observer.

À mi-chemin de l'année 2010 je me suis aperçu que j'avais observé presque 100 astéroïdes. L'adrénaline s'est mise de la partie et j'ai atteint ce plateau en un rien de temps. Puis j'ai repris ma routine, observant de nouveaux astéroïdes de temps en temps. L'Histoire a tendance à se répéter. Quand je me suis rapproché du plateau des 200 astéroïdes, je suis parti à l'épouvante et j'ai atteint cet objectif en 2012.

C'est alors que j'ai réalisé que parmi ces 200 astéroïdes, j'avais observé tous les astéroïdes numérotés de (1) Cérès à (100) Hécate, sauf neuf. C'est à ce moment que j'ai commencé à vouloir observer des astéroïdes spécifiques, ceux qui me manquaient pour compléter la liste des 100 premiers.

Faisons un bond en avant. J'ai atteint cet objectif puis, en 2015, j'en étais rendu à mon 300e astéroïde. Par la suite, et je planche encore pour y arriver, je me suis mis en tête d'observer tous les astéroïdes numérotés de 1 à 200. C'est en cherchant à atteindre ce but que je me suis rendu à mon 400e astéroïde (406 à ce jour).

Mais j'ai atteint un mur. Il me manque les quatre astéroïdes suivants pour relever le défi que je me suis donné : (132) Aethra (mag. 15,0), (143) Adria (mag. 14,6) dans le Scorpion (sera de mag. 14,1 et donc atteignable l'été prochain dans l'Aigle), (157) Dejanira (mag. 17,2) et (193) Ambrosia (mag. 16,0).

Ces quatre astéroïdes sont présentement soit trop faibles ou mal situés dans le ciel pour que je puisse les observer avec mon C-14. Je dois attendre qu'ils se déplacent sur leur orbite de sorte que je puisse espérer les observer.

Je ne suis pas pressé. Entre temps je vais continuer à observer ici et là d'autres astéroïdes dont les numéros sont plus élevés, alors que je planche sur d'autres programmes d'observation qui m'intéressent. Jusqu'à maintenant j'ai observé plus de 1 400 cratères sur la Lune et plus de 1 000 objets à l'extérieur du système solaire, et les possibilités sont infinies. Cela dit, je suis tout à fait ébloui par les observateurs qui travaillent la liste « *Herschel 2500* »! Wow! ✶

Note : Hugues Lacombe est un ancien président du Centre francophone de la SRAC / Société d'astronomie de Montréal. En 2008 il a obtenu le Prix « Observateur » du Rendez-vous des observateurs du ciel (ROC).

John Percy's Universe

Pseudoastronomy

by John R. Percy FRASC
(john.percy@utoronto.ca)

Pseudoscience is defined by the Merriam-Webster dictionary as "a system of theories, assumptions, and methods erroneously regarded as scientific." The operative word here is *erroneously*. It is found across the sciences[1] and is especially problematic when it affects our health or environment. It's used to promote some health products ("snake oil"), and by some climate change deniers.

Astronomy has more than its share of pseudoscientific connections, in part because of its public interest, and its many connections with history, culture, and other disciplines. For decades, Professor Andrew Fraknoi (Figure 1)—an RASC Honorary Member—has been a leader in debunking pseudoastronomy. I recommend any of his writings and resources on the topic (see note[2] and Fraknoi, 2004). *Skeptical Inquirer*, published bi-monthly by the Committee for Skeptical Inquiry (www.csicop.org/si), formerly the Committee for the Scientific Investigation of Claims of the Paranormal, has been a valuable antidote to pseudoscience for more than 40 years. Its editors and authors deserve our thanks. For years, Phil Plait's badastronomy.com was a useful and popular resource on pseudoastronomy, and he continues his good work as "The Bad Astronomer." Pseudoastronomy overlaps with astronomical misconceptions (Percy, 2015) in the sense that many people believe (incorrectly) that the pseudoastronomy is scientifically correct.

Astrology was initially an attempt to understand the nature and cause of events on Earth. It connected these events to the gods, represented by the Sun, Moon, planets, and stars. Now it's thought of more as a "predictive" pseudoscience, linked to people's personalities. For millennia, astronomy and astrology were almost indistinguishable but parted company when modern science blossomed in the Renaissance. Sadly, astrology is still with us in a big way, even though it has no scientific basis or evidence, other than the powerful placebo effect. But "it's not in the stars."

Moon madness is a variant of this. It's the belief that various forms of madness peak at full Moon. There is no evidence for this. It may be a case of observational bias: if something mad happens, and the Moon is visible and bright, then you notice it. If the Moon is not visible and bright, you don't. This is an example of a very serious bias in some scientific studies—especially medical and psychological studies: positive results or observations get published, negative ones do not, even if they are important.

Figure 1 — Professor Andrew Fraknoi, Foothill College, California, an Honorary Member of the RASC, and an eloquent and effective debunker of astronomical pseudoscience.

Archaeoastronomy has been a fruitful spawning ground for pseudoastronomy, largely because we know so little about the astronomy of pre-technological civilizations. Most evidence has been lost in time, and some narrowly focused scholars (including astronomers) have a bad habit of reading their own interpretations into whatever evidence survives. Nevertheless, archaeoastronomy is a vibrant, legitimate, *interdisciplinary* topic, of great interest to both scholars and the public (Percy, 2016).

Erich von Däniken (born 1935) is a Swiss author and hotelkeeper (and convicted fraudster and embezzler and alleged plagiarist). He has written numerous books (notably *Chariots of the Gods*) which maintained that extraterrestrials were responsible for many of the artifacts and achievements of our ancestors—the Pyramid of Cheops, for instance, and perhaps even the concept of religion. These ideas have been thoroughly debunked (e.g. Story, 1980), but his books continue. He has received prizes and awards, including an honorary doctorate. Documentaries based on his books continue to air on the History Channel and the dubiously named "Discovery Channel."

Speaking of the alleged work of extraterrestrial visitors: *crop circles* were a phenomenon that came and went, a generation ago. Like many such phenomena, they were fanned by media coverage but were of less interest after the confessions of the terrestrial pranksters who created them.

Flying saucers—one interpretation of *Unidentified Flying Objects* (UFOs)—are perhaps the most potentially significant pseudoscientific claim, since the proof of extraterrestrial life, especially here on Earth, would be the most exciting scientific discovery ever. I wish! But decades of intensive surveillance of the sky by astronomers, meteorologists, the military, and others have failed to turn up any convincing evidence. And if millions of Americans are being kidnapped by extraterrestrials, why isn't the FBI doing anything about it? If UFOs exist and are being hidden, I can't believe that this wouldn't get leaked. But UFOs are alive and well in current TV series such as *Roswell* and *Project Blue Book.* The Center for UFO Studies, originally established by astronomer Allen Hynek, is one of several organizations that continue to compile UFO reports—just in case.

Then there was the *face on Mars.* On one of thousands of low-res images of Mars from orbit, there was a feature which looked vaguely like a "human" face—presumably the work of artistic Martians. But on higher-res images, it was clearly a natural feature. So, this phenomenon can be classified along with other "things that NASA (and the government) is hiding from us," including the belief that the Apollo Moon landings were faked, that there are alien corpses in an aircraft hangar in Nevada, and there's an unseen massive planet in our Solar System, hiding behind the Sun.

Also speaking of extraterrestrial influences: there's the much-more-intriguing "Velikovsky Affair," which many older readers may remember. Immanuel Velikovsky (1895–1979) was a Russian-American psychiatrist, psychoanalyst, and independent scholar. He spent much time and effort trying to reconstruct and reconcile the chronologies of ancient mythology, archaeology, and written sources, including the Bible. From these studies, he concluded that Earth had suffered catastrophic global events, resulting in e.g. the Deluge, the destruction of Sodom and Gomorrah, and Joshua's "Sun standing still." He attributed these to a wholesale rearrangement of the Solar System during the last few millennia, in which Venus erupted from Jupiter, made a close pass by Earth, then settled into its present nearly circular orbit, in violation of all the laws of motion and gravity. To deal with this problem, Velikovsky claimed that celestial motions were actually dominated by electromagnetic effects.

Velikovsky's work might have passed unnoticed, but certain eminent astronomers were distressed by his impossible planetary scenario, and threatened a textbook boycott of Macmillan, Velikovsky's publisher. Instead, his *Worlds in Collision* was transferred to Doubleday, and became a best-seller. By the 1960s, Velikovsky became a "persecuted" hero of the counter-culture and was invited to speak on many university campuses (including mine) by people who should have known better. In 1972, the CBC aired a one-hour documentary about him and his work, and the BBC soon followed. His cause was taken up by various individuals and groups but, after his death in 1979, his work gradually faded from memory.

Velikovsky took his work seriously and worked hard to rebut his critics. It's said that he was particularly annoyed at the flippant tone that Carl Sagan used in his debunking. It's generally agreed by scholars also that, unlike von Däniken, Velikovsky was neither a charlatan nor a crank. Nevertheless, his astronomical claims are completely untenable, His revised chronology of antiquity has been thoroughly rejected by scholars, as have the specifics of his theories of global geological catastrophes. To give him credit, though, scientists and the public are now much more aware of the reality of impacts by asteroids and comets—but not during recent times.

Speaking of catastrophes, *The Mayan Apocalypse* came and went uneventfully on 2012 December 21. To me, it was like worrying that, when my car's odometer turned over at 99,999 km, my car would explode. Frankly, I was more concerned about *Y2K*, since it depended on the ability of fallible human beings to program the world's electronic devices correctly.

Then there's *creationism.* I have neither the space nor the knowledge to write an in-depth discussion on science and religion, but creationism can certainly venture into the realm of pseudoscience when it tries to use dubious evidence, especially for *young-Earth creationism.* In any case, young-Earth creationism is just one interpretation of one scripture of one religion. See (3) for an excellent resource.

Reflections

What are we to learn from these several decades of pseudoastronomy? One is that it doesn't go away as scientific knowledge increases. As in the "clout the rat" game, it just reappears in some other guise.

And it doesn't help to try to censor it or boycott its publisher. As "the Velikovsky affair" showed, that just attracts more attention and sales. It also reflects badly on those who do it.

Reputable newspapers publishing daily horoscopes claim that it's "for entertainment only." We might be tempted to assume that all pseudoscience is "for entertainment *only.*" It certainly occupies a large chunk of the "popular" media. Unfortunately, many people believe it. Surveys consistently show that up to half of Americans "believe" in astrology, visits from extraterrestrials, and young-Earth creationism.

We astronomers are obligated to deal with it somehow. Asking us to spend months or years researching an effective rebuttal is asking a bit much, especially as the resulting rebuttal is not likely to sell many copies. There have been excellent rebuttals of von Däniken's (Story, 1980) and Velikovsky's (Goldsmith, 1977) work, but it's not clear that they had much impact. That's where we depend on our colleagues such as Andrew Fraknoi and Phil Plait and Carl Sagan and others who are or were willing and able to use their exceptional skills as communicators.

We should all know the basic evidence against the main pseudoastronomy topics. Our students will probably ask about them. We might be able to use their interest as an attraction to more serious astronomical topics. Fraknoi (2004) lists some classroom activities that can be used to debunk these topics.

We can't all be Carl Sagan, but we can all encourage young (and older) astronomers to engage with the public, and train them to do so, effectively. Also, since so much pseudo-astronomy depends on interdisciplinary connections, it's important to be willing and able to collaborate with scholars in other disciplines. We must also remember that science is open-ended in that something that may seem like pseudoscience now may turn out to have some basis in reality. But there has to be evidence, and "extraordinary claims require extraordinary evidence"—a phrase popularized by Carl Sagan.

Most of all, let's not forget that the Universe that astronomers observe and study and understand is as exciting as anything that pseudoscientists have described—and it's real! It's based on evidence and critical thinking. Let's reach out to the public and say so! ✶

Notes

1. en.wikipedia.org/wiki/Pseudoscience

2. bit.ly/pseudoastro

3. aas.org/files/resources/An_Ancient_Universe.pdf

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John Percy FRASC is Professor Emeritus, Astronomy & Astrophysics and Science Education, University of Toronto, and a former President (1978–80) and Honorary President (2013–8) of the RASC.

CFHT Chronicles

Welcome 2019!

by Mary Beth Laychak, Outreach Program Manager, Canada-France-Hawaii Telescope.

2018 was another excellent year for science at CFHT and we are starting 2019 off strong!

A SPIRou Update

On 2019 January 24, SPIRou passed its final acceptance review. It is now ready to begin science operations. As regular readers of our column will recall, SPIRou arrived at CFHT last January in 13 crates amid one of the worse winters on Maunakea in memory. Over the past year, SPIRou was reassembled and the science team and CFHT staff tested its performance. They looked at the wavelength domain, resolving power, spectral response, radial velocity precision and polarimetric capabilities. They compared the measured performance to the expected performance as part of the final acceptance.

The acceptance tests show that SPIRou behaves as expected, apart from two areas. First, the throughput is a little lower in the bluest spectral range than anticipated. Recall that SPIRou is an IR instrument, so the bluest range is the YJ photometric band spanning 1-1.4 microns. Secondly, the instrument has a brighter thermal background in the reddest spectral regions. The brighter background comes from the warm components of the instrument whose thermal emission becomes strong at 2.3 microns and beyond, compared to the flux of the dim stars that SPIRou will observe.

SPIRou meets expectations as a spectropolarimeter. The instrument's current velocimetric precision is 2 m/s rms, with data reduction and the correction of the telluric lines from the Earth's atmosphere as the current limiting factor. In a nutshell, it is ready for science.

Figure 1 — Team Canada take 2 at the New Horizons *flyby (left to right) Frederic Pelletier, Stephen Gwyn, and JJ Kavelaars.*

The review panel included Magali Deleuil (AMU/LAM), panel chair Pierre Kern (CNRS/INSU), Gaspare LoCurto (ESO), Guy Perrin (CNRS/INSU), John Rayner (UH), Andy Shenis (CFHT director of engineer), panel co-chair Doug Simons (CFHT executive director), and Michael Toplis (OMP). With the green light, SPIRou will begin science operations on February 11 (after writing this column, but before publication).

SPIRou has 50 nights scheduled in the 2019a semester and 300 nights allocated over the next four years for the SPIRou Legacy Survey. It is an exciting time for the instrument and we look forward to its discoveries!

Now on to our 2018 Science Recap:

On New Year's Eve, the NASA *New Horizons* spacecraft passed by an object known as 2014 MU69, nicknamed Ultima Thule. The name comes from Greek and Roman literature and map-making, meaning the farthestmost northern place, almost mythical in its existence. It's an appropriate nickname for the object, as the flyby of 2014 MU69 was the farthest planetary flyby in history.

The *New Horizons* mission rocketed to fame in July 2015 when it passed by Pluto. The flyby gave us the best images of Pluto to date and showed everyone the dwarf planet's "heart," a feature on Pluto's surface that became the arguably the most famous image of Pluto. After the Pluto flyby, the *New Horizons* team received a mission extension to continue studying the outer Solar System through 2021. With the mission extended, the team began the search for potential new targets for *New Horizons*. The search for potential targets utilized many of the telescopes in the world, including the biggest cameras on Maunakea at the Canada-France-Hawaii and Subaru telescopes.

As science would have it, astronomers used CFHT to conduct a survey of the outer Solar System called Canada-France Ecliptic Plane Survey (CFEPS). Started in 2003, it provided the very first detailed map of the outer Solar System. Two of the astronomers leading the survey, JJ Kavelaars from Canada and Jean-Marc Petit from France, used the CFEPS map to determine which part of the sky was most likely to contain an object that met *New Horizons*' criteria.

In 2014, the *Hubble Space Telescope* turned toward the CFEPS field and discovered 2014 MU69. (I'll be referring to the object as MU69 for the rest of the article.) MU69 is very faint, very small—roughly just 30 km in diameter—and about 6 billion km away from Earth. Only the *Hubble Space Telescope* could find the object, but they would not have known where to look without the CFHT data.

Finding MU69 was hard, getting there took very, very careful planning and another excellent map. Once *New Horizons* passed by Pluto, the spacecraft had to make an early and precise change of course to reach MU69. While *Hubble* is an excellent telescope, it is hard to determine exactly where *Hubble* is pointing to the level of precision needed for the course correction. Using CFHT data, another Canadian astronomer, Stephen Gwyn, produced a catalogue of stars. In Gwyn's catalogue, the position of the stars is known to 20 milliarcseconds or roughly the diameter of Queen Elizabeth's eye on a Canadian dime one kilometre away (thanks Stephen for doing the math). Needless to say, it's an incredible map. Gwyn's precise stellar map was used to calibrate the *Hubble* image, which allowed the *New Horizons* team to calculate the exact orbit of MU69. Once they had MU69's orbit, the team changed the path of *New Horizons*.

Figure 2 —Team Canada at New Horizons *flyby, (left to right) Stephen Gwyn, JJ Kavelaars, Alex Parker, and CFHT outreach manager Mary Beth Laychak (me!)*

"Using CFHT data, we were able to tell the *New Horizons* team where to look for MU69, and after they found it, we used maps generated using CFHT to tell the team exactly where MU69 was!" said Gwyn.

Astronomers, known as the *New Horizons* hazard watch team, used the probe's own camera to look for potential hazards orbiting the object. *New Horizons* is travelling at 50,000 km/h. At that speed, even a piece of dust the size of a rice grain can cause catastrophic problem to the piano-sized *New Horizons* probe. Early in December, *New Horizons* was given the go ahead to stay on its path to MU69. The probe passed 3500 km from the surface of MU69 at 12:33 p.m. EST on December 31.

Canada has another connection to the *New Horizons* mission: the project's chief navigator is Frederic Pelletier, a Québec City native. Pelletier and his eight-person team are responsible for making sure *New Horizons* is on course, not only for the flyby, but as the probe continues past MU69.

I was with Dr. Gywn and Dr. Kavelaars and their families at the Johns Hopkins' Applied Physics Lab for the flyby on New Year's Eve and on New Year's Day when the first pictures were released. Before the flyby, APL hosted several talks by the *New Horizons* team and showed one of the last images *New Horizons* took of MU69 before the flyby. Unlike the Pluto flyby, MU69 was only eight pixels on the last image before flyby. It was clearly elongated and looked a bit like an eggplant. Pelletier could not share any of the telemetry information with us, but Gwyn noticed he was in a pretty good mood the night of the flyby. We decided that was a good sign that *New Horizons* was on the right course. That's the perk of sitting next to someone who knows the chief navigator.

When the clock struck midnight, everyone celebrated the start of 2019, but the celebration kicked up a notch during the countdown to closest approach. Because of the distance between Earth and *New Horizons*, we did not see any images that evening. It takes six hours for the data to come back to

Figure 3 —Cheers to acceptance! The CFHT staff celebrates SPIRou's acceptance with a little bubbly. (left to right) Greg Barrick, SPIRou project manager at CFHT, Claire Moutou, CFHT SPIRou instrument scientist, Pascal Fouque, CFHT astronomer, Andy Shenis, CFHT director of engineering.

Earth through NASA's Deep Space Network. Everyone went home and reconvened at 10 a.m. the next day to hear if *New Horizons* had survived the encounter.

The mood in the room the next morning was tense but excited. The auditorium screen displayed a live feed into mission control, located at another location on APL's campus. As data from the spacecraft was received, the team in mission control updated the mission operations manager, or MOM, Alice Bowman. We watched as more and more subsystems were declared "green," until finally Bowman announced that *New Horizons* was alive, well, and ready to send data home.

Then everyone cheered just like in every space movie. It was amazing.

A bit later, the entire *New Horizons* science team, including Gwyn, Kavelaars, Pelletier and Alex Parker, a former grad student of Kavelaars, took a victory lap around the auditorium. For all the science team members it was an amazing moment, but they really just wanted to see the pictures.

New Horizons sent home preliminary, highest-priority data before losing contact for a few days as it moved behind the Sun. The data stream resumed on January 9, and the *New Horizons* team anticipates it will take 20 months (!) to download all the data. Why so long? The download speed is one to two kilobytes per second.

So what do we know about MU69 today? The first images showed us a snowman or BB8 from *Star Wars*. The two lobes comprising MU69 are a contact binary, meaning they gravitated towards each other until they touched. No collision needed. The detailed images are revealing new topographic details including small pits 0.7 km across and a larger, circular feature about seven kilometres in size. These features may be impact craters, collapse pits, or evidence of ancient venting of materials.

The *New Horizons* team released a movie on February 8 (as I'm writing this). This latest image shows the departing view of the spacecraft. Instead of a snowman, the lobes look less round in this from-behind image. The larger lobe is flatter, looking more like a pancake and the smaller lobe is "shaped like a dented walnut."

More information about MU69 will be revealed over the next 20 months as images trickle in. I am excited to see what our new little KBO friend shows us. ✶

Mary Beth Laychak has loved astronomy and space since following the missions of the starship Enterprise. She is the Canada-France-Hawaii Telescope Outreach Coordinator; the CFHT is located on the summit of Maunakea on the Big Island of Hawaii.

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Dish on the Cosmos

Repeated Repeating Fast Radio Bursts

by Erik Rosolowsky, University of Alberta
(rosolowsky@ualberta.ca)

This column combines two topics that have already appeared in this space: the Canadian Hydrogen Mapping Experiment (CHIME, April 2016) and repeating fast radio bursts (FRBs, April 2017). The CHIME Telescope is a novel radio-telescope design where the principal goal is to the detect sound waves of matter in the early Universe. However, several Canadian astronomers realized that the facility could be applied to several other corners of astrophysics, including the study of FRBs. FRBs are a relatively recently discovered phenomenon that is largely explained by the name: they are millisecond-long bursts of radio waves from space.

FRBs have driven a lot of great excitement in the astronomical community in a race to discover what is causing these strange signals from space. The original discovery of FRBs was quite suspicious, living up to the scientific principle that nearly all discovery begins with "Hmmm, that's weird," rather than the more classic "Eureka!" The bursts were originally only seen with a single telescope, suggesting some local interference at that telescope. However, with dedicated efforts, FRBs began to be detected at other facilities and were confirmed to be astronomical in origin. A major breakthrough came in 2016 when a previously discovered FRB source was discovered to repeat its burst. This discovery immediately ruled out explanations for the bursts that relied on explosive or destructive events like supernovae. Whatever was happening only had a minor effect on the emitting objects.

Theoretical astrophysicists have an arsenal of explanations for strange phenomena, and FRBs showed all the signs of arising from a "compact object" meaning a black hole, neutron star, or white dwarf. These are the usual suspects because they have extreme densities of matter, leading to strong gravitational fields that can drive highly energetic bursts. The millisecond-long timescale makes us suspect neutron stars. Neutron stars come from stars that are sufficiently massive to end their lives with a supernova but with low enough mass to avoid collapsing into a black hole. These stars have masses between 1.5 and 2 times the mass of the Sun but with a radius of only 12 km. This huge mass density brings enough gravitational force to pull magnetic fields together, concentrating the fields into high-energy densities. The small size scales mean that the neutron star environment can react quickly to abrupt changes like ruptures in the star's crust or a sudden bubbling of the magnetic field, leading to bursts of energy. Thus, neutron stars fit the profile of an object that can create a sudden burst of radio emission that is bright but only milliseconds long and does not require destroying the object. After the first repeating FRB was discovered, most astronomers suspected that neutron stars were going to be the answer to the puzzle.

Confirmation or rejection of the neutron-star model is going to just be a matter of numbers. While astronomical headlines frequently describe the "first" or "oldest" or "brightest" objects discovered, most of the actual astrophysics happens by studying large numbers of objects. This strength in numbers comes because of our short lives compared to the time it takes for the cosmos to change. Astronomers cannot watch one object over its full lifetime of evolution, so instead they find many objects to infer evolution. While FRBs are fast enough

Figure 1 — The CHIME Telescope is designed to provide a large collecting area while also surveying a large part of the sky above the telescope, allowing efficient surveying of the radio sky for FRBs. Image Credit: CHIME

to observe, we cannot watch through the long time it takes to set the stage for FRBs to happen. Thus, we urgently needed more repeating FRBs to understand their origins.

The CHIME Telescope (Figure 1) was a nearly perfect facility to start searching for many FRBs. It was designed to watch a huge part of the sky as it rolled above the telescope for five years, building up the faint signature of the early Universe. A few key Canadian astronomers, including Vicky Kaspi from McGill and Ingrid Stairs at UBC, worked hard to attach a second signal-processing system to the CHIME Telescope that searched the incoming data stream for signatures of the FRBs. The primary CHIME mission collects data slowly, building up a signal over time. FRB searches require slicing up the signal into tiny chunks of time at different radio frequencies to find FRBs. The second system is designed to carry out this signal searching efficiently, only retaining little sections of the data around detected FRBs.

In the summer of 2018, the CHIME FRB system was turned on and it began finding FRBs immediately. The results quickly proved that the new approach would be a success. In just a few weeks of operations, CHIME discovered 13 new FRBs with the prototype system and they have begun major operations that continue to collect new detections.

This search process would be relatively simple except for the complicating effects of plasma dispersion. The space between stars and galaxies is occupied by low-density matter, most of which is ionized where the electrons and protons that compose atoms are separated from each other. When a radio wave passes through this plasma, the electric field in the electromagnetic wave pulls the charged particles apart. Since the electrons are much less massive than the protons, they get moved faster. The moving electric charges alter the local electric field, which has the effect of slowing down the radio wave. Radio waves travel at the speed of light in a vacuum, but the ionized gas isn't a vacuum, so the waves travel a little slower through the plasma. The difficulty arises because the plasma dispersion slows down low-frequency radio waves more than high-frequency waves. A single burst of radiation from an FRB will give off radio waves at a broad range of frequencies, but the waves with the 800 MHz frequencies that CHIME detects will travel through space and arrive ahead of 400 MHz waves. Fortunately, the difference in time only depends on the frequencies of waves that we know and the amount of plasma between the emitter and the telescope. This amount of material is quantified in a measurement called the dispersion measure. Dispersion smears out bursts, making them hard to detect. But once they are detected, the time profile of the burst can indicate how much plasma is between the observer and the emitter. This property makes it possible to use the dispersion to find out how far away the FRB sources are. The results suggest that the FRBs detected so far originate outside of our galaxy, but likely in other relatively nearby galaxies.

The dispersion measure provided a key part of the evidence for when CHIME discovered a second repeating FRB. The resolution of the CHIME Telescope is poor, and it cannot distinguish individual galaxies from each other. Thus, if it found a possible repeating FRB from one direction on the sky, it could easily be different objects found in the same part of the sky. However, if these FRBs originated in different galaxies, then the dispersion measures of each of the pulses would be different. CHIME was able to find an FRB that appeared to repeat from the same part of the sky, and critically, each burst had an identical dispersion measure as the other bursts. Thus, this was almost certainly the same object giving off repeat FRBs. There still isn't a clear resolution of what the objects are, but this single repeating object was one of the first 13 objects that CHIME found. With CHIME expected to find thousands of FRBs, several more repeaters will be discovered, winning the numbers game and resolving the mystery of the FRB.

Read more:

https://arxiv.org/abs/1901.04524

https://arxiv.org/abs/1901.04525 ✶

Erik Rosolowsky is a professor of astronomy at the University of Alberta where he researches how star formation influences nearby galaxies. He completes this work using radio and millimetre–wave telescopes, computer simulations, and dangerous amounts of coffee.

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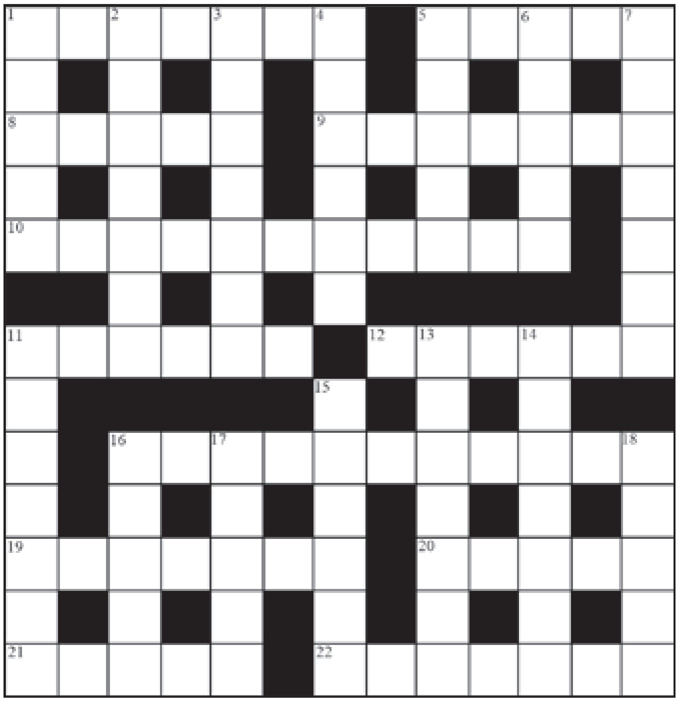
Astrocryptic

by Curt Nason



ACROSS

1. Picture me aging around a pulsar (7)
5. Take one for an enterprising helmsman (5)
8. Get a shower in your side of the bed (5)
9. She found a timely brightness relation when she cooked a vittle (7)
10. Take a turn at finding actors to figure a mirror (4,7)
11. Global disaster from a demonic star (5,1)
12. Prim stellar motion (6)
16. The IAU would rarely select opium for a constellation (11)
19. Zeus casually sported a colourful stain (3,4)
20. Atlas was one around Saturn (5)
21. Outlasts bright patches on Ceres (5)
22. Porters reassemble and file them after outreach events (7)

DOWN

1. Celestial mechanic helped get a fix on Ceres (5)
2. Mass problem becomes a dark matter (7)
3. Draconic period when mythical dragon turns about Index Catalogue (7)
4. Add cabbage head to salsa and stir for a fairly bright red asteroid (1,5)
5. Disassemble a kit before one is in Grus (5)
6. Blazingly bright light for stars that lie between K and G (5)
7. Whole number required to turn it green (7)
11. A northeast star variably shines low in summer (7)
13. Need extraordinary proof to locate an observatory here (7)
14. Take a tip from Dubhe (7)
15. Hoffman and Beatty bombed in northern Venus (6)
16. Dial turns after time from stretching force (5)
17. Irregular pulse detected under Orion (5)
18. Basin highly impacted by the Moon (5)

Answers to February's puzzle

ACROSS

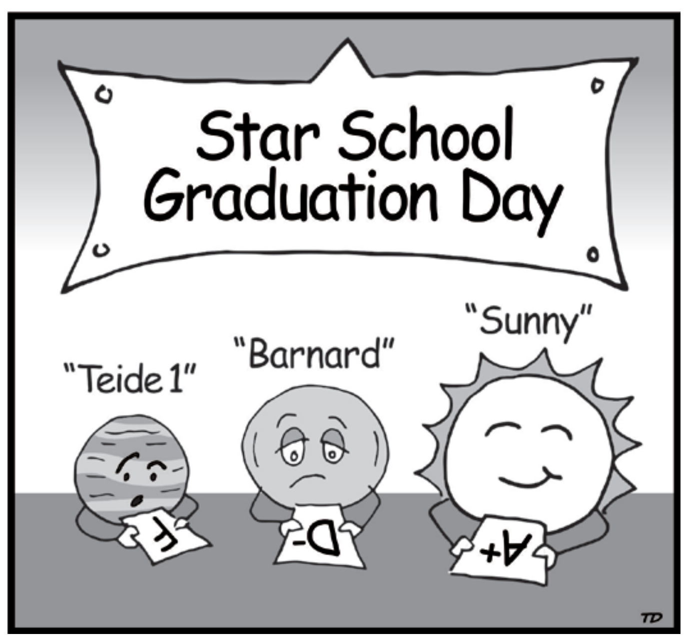
1 GEMINID (anag); **5** MAJOR (2 def); **8** METIS (anag); **9** MIRANDA (Mir+and a); **10** WHOOPING CRANE (anag+def); **12** ANSAE (an(n)ag); **13** LACUS (anag-a); **15** SPACE CAPSULES (2 def); **18** AQUARII (anag-o + ii); **20** INDUS (in+rev); **21** NIELS (anag); **22** NULLIFY (anag)

DOWN

1 GAMOW (GA+def); **2** METEORS (anag+s); **3** NOSEPIECE (2 def); **4** DEMONSTRATION (anag); **5** MIR (Mira-a); **6** JENNA (2 def); **7** READERS (2 def); **11** CELESTIAL (r=l+anag); **12** ALSHAIN (anag+L); **14** CHLADNI (ch+lad+rev **16** AMUSE (2 def); **17** SISSY (hid); **19** RAS (2 def)

It's Not All Sirius

by Ted Dunphy



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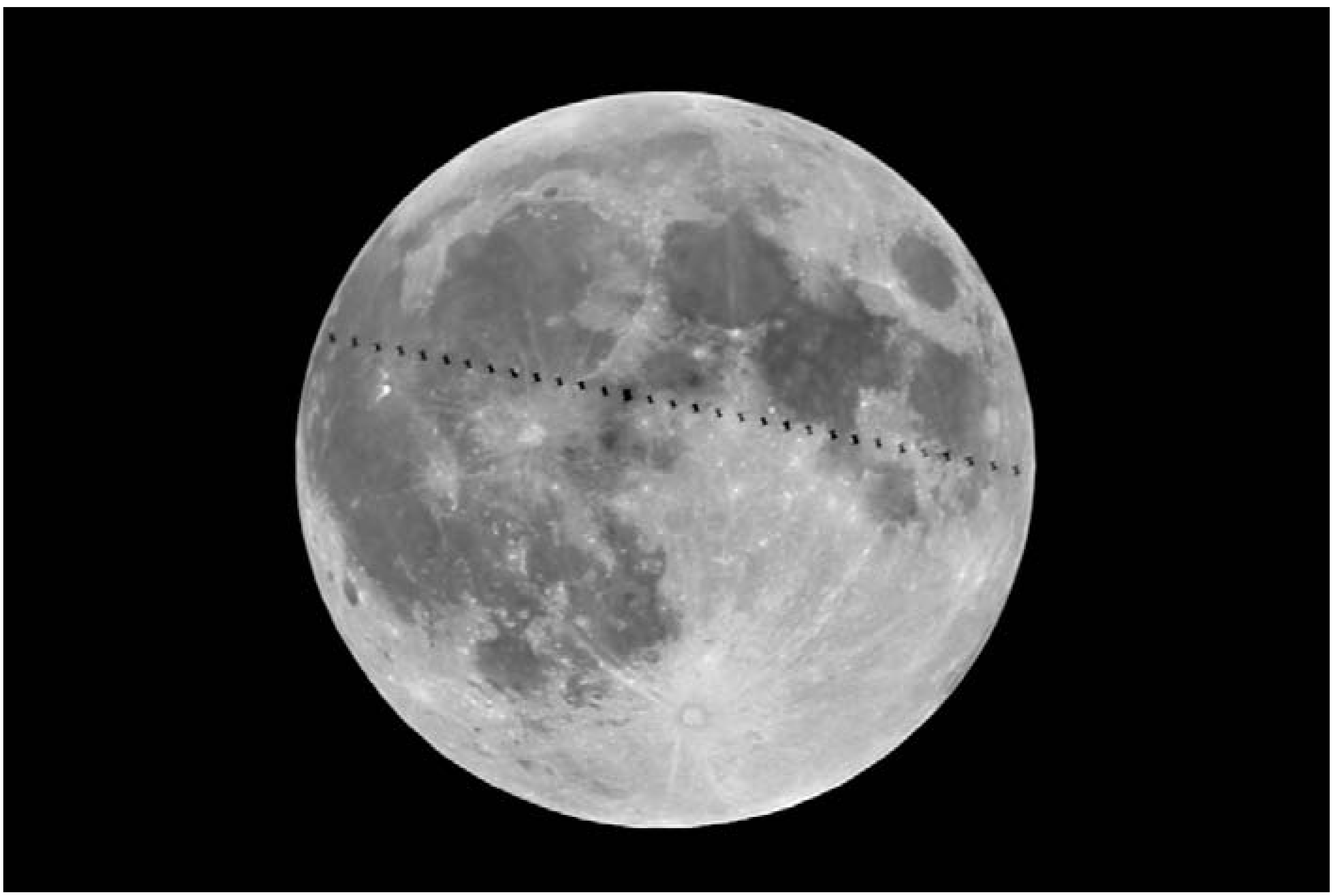

It's not easy imaging an ISS lunar transit, but Kevin Watson was up to the task. This is a composite image of the International Space Station *transiting the moon, about three hours before the total lunar eclipse on January 20. He used Images Plus, Photoshop and used 31 frames extracted from HD video (1920x1080 @ 24 fps), ISO 200, 1/3200 secs. Background is a stack of all 31 frames. He used a Nikon D7000, Celestron Omni XLT 150 (6″ ƒ/5 reflector) on CG4 mount.*

Journal

Roman Kulesza also braved the cold temperatures to enjoy the total lunar eclipse. He imaged the event on January 21 at 12:24 a.m. The exposure is just four seconds using his homemade 10-inch telescope at ƒ/5 and a modified Canon Xsi camera.