The Journal of The Royal Astronomical Society of Canada

Journal

Le Journal de la Société royale d'astronomie du Canada

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IN CANADA

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- Finding Unknown Asteroids
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- Light Speaks to Us
- Best Project Award at the 2022 Canada-Wide Science Fair

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Royal Astronomical Society of Canada

Société Royale d'Astronomie du Canada

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This incredible image of the Pleiades was taken by Dave Robitaille from his backyard in St-Rene de Matane, Québec, on 2022 October 22. Dave used a Celestron RASA 11 at ƒ/2.2 on a Sky-Watcher EQ8 Mount with an ASI2+600 MC Pro camera cooled at –20 °C. Total exposure was 60 × 120 seconds, stacked. Processing was done in PixInsight.

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.

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President's Corner

Presentation Pointers

by Charles Ennis,
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Perhaps you're scheduled to do a presentation on an astronomy topic dear to your heart. You want it to be successful. But how can you determine if what you want to communicate is getting through? The audience's reaction to your presentation is one indication, but can you set it up to ensure that their reaction is going to be a positive one? If you see that people are nodding off in the audience, it may be too late to recover. Maybe you get feedback later that can help you with future presentations, but can you get that while your presentation is in progress?

Ask yourself some questions: What are your audience's expectations? Do they match yours? What do they want from your presentation? How much do they already know about your subject? They may be looking for answers outside of what you expect. You may want to tell them how the JWST works. Do they know that it is an infrared telescope? Do they understand why it needs to be one? Do they understand how far away it is parked in its Lagrange-point orbit? Do they know what a Lagrange point is? Do they appreciate the scale of the Universe around them? You may be excited about telling them what this space telescope has done, but they may want to know why it was put up there in the first place. Why was this necessary? Why not just use a telescope down here? What do we get from this enormous expense? You may want to tell them about how light pollution affects viewing, but perhaps your audience wants to know how it affects them. Okay, so it affects your ability to see things up there, but how does this affect us? Do they understand that light pollution adversely affects their health and safety?

Another thing to consider is the age of your audience. Children are more likely to want something that excites and interests them and not deep scientific details. They want hands-on things that get them involved in the learning experience. They'll relate to scale models of the Solar System that they can walk through to get a sense of the scale of the Universe around them. They'll have fun dropping marbles into sandy surfaces to make craters. In later years, they'll be looking for methods to get data to make their own decisions on what is going on in the Universe around them. Don't just give them facts: Teach them how to think for themselves. Teach them how to explore. They may be checking your topic out to see if this is something they'd like to pursue themselves as a hobby or career. They may want to know how to get involved in astronomy at this stage in their lives, when they may not have a lot of money to devote to it. They'll want to know how to use that telescope to get that data and then what to do with the data they've collected.

As well, consider what cultural background your audience comes from. You were given an "official" astronomical perspective when you went to school, and you probably picked up some other perspectives from the cultural perspective of your family. When you look up at the sky you may see the Big Dipper, but maybe what they see is a plough, a wagon, a shepherd, a bird, a boat, or seven sages. If you're telling them about the "teapot" in Sagittarius, do they understand what you mean? Maybe what they see is a basket or a dipper? If you know in advance what the cultural background of at least part of your audience is likely to be, look up that culture in our World Asterism Project lists and find out what they do with the sky. They'll appreciate you respecting their perspectives and you'll probably learn something yourself in the process, which will lead to even better presentations in the future.

You should also anticipate audience questions. What sorts of things is this audience likely to ask you about this topic? What is their understanding of the topic likely to be? Design your presentation to engage your audience and get feedback. Don't just talk to your audience, engage them. Ask them questions. As your understanding of their understanding develops, adjust and give them the information they want. The most successful presentations start where you expect and end up someplace unexpected. Every time I teach, I learn something new that I can pass on to others later. ✶

News Notes / En manchette

Compiled by Jay Anderson

Black hole blows dusty ring

An international team of scientists has achieved the milestone of directly observing the long-sought, innermost dusty ring around a supermassive black hole, at a right angle to its emerging jet. Such a structure was thought to exist in the nucleus of galaxies but had been difficult to observe directly because intervening material obscured our line of sight.

"This is a very exciting step forward to view the inner region of a distant galaxy with such fine detail," said Gail Schaefer, Associate Director of the Center for High Angular Resolution Astronomy (CHARA) Array.

A supermassive black hole is believed to exist at the centre of every large galaxy. As material in the surrounding region gets pulled toward the centre, the gas forms a hot and bright disk-like structure. In some cases, a jet emerges from the vicinity of the black hole in a direction at a right angle to the disk. However, the disk, which is essentially the "engine" of this active supermassive black hole system, has never been directly seen because it's too small to be captured by conventional telescopes.

One way to approach this key structure is to directly view the outer "dusty ring." Interstellar gas contains dust grains—tiny solid particles made of heavy elements—that can only survive in the outer region where temperature is low enough (< ~1500K) as otherwise the metals would evaporate. The heated dust emits thermal infrared radiation, and so would appear as an outer ring around the black hole, provided the central system indeed has a flat structure. The detection of this structure would be a key step in delineating how the central engine works.

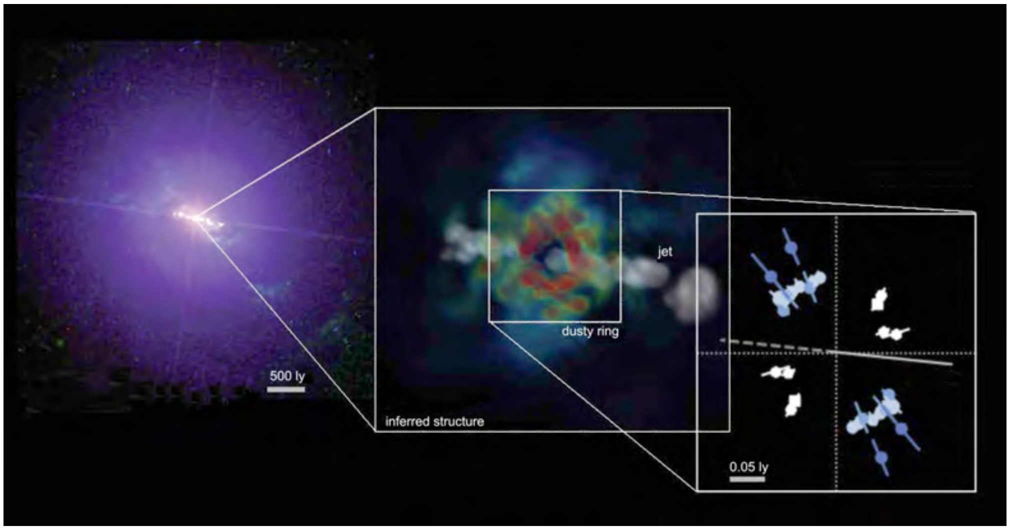

Figure 1 — This Hubble *image shows the star cluster NGC 4151 in the Large Magellanic Cloud. Two filters were used to gather data, one at visible wavelengths the other at near-infrared wavelengths. Following chromatic order, the shorter wavelength visible light data is blue, while the longer near-infrared data is red. Image: NASA, ESA and P. Goudfrooij (Space Telescope Science Institute); Processing: Gladys Kober (NASA/Catholic University of America).*

Attempts to see this structure from edge-on directions are difficult, because the system is obscured by the same dust, which absorbs light coming from more central regions. In this new investigation, the team focused on a system with a face-on view, the brightest such object in the nearby Universe. Even so, detection required very high spatial resolution in infrared wavelengths, and at the same time, a large array of telescopes suitably laid out to observe objects at different orientations.

The Georgia State University CHARA Array infrared interferometer at the Mount Wilson Observatory in California is the only facility that meets both of these requirements. The array consists of six telescopes, each of which has a one-metre-diameter mirror, that are combined to achieve the spatial resolution of a much larger telescope. While each individual telescope is relatively small, the array layout is optimized to observe objects in a variety of angles, and with large distances between telescopes, to achieve a very high spatial resolution. The CHARA Array actually has the sharpest eyes in the world at infrared wavelengths.

Observing the nucleus of a galaxy in the near infrared allows astronomers to examine the innermost regions of a disk, at the point where temperatures have fallen just enough to avoid sublimation of the dust.

The researchers were able to observe a dusty ring, at a right angle to the emerging jet, in the centre of the galaxy NGC 4151. According to the research team, "the structure is elongated perpendicular to the polar axis of the nucleus, as defined by optical polarization and a linear radio jet." Modelling the structure suggests a thin ring with a minor/major axis ratio of ~0.7 at a radius of ~ 0.1 ly. This is consistent with a structure in which sublimating dust grains are distributed preferentially in the equatorial plane in a ring-like geometry, viewed at an inclination angle of ~40°.

"We've been hoping to see this structure in a bare nucleus object for a long, long time," says Makoto Kishimoto, principal investigator of the project at Kyoto Sangyo University.

A big boost was that each telescope has recently added a new system called "adaptive optics." Matt Anderson, a postdoctoral researcher at the CHARA Array, says "This greatly increased the injection rate of the light, compensating for the relatively small collecting mirror to observe the extragalactic target, which is much fainter than the stellar targets typically observed in our galaxy."

Over the last nearly 40 years, researchers in the field believed that such a dusty ring is a key to understanding different characteristics of accreting supermassive black hole systems. The properties observed depend on whether we have an obscured, edge-on view or clear, face-on view of the nucleus of the active galaxy. The detection of this ring-like structure validates this model.

Furthermore, the detection probably is not just an indication of a flat structure. Additional studies at slightly longer infrared wavelengths have shown that the structure, an even larger outer region, seems elongated along the jet, and not at a right angle to it. This has been interpreted as an indication for a dusty wind being blown out toward the jet direction from the disk. The present finding—that the inner structure looks flat and perpendicular to the jet—is an important link to the windy structure and its interaction with the rest of the galaxy surrounding the active black hole system.

The team is working to get a more detailed image of the central region by building a new instrument at the CHARA Array that can resolve even finer-scale structure of the source.

The project is a result of a collaboration with an external team of scientists led by Makoto Kishimoto at the Kyoto Sangyo University who was awarded open access time at the array through the National Optical-Infrared Astronomy Research Laboratory (NOIRLab). Scientists at Georgia State University's CHARA Array include Matthew Anderson, Theo ten Brummelaar, Christopher Farrington, Laszlo Sturmann, Judit Sturmann, Gail Schaefer, and Nic Scott. The CHARA Array is funded by the U.S. National Science Foundation and Georgia State's College of Arts and Sciences and the Office of the Vice President for Research and Economic Development.

Compiled with content provided by Georgia State University.

Haumea intrigues

Haumea, a Pluto-sized body located at the outer edge of the Solar System, may be one of the strangest worlds in the Sun's collection of planets. Haumea sports a distinctive football shape, an extremely rapid rotation, two moons, and a ring system—almost a miniature Solar System on its own. Now, the origins of this strange assembly may have been revealed by NASA scientists.

Haumea is located in the Kuiper belt, a collection of icy debris and cometary bodies out past the orbit of Neptune, at a perihelion distance of 35 au. A "day" on Haumea lasts just four hours, causing the planet to adopt a shape that resembles a deflated football with a long axis radius of about 780 km and a short axis of about half that. That rotation rate is faster than any other Solar System object of a similar size.

Haumea also has a surface that is mostly made of a kind of water ice, unlike most of the other bodies in the Kuiper Belt. This water-ice composition is shared by some of Haumea's siblings that also appear to share the same orbit as the dwarf planet. This has led scientists to conclude Haumea and these icy bodies share the same origin and that they form the only "family" of related objects found in the Kuiper Belt—the "Haumean family."

Using computer simulations, NASA scientists including Goddard Space Flight Center in Greenbelt, Maryland, post-doctoral student Jessica Noviello investigated the question: "How did something as weird as Haumea and its family come to be?"

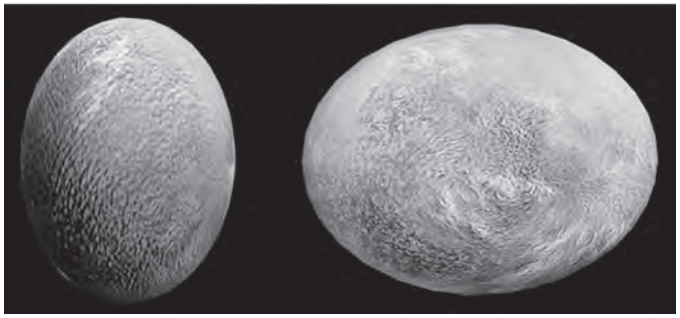

Figure 2 — A model of Haumea in two sections. Image: NASA Visualization Technology Applications and Development (VTAD).

Computer simulations are necessary to achieve this due to the fact the dwarf planet is too far away to measure precisely using an Earth-based telescope, and Haumea is yet to be visited by a space mission. The simulations allowed the team to "take apart" Haumea and then rebuild it from scratch in order to understand the chemical and physical processes that shaped the dwarf planet.

"To explain what happened to Haumea forces us to put time limits on all these things that happened when the Solar System was forming, so it starts to connect everything across the Solar System," team member and Arizona State University in Tempe, professor of astrophysics, Steve Desch said in a statement. "There are a lot of odd, 'gee whiz' parts to Haumea, and trying to explain them all at once has been a challenge."

The model developed by the team started with the input of just three pieces of data about Haumea; its estimated size, its estimated mass, and its short four-hour-long "day."

Using this information, Noviello was able to determine how the dwarf planet's mass is distributed and how that distribution has influenced its spin. From here the researcher set about simulating billions of years of evolution for Haumea, searching for the right set of features that would result in the dwarf planet astronomers observe today.

"We wanted to understand Haumea fundamentally before poking back in time," Noviello said.

The team made the assumption that the infant Haumea was around 3 percent larger than its current size with this difference accounting for the creation of its Kuiper belt siblings. The scientists also assumed the young dwarf planet rotated at a different speed and that its volume was larger than it is today.

Altering the features of Haumea in the models they developed allowed the team to run dozens of simulations, viewing how small changes like increasing or decreasing the size of the dwarf planet changed its evolution. Arriving at a model that delivered a simulated Haumea just like astronomers observe today told the team they had hit on the right early features and the current evolutionary path for the Kuiper-belt dwarf planet.

At the end of the modelling exercise, Noviello and her colleagues hypothesized that Haumea was formed from a gentle grazing collision of two similar-sized KBO objects, shedding ice and rocks that were then lost in the distant Solar System. The cores of the two bodies merged, after which heating from radioactive elements caused heavier material in the young body to settle to the middle while ices rose toward the surface.

"When you concentrate all the mass toward the axis, it decreases the moment of inertia, so Haumea ended up spinning even faster than it does today," Desch said. This would result in rotational speeds fast enough to throw off surface ice, which went on to form the members of the Haumean family plus the two moons and the ring. The lost material carried away angular momentum, resulting in a decrease in Haumea's rotation rate. Further heating then allowed water from surface ices to sink to the core, causing rocky material there to swell to a large but less dense clay core, slowing Haumea's rotation even more.

In a final note, the research team notes that radiogenic heating would have allowed Haumea to sustain a liquid water ocean for about 250 million years. Their research paper concludes that "Haumea could indeed be an ancient potential ocean world of the Solar System, the most distant one known. This may have grand implications for the search for habitability in the Solar System and beyond, as an understanding of life's physical limits is determined by the environments in which it can survive. In addition to the potential importance for ocean world studies, constraining the evolution and timescale of Haumea puts limits on events that involved the outer Solar System, particularly Neptune's migration."

Compiled in part with material provided by NASA

New NEAs come out of hiding

Twilight observations with the US Department of Energy-fabricated Dark Energy Camera at Cerro Tololo Inter-American Observatory in Chile, a program of NSF's NOIRLab, have enabled astronomers to spot three near-Earth asteroids (NEAs) hiding in the glare of the Sun. These NEAs are part of an elusive population that lurks inside the orbits of Earth and Venus. One of the asteroids is the largest object that is potentially hazardous to Earth to be discovered in the last eight years. This is a notoriously challenging region for observations because asteroid hunters have to contend with the glare of the Sun.

By taking advantage of the brief yet favourable observing conditions during twilight, just before and after nautical twilight, the astronomers found an elusive trio of NEAs. One is a 1.5-kilometre-wide asteroid called 2022 AP7, which has an orbit that may someday place it in Earth's path. The other asteroids, called 2021 LJ4 and 2021 PH27, have orbits that safely remain completely interior to Earth's orbit. Also of special interest to astronomers and astrophysicists, 2021 PH27 is the closest known asteroid to the Sun with a semi-major axis of 0.462 au and approaching the Sun to within 0.133 au. As such, it has the largest general-relativity effects of any object in our Solar System, and during its orbit, its surface gets hot enough to melt lead.

"Our twilight survey is scouring the area within the orbits of Earth and Venus for asteroids," said Scott S. Sheppard, an astronomer at the Earth and Planets Laboratory of the Carnegie Institution for Science and the lead author of the paper describing this work. "So far we have found two large near-Earth asteroids that are about 1 kilometre across, a size that we call planet killers."

2021 PH27 has a strong interaction with Venus and has a small probability of colliding with that planet in about 1,000 years. 2022 AP27 is about 1.5 km in size with a perihelion of 0.87 au and an aphelion near Jupiter. It has an orbital period of almost exactly 5 years, and is well away from Earth when at opposition, at least for the time being.

"There are likely only a few NEAs with similar sizes left to find, and these large undiscovered asteroids likely have orbits that keep them interior to the orbits of Earth and Venus most of the time," said Sheppard. "Only about 25 asteroids with orbits completely within Earth's orbit have been discovered to date because of the difficulty of observing near the glare of the Sun."

Finding asteroids in the inner Solar System is a daunting observational challenge. Astronomers have only two brief 10-minute windows each night to survey this area and have to contend with a bright background sky resulting from the Sun's glare. Additionally, such observations are very near to the horizon, meaning that astronomers have to observe through a thick layer of Earth's atmosphere, which can blur and distort their observations.

Discovering these three new asteroids despite these challenges was possible thanks to the unique observing capabilities of DECam. The state-of-the-art instrument is one of the highest-performance, wide-field CCD imagers in the world, giving astronomers the ability to capture large areas of sky with great sensitivity.

Astronomers refer to observations as "deep" if they capture faint objects. When hunting for asteroids inside Earth's orbit, the capability to capture both deep and wide-field observations is indispensable.

"Large areas of sky are required because the inner asteroids are rare, and deep images are needed because asteroids are faint and you are fighting the bright twilight sky near the Sun, as well as the distorting effect of Earth's atmosphere," said Sheppard. "DECam can cover large areas of sky to depths not achievable on smaller telescopes, allowing us to go deeper, cover more sky, and probe the inner Solar System in ways never done before."

As well as detecting asteroids that could potentially pose a threat to Earth, this research is an important step toward understanding the distribution of small bodies in our Solar System. Asteroids that are further from the Sun than Earth are easiest to detect. Because of that, these more-distant asteroids tend to dominate current theoretical models of the asteroid population.

Detecting these objects also allows astronomers to understand how asteroids are transported throughout the inner Solar System and how gravitational interactions and the heat of the Sun can contribute to their fragmentation.

Prepared with material provided by the Association of Universities for Research in Astronomy (AURA).

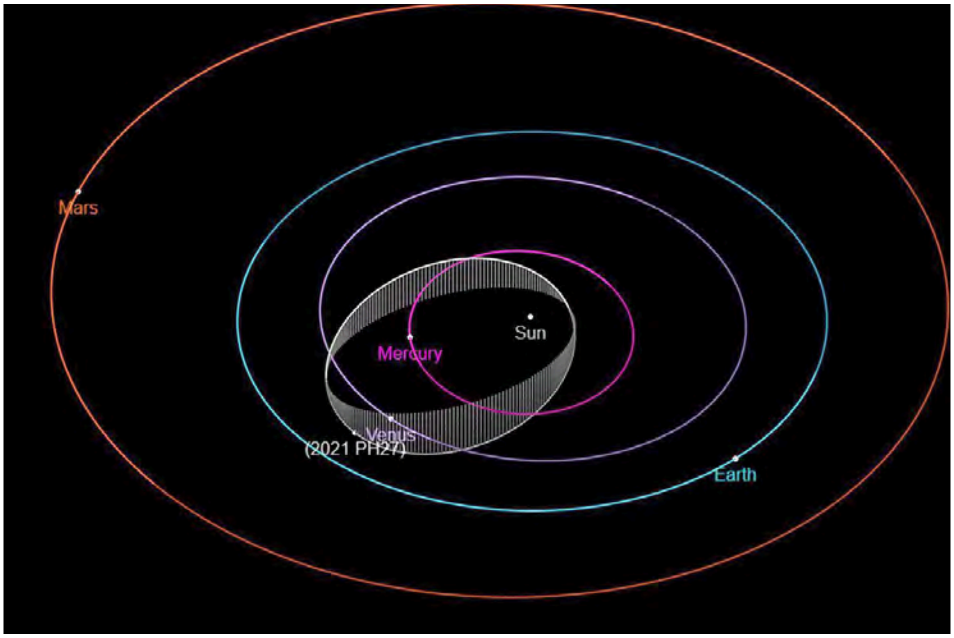

Figure 3 — Orbit diagram of near-Earth asteroid 2021 PH27 compared to the inner planets. Image: NASA/JPL-SSD.

Black hole next-door neighbour

Astronomers using two Mauna Kea Observatories, W.M. Keck Observatory and the Gemini North telescope, have found the closest known black hole to our planet. Located a mere 1,560 light-years away from Earth in the constellation Ophiuchus, the black hole, named Gaia BH1, is three times closer to us than the previous record-holder.

The new study, which includes data from Keck Observatory's High-Resolution Echelle Spectrometer (HIRES) and Echellette Spectrograph and Imager (ESI), is published in the journal Monthly Notices of the Royal Astronomical Society.

A research team led by the Max Planck Institute for Astronomy (MPIA) made the discovery by tracking Gaia BH1's companion—a bright Sun-like star that orbits the black hole once every 185.6 days at about the same distance as the Earth orbits the Sun.

"Take the Solar System, put a black hole where the Sun is, and the Sun where the Earth is, and you get this system," said lead author Kareem El-Badry, an astrophysicist at MPIA and the Harvard–Smithsonian Center for Astrophysics. "While there have been many claimed detections of systems like this, almost all these discoveries have subsequently been refuted. This is the first unambiguous detection of a Sun-like star in a wide orbit around a stellar-mass black hole in our galaxy."

Stellar-mass black holes form when dying massive stars collapse in on themselves. To find these dark, hard-to-detect objects, El-Badry's team combed through data from the European Space Agency's (ESA) *Gaia* spacecraft, which is designed to measure the motion of one billion stars in the Milky Way as they orbit around the centre of our galaxy.

One star's behaviour caught the team's attention; its orbit was larger than expected for its orbital period, suggesting the presence of a massive, unseen companion. For a more detailed look, the researchers conducted follow-up observations at several ground-based telescopes, including Gemini North and Keck Observatory in Hawai'i, and determined the star's companion is a black hole that is 10 times more massive than the Sun.

"I have been searching for a system like Gaia BH1 for the last four years, trying all kinds of methods—but none of them worked," said El-Badry. "It has been elating to see this search finally bear fruit."

Using data from ESA's *Gaia* astrometry mission, astronomers have identified the closest known black hole, less than 1,600 light-years away from Earth. The black hole is orbiting a star similar to our Sun, and was identified by tracking the star that the black hole is orbiting. It is expected to be the first one of many black holes to be discovered using the same method. At the same time, the properties of the binary star system are unexpected, indicating a serious gap in astronomers' understanding of how such systems form in the first place.

There are an estimated hundred million stellar black holes in our home galaxy, the Milky Way, but only a small fraction has been detected so far. Some have been detected by gravitational wave detectors, which have measured almost a hundred mergers of stellar black holes, yielding additional data about black hole masses. Of those few dozen stellar black holes that have been detected using telescope observations, most orbit a companion star closely enough for the black hole's gravity to pull hydrogen gas from the companion star into a so-called accretion disk that surrounds the black hole. The gas then becomes hot enough in the process to emit considerable amounts of X-rays. There are 20 known "X-ray binaries" of this kind, with an additional 50 candidate objects.

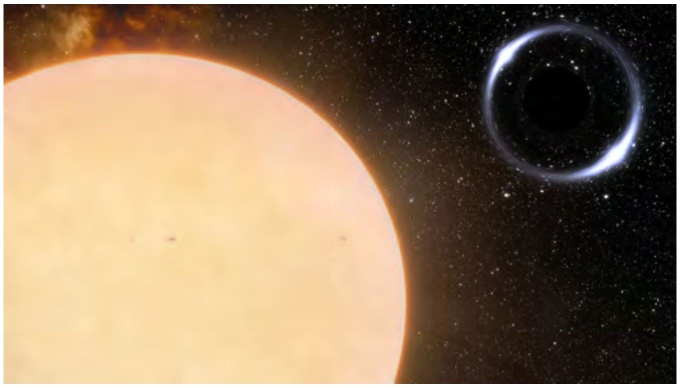

Figure 4 — Artist's impression of the closest black hole and its Sun-like companion. Image: International Gemini Observatory/NOIRLab/NSF/AURA/J. da Silva/Spaceengine/M. Zamani

There have been several attempts to also find "quiescent" black holes in binary systems—black holes without an X-ray-emitting disk. Over the past few years, there have been several claims of quiescent black hole discoveries that tried to deduce a binary's orbit and the mass of an unseen companion exclusively from stellar spectra. However, all but one of them have since been challenged or downright refuted by follow-up studies. The key problem: Spectra give only part of the information about stellar motion, and hence about the orbit and about the companion's mass.

For a few years now, there has been hope that ESA's astrometry mission *Gaia* would open up a new way of detecting and characterizing black holes in binary star systems by providing information that is complementary to what stellar spectra deliver. *Gaia* is designed for ultra-precise measurements of stellar position. This includes the ability to detect a visible star's motion on the sky, and from that to deduce the presence of an unseen companion.

This kind of binary containing a black hole would still be very rare, compared to the overall number of binaries. In this case, *Gaia*'s scope is just as important as the survey's accuracy: high-quality data for more than a hundred thousand binary systems makes for a fair chance to find the needle in the haystack, the black hole binary among the many ordinary binaries.

When *Gaia*'s data release 3 (Gaia DR3), the first to contain the orbital data for binary systems detected with *Gaia*, was published in mid-June 2022, Kareem El-Badry, together with

Max Planck Institute for Astronomy director Hans-Walter Rix and their colleagues directly set about sifting the data for likely candidates. Generally, as two objects in a binary system orbit each other, they each trace out a tiny ellipse in the sky. Gaia DR3 contains data for 168,065 such tiny ellipses, or parts thereof.

Applying selection criteria that were particularly likely to pick out systems in which a luminous star is dragged around by an invisible companion with considerable mass, the researchers narrowed their set down to six possible candidates. All six candidates warranted a closer look: with the help of the complementary information of radial-velocity measurements derived from the star's spectrum, that give us information about motion directly toward or away from us. Using existing spectral data available in astronomical archives, the astronomers were able to rule out three of the candidates right away. In those cases, the available radial-velocity data flatly contradicted the *Gaia* reconstruction of the binary orbit.

Another candidate could be ruled out by the bad fit of the *Gaia* data to the reconstructed orbit, with an orbital period so long that *Gaia* should not have been able to measure it in the first place. A fifth candidate is still under consideration, awaiting additional spectral measurements.

The remaining candidate, Gaia DR3 4373465352415301632, which the researchers have dubbed "Gaia BH1," fit the bill very well. For added certainty, the astronomers also performed additional targeted observations of Gaia BH1: with the 6.5-m Magellan Clay telescope, the 8.1-m Gemini-North telescope, the 10-m Keck I telescope and, for the lion's share of the new data points, the 2.2-m ESO/MPG telescope that MPIA operates at ESO's La Silla observatory.

The orbital reconstruction held up. Gaia BH1 was a system with an invisible object of about 10 solar masses orbiting a star very similar to our own Sun once every 185.6 days. The distance between star and companion is about the same as the average Earth-Sun distance. If the 10-solar-mass-object were another star, it would necessarily be much brighter than its companion. Instead, neither *Gaia* nor follow-up observations show any trace of a second star.

This makes Gaia BH1 an excellent candidate for a black hole—and at a distance of around 1560 light-years, by far the black hole closest to Earth that astronomers have yet found, less than one-third the distance of the previous record-holder!

Statistically speaking, the closeness implies that there should be numerous similar systems throughout the galaxy. Putting a number to the "numerous" is hard, though. But El-Badry and his colleagues have a fairly good estimate that the next big *Gaia* data release, DR4, currently expected not before the end of 2025, should allow for the discovery of dozens of similar systems.

Gaia BH1 is a spectacular find, but also a puzzling one. It is difficult to explain how a system like this could have formed in the first place. Specifically, the progenitor star that later turned into a black hole would be expected to have had a mass of at least 20 solar masses, which means its lifetime would have been very short—on the order of a few million years. If both stars formed at the same time, this massive star would have turned into a supergiant, puffing up and engulfing space to far beyond the stars' common orbit, before the other star would have even had the time to become a proper, hydrogen-burning ("main sequence") star.

It is not at all clear how the solar-mass star could have survived that episode, ending up as apparently normal as the observations of the black hole binary indicate. Theoretical models that do allow for survival all predict that the solar-mass star should have ended up on a much tighter orbit than what is actually observed.

This leaves more unusual formation scenarios. For instance, the two original stars could have formed as part of a star cluster. Initially, they would have been considerably farther apart, so the massive star's supergiant phase would not have disturbed the solar-mass star's evolution. Close encounters of the system with additional stars in the cluster could later have changed the orbit to its present much smaller size.

Alternatively, the system could in fact have not two, but three components: Two massive stars instead of one, in close orbit with each other, and the one-solar-mass star orbiting the massive pair at a greater distance. The two massive stars would prevent each other from turning into supergiants. In that case, the 10-solar-mass object might not be a single black hole, but a pair of black holes in close orbit around each other. Since that orbiting pair would exert slightly different gravitational forces on the one-solar-mass star, precise future observations might confirm or rule out that possibility.

All in all, Gaia BH1 is at least three things in one: It is an exciting discovery of the closest known black hole, less than a third as far as any black hole detected previously. It is a promise of future similar discoveries to come within the next few years, but also a sobering reminder of the limits of current astronomical knowledge about the formation of binary or, more generally, multiple star systems. ✶

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The Canadian Astronomy Data Centre: Canadian Astronomy and the Beginnings of Big Data

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Abstract

The Canadian Astronomy Data Centre at the Dominion Astrophysical Observatory in Victoria, B.C., was created in 1986 to help Canadian astronomers access data from the Hubble Space Telescope (HST). During the development of the CADC, its experts worked together with astronomers from the Space Telescope Science Institute and the European Space Agency to create archives for HST and make its data available to astronomers through the internet, which was then in its early days. The result was a notable Canadian contribution to HST and the establishment of a Canadian home for digital astronomical data. CADC played an important role in the establishment of the internet in Canada and is now involved in the major changes in astronomy relating to the availability of large quantities of astronomical data. This article discusses the challenges faced by the CADC and its staff during its first decade of operations.

Introduction

Amongst the many ways the *Hubble Space Telescope* (HST) has changed astronomy, one of the most important yet least known has been its role in making astronomical data more accessible to scientists and others. From the time of its launch in 1990, HST observations have been stored in archives and made available to anyone who wants them. The explosion of computing power and data storage capacity, along with the rise of the internet in the 1990s, vastly expanded the availability of data from HST and other telescopes located in space and on the ground. Today many astronomers go to data archives rather than to telescopes to make important discoveries. The creation of digital data archives for HST presented technical and conceptual difficulties that were resolved with help from astronomers and other experts based at the National Research Council of Canada's (NRC) Dominion Astrophysical Observatory (DAO) in Victoria, B.C.

HST's science operations centre is located at the Space Telescope Science Institute (STScI) on the campus of Johns Hopkins University in Baltimore, Maryland. STScI was established in 1981 in preparation for HST operations, and today it also contains the control centre for the James Webb Space Telescope (JWST), which was launched in 2021. Before HST was launched, STScI began creating an archive for HST images and other data. Since HST was a joint program involving both the U.S. National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), the ESA established its own HST data archive to serve European astronomers. Although Canada is not a formal partner in the Hubble program, the NRC responded to widespread calls from Canadian astronomers for an archive of their own for Hubble data. As a result, the development of the Canadian Astronomy Data Centre (CADC) at the DAO began in 1986.

Together with the archives at STScI and in Europe, CADC is one of the three archives in the world that store and disseminate HST data. The staff at the CADC helped their STScI and ESA colleagues deal with technical issues to create workable digital archives of astronomical data. As well, the CADC made a major contribution to the evolution of the internet in Canada. This article will cover the history of the CADC and discuss its contributions to astronomical archives and to the internet which has become so important to Canadians.

Background

While the idea of placing telescopes in space beyond the Earth's atmosphere goes back to the 1920s, the first serious proposal for a space telescope was made in 1946 by astronomer Lyman Spitzer Jr., who spent most of his career at Princeton University. Soon astronomical telescopes began flying on brief suborbital flights on rockets developed during and after World War II, and in the 1960s telescopes began being launched into Earth orbit. Years of lobbying by Spitzer and others paid off in 1977 when NASA won approval to begin building a large orbiting astronomical observatory that became known as the *Hubble Space Telescope*. HST is a 2.4-metre-aperture Ritchey-Chrétien Cassegrain telescope equipped with room for five instruments and three fine-guidance sensors that were designed to be changed out by astronauts visiting from the U.S. *Space Shuttle*. The instruments operate in optical, ultraviolet, and near-infrared wavelengths.

Figure 1 — The Canadian Astronomy Data Centre received the 100th optical disk containing Hubble Space Telescope *data from the Space Telescope Science Institute in 1992. Left to right are Dennis Crabtree, Don Morton (Herzberg Institute of Astrophysics Director General), Daniel Durand, and Séverin Gaudet.*

HST was built during a time when astronomers were turning away from photographic film and plates toward electronic means of recording and storing images and other data. This was particularly important for space telescopes that operate remotely. From the beginning, most of HST's instruments utilized charge-coupled devices (CCDs) for this purpose.[1]

The Canadian government consolidated its astronomy programs in 1970 under the NRC. The following year, Canada's professional astronomers formed the Canadian Astronomical Society, also known as CASCA, to represent their interests. Most of the NRC's astronomy facilities were placed within the Herzberg Institute of Astrophysics (HIA), which was formed in 1975. At the time, the NRC was responsible for space science, including work that was later delegated to the Canadian Space Agency when it was formed in 1989.[2] The NRC began formal planning for space-based astronomy in April 1974 when the NRC Associate Committee on Astronomy issued a report, *The Future of Ground and Space Based Astronomy in Canada*. The report strongly urged Canadian involvement in astronomy programs using the U.S. *Space Shuttle*. A 1977 working group report on Canadian astronomers' involvement in the Shuttle noted that Canadian astronomers were already involved in HST, and it suggested that Canada offer to supply the main mirror for the space telescope. Fatefully, the offer was apparently never made, and as is well known, the American-made main mirror on HST was found after its launch in 1990 to have been ground to the wrong shape.[3]

While many Canadian astronomers made observations with space telescopes launched before Hubble, it was already clear that many Canadians wanted to make use of HST. DAO astronomer John Hutchings played a key role in the HST program before it was launched, and he went on to serve as a member of the Space Telescope Users' Committee from 1990 to 1994, which he chaired in 1994. Canadian interest in HST is shown by the fact that in the first 27 cycles of HST observing proposals, 361 of the approved proposals came from Canadian astronomers.[4]

As HST was being built in the 1970s and 1980s, digital data were processed using massive mainframe computers within their limits for time and access. As well, data sets were saved on media such as magnetic tapes and large discs for storage or transfer to other computers and to users. While personal computers began to appear in large numbers in offices and homes in the 1980s thanks to advances in microprocessors, they featured text-based user interfaces on monochrome screens. More powerful computer systems such as Sun workstations were required to handle graphics. In the 1990s even more powerful microprocessors led to graphical user interfaces and the processing and storage of images in PCs.[5]

Early on, NASA had decided that the data archive for Hubble should be established at the STScI rather than at the agency's own National Space Science Data Center to be closer to an academic environment. The cost and limited availability of computers and computing time led to concerns about the availability of processing time for HST data at STScI or other places for researchers, especially those from outside the United States. Data archiving for HST became a prime area of cooperation between NASA and the ESA, starting with the 1977 Memorandum of Understanding between the two space agencies on the *Space Telescope*, which stipulated that a copy of the HST archive be set up at ESA's Space Telescope European Coordinating Facility (ST-ECF) located at the headquarters of the European Southern Observatory in Garching, near Munich, Germany, to make this data available to European astronomers. NASA also contemplated supporting archives for HST data in other locations outside the United States.[6]

A Data Centre for Canada

A major study into future directions in Canadian astronomy, *Astronomy in Canada in the 1980s*, called in January 1983 for a "National centre for development of image processing" to be provided with the latest image processing hardware, software, and personnel to "remain at the forefront in hardware and software development in astronomical image processing while developing techniques and software which can be made widely available." The proposal stated that creating one national data processing centre for Canada would save resources since each research group would be spared the need to develop their own data processing software from scratch.[7]

At the time, many Canadian astronomers were working with American and Australian colleagues on a space telescope called *Starlab* that was due to be flown on board the Shuttle, but *Starlab* ended in 1984 after the NRC announced that it would not fund the Canadian portion of the program. When Canadian astronomers met that year, much discussion concerned the need for training opportunities for Canadians in space astronomy. At CASCA's annual general meeting that June in Ottawa, its members passed a resolution urging the Natural Sciences and Engineering Research Council of Canada (NSERC) and Canadian universities to support training for young Canadian astronomers to join international teams developing space observatories. The resolution highlighted STScI as such a place. On September 24 and 25, the Joint Subcommittee on Space Astronomy (JSSA), which reported to both NRC and CASCA, also met in Ottawa. By then, the election of a new Progressive Conservative government earlier in the month after years of Liberal government gave hope of fresh thinking in government that could benefit astronomy. Michael M. Shara, a Canadian astronomer then working at STScI, came to the meeting with a proposal from STScI for Canadian Ph.D. astronomers with two years' experience to work at the institute on preparations for the HST launch, or after the launch, on "data analysis and guest observer support" for HST. The meeting was told that astronomers got encouragement for the idea when they brought it to Larkin Kerwin, then the president of the NRC.[8]

After the September meeting, James Hesser, John Hutchings, and other DAO astronomers quickly moved to "enthusiastically" prepare a proposal for a "centre of Space Astronomy at DAO" for submission to the NRC's Program Selection Committee for its meeting on December 7. In a letter to the CASCA membership, Hesser warned that financial factors could block the proposal even if the Program Selection Committee rated it highly.[9] The proposal itself was a "two-pronged" concept that included an astronomical space instrument design group, and a "national Space Telescope data analysis and archiving facility" that would encourage astronomers and students to use data from HST, and "promote continued development of quantitative image-processing techniques." The data centre would require computers similar to those being installed at DAO for other work, and could fit into a building extension at DAO being planned at the time. It would be especially useful for astronomers located in western Canada and also those in the northwestern U.S. The proposal also noted that the data centre would involve a "considerable extension" from the data that Hutchings would be obtaining in the first year after launch as a member of the Goddard High Resolution Spectrograph (GHRS) instrument team on Hubble. [10]

After Hesser and Hutchings from the DAO successfully convinced the NRC Program Selection Committee of the need for the data centre, the NRC allocated money to purchase computers and workstations to be placed inside DAO to be ready for the anticipated launch of HST in August 1986. Since May 1980, the DAO had been operating a Digital Equipment Corporation (DEC) VAX 11/780 computer system to perform data reduction and serve as a host for image processing. While the system had been enhanced with more memory and disc storage, demands grew through the early 1980s to the point where the system often operated at capacity and users had to wait for access. DAO needed more computing capacity, an NRC submission to the Treasury Board argued, and NRC needed even more equipment to support the data centre for HST data and for Canadians to "remain at the forefront of modern astrophysical research." The submission stated that scientists from outside the U.S. could not be given access to HST data from STScI because its own computing resources were limited. The new data centre would copy, catalogue, and archive all HST public domain data and make it available to all Canadian scientists along with data reduction and software for interpretation of that data. The submission stressed the importance of maintaining "close ties with STScI and in particular [making] use of data processing equipment which is highly compatible with that at STScI."[11]

The Canadian Space Astronomy Data Centre (CSADC) "came to life" in 1986 with the Treasury Board's approval from the year before to purchase computing equipment worth $675,000, including two microVAX systems, an Alliant vector arithmetic computer, a Britton-Lee database machine, and an optical disc system for accessing HST data. DAO got an upgrade to its VAX 11/780 that increased its memory from 4 MB to 16 MB at a cost of $30,000, and a new MicroVAX[12]. The DAO and data centre computers would work together "to allow the cost-effective sharing of peripherals."[13] At the time, STScI was developing the Science and Data Analysis System (SDAS), which was soon put into use at CADC. In addition, the Europeans and Canadians developed STARCAT, the Space Telescope Archive and Catalog, for use with HST. The NRC hired two research associates for the CSADC, Dennis Crabtree, who previously worked on VAX computers at the Canada-France-Hawaii Telescope (CFHT), and Daniel Durand from Laval University. Durand brought experience with detector systems, and as a francophone he ensured that data centre services would be available in both official languages. Durand also developed relationships with European astronomers working with HST data. The NRC named an advisory committee for CSADC consisting of Phil Kronberg of the University of Toronto, Chris Pritchet of the University of Victoria, René Racine of the Université de Montréal, Gordon Walker of the University of B.C., and Stephen Morris and Peter Stetson of the DAO.[14]

Figure 2 — Interns and staff at the Canadian Astronomy Data Centre in 1992. L to R: Robin Blaber, Bruce Enns, Dennis Crabtree, Norman Hill, Daniel Durand, Séverin Gaudet, Wes Fisher, Stephen Morris.

Crabtree, Morris, and Stetson played key roles at the CSADC in its early days, with Morris given responsibility for operating equipment and as interim coordinator, and Stetson, who was developing DAOPHOT software for use with data from HST's main camera, working with Crabtree on other software. Crabtree started at his new post in April 1986 with responsibility for data reduction, and Durand, who worked on databases and catalogues, started the following August. Both of them were often away from Victoria, familiarizing themselves with HST data at STScI starting in 1986, and visiting Canadian astronomers around the country in 1987. Crabtree spent a month at National Optical Astronomy Observatory at Kitt Peak in 1986, where he was trained in the use of the Image Reduction and Analysis Facility (IRAF), a software package developed there that was later installed at DAO on his recommendation. When Durand and Crabtree began nine-month work terms at STScI, they had assumed that astronomers would get their data on magnetic tape sent by mail or courier, but they quickly learned that the institute was moving toward optical discs, and even data transmission using something called the internet. At the time, astronomers around the world were in the process of transitioning to digital media for data acquisition and storage from glass photographic plates.[15]

A Difficult Year

The year 1986 turned out to be a difficult year for the fledgling data centre. The disaster that claimed the *Space Shuttle Challenger* and its crew on January 28 meant that HST would not be launched that year as planned, and indeed its launch was held up until 1990. In the wake of the launch postponement, CSADC decided to set up a "smaller scale astronomical data archive," with data from the NASA Data Centre, the Infrared Astronomical Satellite (IRAS), which had been launched in 1983; the International Ultraviolet Explorer (IUE), which had been in orbit since 1978; and ground-based instruments. At that time, the centre's peripherals weren't ready, so computing time at CSADC was offered to researchers who needed it for modelling or simulations. The data centre staff was also thinking of developing software to facilitate the archiving and use of astronomical data. Until an expansion of the DAO office facilities took place, the CSADC had to be squeezed into existing office space at DAO. Due to delays in hiring computer programmers for the data centre, other staff from DAO who were interested in space astronomy stepped in to do this work.[16]

Another blow landed on Canadian astronomers that year in the form of budget cuts. On February 26, the Progressive Conservative government of Brian Mulroney introduced a budget that sought to contain the federal budget deficit with a round of spending cutbacks. Later in the year, cutbacks were announced that specifically affected many NRC astronomy programs, including causing the closure of the Algonquin Radio Observatory in Ontario.[17] While the data centre budget was not actually cut, many other astronomical programs were reduced or curtailed at the time, and it is likely that the CSADC budget would have been larger in the absence of the budget austerity. Many astronomers who were suffering from the cutbacks looked at the data centre in a more critical light. Gordon Walker of the University of B.C. informed Jim Hesser of DAO that some astronomers viewed the data centre as a "potential sacrifice," others believed that the CSADC computers were being integrated into the DAO's equipment, and many spoke of the fact that the CSADC did not yet have its own leadership. John Glaspey of the Université de Montréal wrote Hesser that "the rest of us are begging for nickels and dimes to put together the most basic data analysis facilities" while the CSADC gets funded despite the postponement of the HST launch. He also noted the "intermixing of CSADC funding with DAO operations." Claude Carignan of the U de M also told Hesser that with the delays facing HST, "I surely don't see the urgency of upgrading what I consider already as a quite decent installation."[18]

Hesser, who had become director of the DAO in December 1986 at the same time he got these letters, responded that he could not let the equipment sit idle during the wait for HST. "We are searching for areas in which we can use the equipment and expertise we do have to serve the [Canadian astronomical] community." Andy Woodsworth, a radio astronomer whom HIA Director General Donald Morton named as CSADC Coordinator as the year ended, told Carignan that the work of archiving and distributing HST data was too complex and expensive for most universities. He pointed out that STScI would not be equipped to help visiting academics: "Canadian users will find that, even if Baltimore is closer than Victoria, they will not get much computer time at the STScI." He also said that contrary to the impression that the CSADC might be supporting DAO work, there were concerns at the DAO about having to use its resources to support the CSADC. As well, some equipment purchases were put off due to the delays in the launch of HST, and astronomers at the data centre worried about upcoming purchases that would be necessary if CSADC equipment was to remain compatible with STScI.[19]

Hesser was aware that more and better communication with Canadian astronomers was needed to save CSADC from the chopping block. He made plans to have CSADC astronomers meet with astronomers in other parts of the country, and regular updates on the data centre started appearing in *Cassiopeia*, the quarterly CASCA publication that went out to all Canadian professional astronomers. In December 1986, the first CSADC newsletter quoted the deputy director of the STScI, Garth Illingworth, on the availability of computer time at the institute for HST users: "We expect that the majority of the computational effort needed to analyze HST data, including the archival data, will be done at the researcher's home institution. … Clearly routine access by HST researchers, be they US-based or from the international community, will not be possible."[20]

CSADC and the Internet

In addition to new personnel and computers capable of storing and handling astronomical data, plans for CSADC in 1986 also included connecting to computer networks that were being developed at the time to move various forms of data electronically across long distances.[21] At the time, personal computers were coming into use, along with networks that were used to share files and for early forms of email. Today's internet is deemed to have descended from the ARPANET sponsored by the Advanced Research Projects Agency (ARPA) of the U.S. Department of Defense, which began linking distant computers together in 1969. As military uses were spun off from ARPANET in the early 1980s, Usenet, Bitnet, and many regional and local networks were coming into existence. As late as 1992, soon after ARPANET was closed and the internet was being opened to all, internet users were still made up of almost even numbers of governmental, educational, military, non-profit and commercial entities. Later on in the 1990s, large numbers of individuals and businesses began connecting to the internet.[22]

It is important to note that the internet in Canada sprang from Canadian networks that were inspired by computer networks in the U.S. but were separate until the late 1980s. Following news of the creation of ARPANET, Canadian universities began to develop similar networks of their own in the early 1970s. Creating such networks in Canada proved to be more challenging than south of the border because of Canada's much smaller population and its far greater distances between population centres. In those days of limited telephone and data lines that involved expensive long-distance charges, the greater expense involved in tying Canadian computers together was a major issue. Many Canadian universities formed regional networks while discussions continued over the formation of national networks. Over time, the Canadian government in the form of the Defense Research Establishment and the Department of Communication (a forerunner of today's Innovation, Science and Economic Development Canada) became involved, along with Canadian telecommunications companies, and even amateurs who linked up to Usenet and Bitnet.[23]

In 1986, the NRC became more interested in computer networks as it sought to boost collaboration with researchers in academic and industrial settings in a whole variety of scientific disciplines. That year the NRC appointed Roger Taylor to head up a new Division of Informatics to put together a state-of-the-art computer network that would encompass NRC facilities from coast to coast. In February 1987 Andy Woodsworth contacted Taylor and other NRC officials in non-astronomical disciplines to inform them that the newly formed CSADC was planning to handle data from HST, which meant that it would tie into NASA computers and the NSFnet, then a major academic computer network in the U.S. supported by the National Science Foundation (NSF). To facilitate data sharing for its network, the NSF had chosen TCP/IP (Transfer Control Protocol/Internet Protocol), which had been in use at ARPANET since 1983. A history of Canada's internet noted that the NSF's choice of TCP/IP "was anything but a foregone conclusion," but was an important milestone on the way to the protocol's adoption for the wider internet.[24] The work of creating what was known for a time as NRCnet got approval from the leadership of the NRC in the spring of 1987, but winning endorsements from higher government authorities such as Treasury Board proved to be a protracted and complicated process. A major player in this process was Woodsworth, whose duties at the CSADC were supplemented with his appointment as Project Manager for NRCnet.[25]

There were many issues behind the protracted decision-making in Canada. One was a competing data transfer protocol to TCP/IP with powerful supporters in Canada and elsewhere. In Canada, support for the rival transfer protocol took the form of a competing proposal for a Canadian computer network. By 1989 as the debate raged on, NRCnet had become part of a larger National Research Network (NRnet or NRN) in 1989. That June, the Treasury Board accepted the NRC's proposal for a network that would use TCP/IP until the rival protocol was ready. The approved network was soon given a new name, CA*net, with Woodsworth as Project Manager.[26] Over the next year, work proceeded to set up the new Canadian network and connect it to NSFnet in the U.S. CA*net continued until 1997 through the tumultuous changes that led to today's internet dominated by commercial players, and it was succeeded by the Canadian Network for the Advancement of Research or CANARIE, which operates Canada's research and education computer networks to the present day.[27] Today's internet operates using the TCP/IP protocol, and one reason is that Canada's timely choice for TCP/IP had received a nudge from the NRC's ties to NSFnet to receive Hubble data for the CSADC.

In 1990, Tim Berners-Lee and others at the CERN particle physics laboratory on the French-Swiss border developed the more sophisticated protocols and tools that made the World Wide Web possible. After the first web browser, Mosaic, became available in 1993, new and more powerful browsers soon made the internet more accessible to millions of users.[28] Thanks to the efforts of Canada's internet pioneers, including those at the DAO, Canadians took full part in this technological revolution from the beginning.

CSADC becomes CADC

After the difficulties of 1986, CSADC was engaged in building itself up and gaining credibility with Canadian astronomers during the post-*Challenger* delays in the launch of HST. The two Research Associates, Crabtree and Durand, had completed nine-month postings at STScI early in 1987 and returned to CSADC, Crabtree with full staff status. Hesser and Crabtree began visiting Canadian university astronomy departments to explain the role of CSADC: "Those of us working on the project see it as an important new astronomical research facility, with tremendous potential for facilitating archival research," Woodsworth wrote in *Cassiopeia* in March 1987, noting that CSADC was emphasizing the development of software and systems expertise while assisting university astronomers who wished to develop their own image analysis facilities. With the internet still over the horizon, CSADC was equipped with a Datapac connection, which used dedicated telephone lines supplied by Canadian telecommunications companies to move packet-switched data. At the time, telephone access to Datapac was restricted to 1200 baud modems, although directly connected computers could obtain data at higher speeds. CSADC was joining NetNorth and planning to join the Astronomy/Astrophysics Network that was being proposed by STScI at that time. "One of the key factors for the success of the CSADC will be effective low-cost communication links with our users," Woodsworth explained. That year, CSADC began offering access to various catalogues, including STARCAT, along with electronic discussion groups and mailing lists.[29]

In 1988, the centre got a new name and a new look. "Our name has recently been changed by dropping the word 'Space' [to the Canadian Astronomy Data Centre or CADC]. This was done partly to emphasize NRC's desire that we should archive certain ground-based data sets (this might, for instance, include CFHT CCD images) and partly because of a perception that the old name was too long," a data centre update in *Cassiopeia* explained. "We do not expect any major changes to our current activities, which emphasize the archiving and distribution of data from space observatories, particularly the Hubble Space Telescope." Hesser recalled that Morton, HIA's Director General, promoted the idea of archiving CFHT data at the CADC, which "really had a huge impact through its demonstration of how the field was changing through widespread adoption of digital detectors."[30]

The completion of the DAO's new office extension that year allowed the CADC to move into long-awaited permanent quarters as it upgraded its connections to other computer networks around Canada and the U.S. CADC continued to offer STARCAT and a European database from Europe known as SIMBAD, that "provides complete bibliography since the mid 1950's on all stars, as well as comprehensive lists of cross-identifications, fluxes, the best positions available, etc." [31]

When the Hubble telescope underwent ground testing in February 1989, CADC was involved. "HST was put through an extensive test (GST-5) of all functions. This test includes the distribution of the data acquired during the "observations" to the archival centres in Garching [ST-ECF] and Victoria," CADC reported in the March 1989 *Cassiopeia*, adding that: "We must ensure that we can read the optical disks and build the catalog entries correctly. Après ça, le déluge: we must be able to handle HST data at a rate of some 2 GB/day." CADC had plenty of time to prepare, however, because it could not expect to receive any data until a year after Hubble's launch because data were reserved to the observers requesting them during that period. That report also contained the first reference to the internet in a public CADC report. "DAO has now joined BCnet which, among other things, provides us with access to the US Internet (NSFnet, ARPAnet. etc.)."[32]

Funding for CADC remained a major issue that year. Early on, the NRC agreed to pay for the cost of HST data acquisition from STScI. Although the NRC had set a budget of $4 million a year for space astronomy, which represented an important increase over previous years, a 1989 report from Canadian space astronomers said that they would not be able to take full advantage of this investment because "the current resource levels for the CADC will probably not permit it to handle data archiving, distribution, or user assistance related to new [space astronomy] missions, whether they have Canadian content or not." The report noted CADC had developed a detailed plan to build and operate an archive for data from the CFHT. And new space telescopes such as the *Compton Gamma Ray Telescope* and others operating in infrared and X-ray wavelengths were being developed. Yet because of the long delays to HST's launch and cutbacks to NRC programs, the CADC "has not yet received sufficient resources even to enable it to handle HST data effectively," mainly in terms of funding for personnel. By that time, the CADC had provided popular catalogue and analysis service to Canadian astronomers that had built support within the Canadian astronomical community. And CADC had established credibility with STScI and with European astronomers. "Unfortunately this credibility has also meant that [STScI] have hired away one of CADC's best people." The report called for funding coordinated between NRC, NSERC, and the newly established Canadian Space Agency (CSA) to support data analysis from HST and upcoming missions, and support for Canadian university astronomers using space telescopes.[33]

CADC "kept a very low profile" in the months leading to the launch of the *Hubble Space Telescope* on 1990 April 24. In the months before and after the launch, CADC upgraded its equipment, particularly the "infamous" Britton-Lee database machine and began hiring new personnel in spite of continued tight money. A notable hire during this time was Séverin Gaudet, who brought important computer science and project management expertise to CADC. CADC prepared to receive data from HST with Hutchings, who was on the team for Hubble's GHRS instrument, and Hesser, who was principal investigator on an observing program on HST's Wide Field/Planetary Camera (WF/PC). Woodsworth's two years of work as Project Manager for CA*net and the efforts of others at CADC began to pay off in the summer of 1990 when the network began operations with 56 kbps data speeds to every province through provincial networks. "The implications for the CADC are that our users can now connect to us at much higher speeds and lower costs than was the case with Datapac service." CADC also began turning its plans for the archive for CFHT into reality, and had been asked to propose creating an archive for the twin 8-metre Gemini Telescopes.[34]

Hubble is Launched

Two months into Hubble's mission in June 1990, NASA and STScI announced that their analysis of the first images from HST showed that its main mirror had been precisely ground to the wrong shape. The resulting spherical aberration meant that HST's observations fell short of expectations. Hubble had been designed so that its instruments would be changed out by astronauts from visiting *Space Shuttles*, and a replacement camera for WF/PC was already being built in 1990. Soon the new Wide Field Planetary Camera 2 (WFPC2) was redesigned to compensate for spherical aberration, and scientists at STScI developed an instrument called COSTAR that contained mirrors that would adjust the light paths to other instruments to compensate for the defective primary mirror. Shuttle astronauts installed the new instruments on board HST in December 1993, and the fixes worked.[35]

"The various HST problems have certainly been disappointing to everyone," Woodsworth said in a CADC update in *Cassiopeia* in December 1991. "However, we had now completed all the work necessary to handle HST data, and we will build the archive as planned, with financial support from the Canadian Space Agency." By then, many astronomers had discovered the complicated and difficult application process for observing time on HST, and CADC helped Canadian observers deal with this process by developing software and "cookbooks" to help with the calculations and other work involved in filling out application forms. When applications for HST time later shifted from paper to online forms, STScI eased this process.[36] In 1992 and 1993, more researchers around the world made observations on HST despite its optical problems, and more data became available from STScI, ST-ECF and CADC. The success of the first *Space Shuttle* servicing mission in 1993 heralded the beginning of full operation for HST. By then, Woodsworth had moved on to become the Canadian Project Manager for the Gemini Telescopes and later as the Director General of the NRC's Institute for Information Technology, among other positions. Crabtree succeeded Woodsworth as coordinator at CADC in 1992. Crabtree later moved on to posts at CFHT and Gemini before becoming acting director of the DAO as he neared retirement.

Although the spherical aberration that afflicted HST's mirror represented a serious setback for Hubble, it has been widely noted that HST would have been in far worse condition had it been launched in 1986 instead of being delayed for four years because of the *Challenger* disaster. The launch delays and HST's subsequent mirror problem gave the people at STScI, ST-ECF and CADC valuable time to advance the technology of storing and sharing astronomical data from HST, according to Daniel Durand. "Hubble being launched in 1986, that would have been a disaster, in a sense that when we launch a mission, you really freeze everything," he recalled years later. "You can't do anything to the system for a number of years, so, Hubble being late, they had a humungous opportunity to make the system evolve at the same pace as the technology evolved. And that really made a difference."[37]

Cooperation with STScI and ESA

The work of creating the HST data archive at STScI began in the months before Hubble was launched in 1990, when NASA Goddard contracted Loral AeroSys to build the Data Archive and Distribution Service (DADS). When development problems with DADS delayed its activation to1992, STScI developed an interim archive system, the Data Management Facility, with help from European astronomers at the ST-ECF and Canadians at CADC. Collaboration between the archives at STScI, ST-ECF, and CADC continued, with the Europeans and CADC assessing new storage media as they shifted from optical discs to CD-ROM (compact disc–read-only memory) and onward to DVDs during that decade. By 2005, data were stored on hard drives. The three archives went on to develop new interfaces between the data and data catalogues using the internet. ESA closed the ST-ECF in 2010 and moved its HST archive in 2012 to the European Space Astronomy Centre (ESAC) in Villanueva de la Cañada near Madrid, Spain, where ESA runs its Solar System and astrophysics missions and archives data from these missions.[38]

Sharing and handling digital data was much different in the early 1990s than it was even a decade later. The work of storing, processing, indexing, retrieving, and sharing the data was complicated and difficult. The DADS system for HST became fully operational and open to outside users in October 1994 after 880 gigabytes of data representing all of the HST data contained at the time in STScI's Data Management Facility were converted to data formats compatible with the widely used FITS data format before being transferred on optical discs to the DADS system. In order to ease the work of scientists using Hubble data, CADC developed means of automatically generating preview images for data in the archive, and together with ST-ECF, the CADC developed a data visualization tool known as SkyCat that was usable on the then newly created World Wide Web, the first web-based interface for Hubble data. Handling HST data was further complicated by the fact that data were generated by Hubble's instruments, which were regularly changed out in five shuttle servicing missions between 1993 and 2009. During this time, STScI had to focus its efforts on dealing with Hubble's mirror problem and upgrading its instruments, so much of the work improving archives and user interfaces on the ground was left to ST-ECF and CADC, Hesser explained. [39]

As noted above, the World Wide Web arose in the middle and late 1990s along with new and more powerful computer software and hardware, together with growing bandwidth available to computer users around the world.[40] STScI sought to exploit the growing capabilities of the internet to assist astronomers using HST through initiatives such as the Project to Re-Engineer Space Telescope Observing (PRESTO) and Goddard's Vision 2000 program. On the archival side, STScI began HARP, the Hubble Archive Re-Engineering Project, in 1996 with the goal of streamlining archive operations, improving online access, and reducing costs by moving to lower-cost storage media. One of the features incorporated at this time was on-the-fly calibration of data, which was developed by CADC and ST-ECF. Because uncalibrated data were easier to compress than calibrated data, only uncalibrated data needed to be stored in the archive. Since the data could be calibrated at the time they were retrieved from the archive, astronomical data were therefore shared with astronomers using the very latest and best calibration reference data available at any given time. On-the-fly calibrated data were made available through CADC starting in early 1996, dramatically reducing data storage costs. Starting in 2008, the CADC and ST-ECF took advantage of the increase in computing power by upgrading calibration of data to a cache system where data are calibrated when software and calibration is upgraded, rather than waiting for data requests from users.[41]

Reflecting more than two decades later on the help the astronomers from CADC rendered to the much larger and better funded Space Telescope Science Institute, Crabtree, Durand, and Woodsworth discussed the reasons for their success: "Us and the Europeans, we were much smaller; we didn't have this operational, you know, operating the spacecraft overhead or having to worry about it," Crabtree said. "So, we were much more nimble. And I think, to this day, what makes the CADC successful, is that we had astronomers and software people in the same area, talking to each other, hourly. Or very frequently. It wasn't: 'astronomers write down requirements, hand them over to the software people.'" Durand explained that this approach "fostered more creativity." Woodsworth looked at his two colleagues and observed: "You shouldn't underestimate the value of having real research scientists doing the work that these two guys did. The older model might have been, another model might have been, 'why don't we see if we can get a database expert, a computing science grad who is a database expert, and he could go do what Daniel did. And maybe we can get somebody who's an engineering grad. Maybe he can do what Dennis did, and maybe initially, it would have gone faster, because he didn't have to learn about databases, and that sort of stuff.' But then we never would have had the insight into what astronomers need done that would allow them to make it happen."[42]

Growing Archives

The digitization of data and the arrival of the internet made data sharing among astronomers much easier in the late 1990s than previously. As well, during that time archives became more important sources for HST data for astronomers than observing time on Hubble. By the end of 1998, the year STScI made all HST data available online, the average data retrieval rate from the archive was two to three times the rate of data entry from HST observations. The STScI reported that this marked a departure from the historical practice of using science data from telescopes just once because previous research findings had not been catalogued or made available in an easily accessible form. [43] The fact that much new HST data remained proprietary to investigators for a year after observations were made did slow the sharing of data. STScI Director Robert Williams's decision in 1995 to make the entire data set associated with the first Hubble Deep Field observations available to everyone immediately after it had been processed was a landmark step in making astronomical data available to all.[44] When the STScI archive expanded to cover astronomical observations from other sources including the IUE, the Extreme Ultraviolet Explorer, digitized sky surveys, and radio data from the Very Large Array in New Mexico, it became known as the Multi-mission Archive at STScI (MAST) and later the Barbara A. Mikulski Archive for Space Telescopes, in honour of a U.S. Senator who supported HST. By the end of HST's 29th year in 2019, MAST held more than 2.3 petabytes of data, with 173 terabytes of data from Hubble alone.[45]

Researchers at STScI, the European Space Astronomy Centre, and CADC continue to this day to work closely together on maintaining and improving their archives. Just as the HST archive in Baltimore has expanded to cover other missions, CADC has grown vastly beyond HST, and the Europeans have shifted from an archive for HST to a new location where data from many observatories are stored. Each of the three archives have transformed themselves from a physical archive where astronomers came to process their data that were stored on computers and media such as discs to one where data were moved on the internet.

CADC has gone through expansions and transformations of its own in the 21st century. After beginning as a place where Canadian astronomers went to obtain data from the *Hubble Space Telescope,* CADC soon began archiving, processing, and sharing data from other space telescopes and from ground-based observatories, notably CFHT and more recently Gemini, the James Clerk Maxwell Telescope, and others, including radio telescopes such as ALMA (Atacama Large Millimetre/Submillimetre Array) and CHIME (Canadian Hydrogen Intensity Mapping Experiment). While the amount of data available from HST and other space telescopes has expanded exponentially, so has the quantity of data from observatories such as CFHT, whose data output expanded over the years with instruments such as MegaPrime/MegaCam. CFHT's current expansion program promises further growth in its data output. As new observatories come on stream on Earth and in space, the amount of data available from CADC and other archives is already exceeding the imaginations of astronomers from the time CADC was created. In 2020, CADC held 1.6 petabytes of data in 310 million files from 219 different astronomical instruments. Nearly five million petabytes of data were downloaded from CADC in 2020. There were 100 million downloads that year or three downloads per second to users around the world. The staff complement for CADC grew from about a dozen in 2002 to 20 in 2022.[46]

While computers used by astronomers can store and process large amounts of data, the explosive growth in the quantity of available data from newer instruments has defied the capacities of these computers. This has led to the rise of cloud computing where data are processed where they are stored. J.J. Kavelaars, an astronomer who began using CADC when he started work at the DAO in 2002 and today is the Head of CADC, explained in an interview that the growing need for storage capacity led the CADC in 2008 to encourage the creation of CANFAR, the Canadian Advanced Network for Astronomy Research, which uses storage facilities at the University of Victoria, Simon Fraser University, and other Canadian universities. CADC was also being encouraged to move its astronomical data offsite from the DAO into CANFAR at that time because the NRC was questioning whether it should be paying for this storage capacity that was being used by university researchers.[47] At the time, the federal government was consolidating its computing support systems into Shared Services Canada. And the shift of CADC data to CANFAR was further encouraged by a 2014 cyberattack by "a highly sophisticated Chinese-state sponsored actor" against the NRC's computer systems. Much of the vision and the work of moving the astronomical data to CANFAR was spearheaded by David Schade, who headed CADC at the time, and Chris Pritchet of the University of Victoria.[48]

In recent years, processing applications on computers have moved to containerized computing, which Kavelaars said makes it easier for users to choose applications in the cloud they need to process their data, which is also in the cloud. In the words of Dennis Crabtree: "The CADC is now in a different model altogether than it was in before, when I was associated with the CADC. The original idea was, the CADC would have the data and the astronomers would travel to the CADC. But then the internet came along, and what would happen is that the data would flow to the astronomer from the CADC. All that data [now] sits in the cloud, with the storage and the computing ... So, data never moves; what moves now is the software. So the CADC went from moving astronomers to moving data to where astronomers now move software."[49]

Conclusion

Many scholars have written that the rise of massive astronomical archives such as those discussed in this article and those related to astronomical survey programs such as the Sloan Digital Sky Survey means that growing numbers of astronomers are doing their work without reference to observatories or their own observations as they did in the past. Historian W. Patrick McCray has written about the larger groups of astronomers that have become involved in each discovery and each published paper, and how the shift of astronomical work from telescopes to archives has changed the nature of astronomy itself, making it more reliant on gigantic instruments and databases in a manner similar to particle physics.[50]

Most of today's archives of astronomical data are based in the United States and Europe. The creation of the CADC has ensured a Canadian presence in the world of big astronomical data, making data available to Canadian researchers and providing exposure for Canadian astronomical research. In a relatively short time, observations have changed from being stored on glass plates hidden away in observatory basements to being widely available through cloud computing. Big data in astronomy means astronomers have observations of growing numbers of objects available in multiple wavelengths at their fingertips. Easy access to multiple observations from the past and present mean that changes in astronomical objects can be easily tracked over time. Growing availability of data in terms of wavelength and time provides previously undreamed-of opportunities to learn about our Universe.

CADC was created in the 1980s as a means for Canadian astronomers to gain access to the anticipated trove of data from the *Hubble Space Telescope*. Today in the age of big data in astronomy, CADC means much more to Canadian astronomers and to astronomers from other parts of the world who wish to share in the bounty of astronomical instruments in space and on the ground. Although Canada was never a formal partner in Hubble, CADC became Canada's contribution to the work of HST, just as HST contributed to the evolution of Canadian astronomy in part by inspiring the creation of CADC. The development of on-the-fly calibration in Europe and Canada constituted a major contribution to the work of HST and other astronomical instruments. In the words of Jim Hesser: "CADC and the ST-ECF complemented STScI efforts in a manner that brought great value to the international partnership that was unforeseen when we started in 1986. The value of the excellent relations that slowly but steadily built between STScI and NRC/DAO/CADC has been of enormous value to Canadian astronomy."[51] Although the CADC's infrastructure has shifted from computer and disc storage at the DAO to cloud computing in CANFAR, Kavelaars argues that in some ways, things haven't changed: "The CADC was essentially cloud-based computing from the very first day because we were providing access to data over the internet that you could just retrieve, which was essentially a cloud data repository. … That transition was basically from NRC hardware to university-funded hardware, and we no longer have anything to do with maintaining the physical infrastructure."[52]

Because of the work of Canadian astronomers and instrument makers with Hubble, CFHT, and other telescopes, along with the relationships established through CADC, it is no surprise that the Canadian Space Agency joined NASA and ESA as a full partner in the *James Webb Space Telescope*, contributing one of its four instruments and its Fine Guidance Sensors.[53] After many years of development, JWST was launched on 2021 December 25, and its data are already flowing into archives like MAST and CADC. Soon those data will be joined by observations from even newer and more powerful astronomical instruments. ✶

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Endnotes

1 The development of HST is covered in Robert W. Smith, *The Space Telescope: A Study of NASA, science, technology and politics* (Cambridge: Cambridge University Press, 1993); and Christopher Gainor, *Not Yet Imagined: A Study of Hubble Space Telescope Operations* (Washington: National Aeronautics and Space Administration, NASA SP-2020-4237, 2021) pp. 1–52, 120–124.

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3 NRC Associate Committee on Astronomy, *The Future of Ground and Space Based Astronomy in Canada* (Ottawa 1974); Working Group on Space Astronomy, *A Report Submitted to the Ad Hoc Committee on Canadian Scientific Experiments for the Space Shuttle/Spacelab Programme* (Ottawa: National Research Council of Canada, 1977), pp. 4-6. For more on the spherical aberration that afflicted HST's main mirror, see Gainor, *Not Yet Imagined*, pp. 26–32, 53–75.

4 For more on Canadian efforts in the 1970s and 1980s to develop space telescopes, see Christopher Gainor, "*Starlab* and the Beginnings of Space Astronomy in Canada," *JRASC*, December 2020, pp. 266–275. Dr. Hutchings was also a longtime member of the teams for the Goddard High Resolution Spectrograph and the Space Telescope Imaging Spectrograph on HST. Each proposal cycle for HST corresponds to roughly a year. See Gainor, *Not Yet Imagined*, pp. 347–350.

5 Paul E. Ceruzzi, *A History of Modern Computing, Second Edition* (Cambridge Massachusetts: The MIT Press, 2003) 243–306.

6 Hubble Second Decade Committee, "The Hubble Data Archive: Toward the Ultimate Union Archive of Astronomy" (Baltimore, STScI, December 2000), 6–8; Jim Hesser, email to Chris Gainor, "Re: CADC question," 2017 July 14; NASA HST policy guidelines 3, "Foreign Data Coordinating Facilities," attached to letter from W.R. Lucas, Director, Marshall Space Flight Center, to Dr. Noel W. Hinners, Director, Goddard Space Flight Center, 1984 July 3.

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11 Treasury Board Submission, NRC, 1985 August 8, "Approval to upgrade the main computing system at NRC's Dominion Astrophysical Observatory in Victoria, B.C.;" attached to a letter from Stephen C. Morris to several astronomers, 1985 October 21, "Status of Space Telescope Data Centre Project." See also Program Selection Committee 1984–85, "Proposal for Additional Resources," NRC, December 1984. These and other papers from 1985 and 1986 were shared with the author by Dennis Crabtree.

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14 Sidney van den Bergh, "NRC Space Data Centre at DAO," *Cassiopeia* No. 48 (September 1985), 7; and "CSADC Working Group Progress Report – 1986 December 22". See also Gordon Walker and Peter Stetson, "The Canadian Space Telescope Data Centre," attached to letter from Gordon Walker to Sidney van den Bergh, 1986 January 16; Oral History Interview (OHI) by author with Dennis Crabtree, Daniel Durand, and Andrew Woodsworth, 2019 August 17, p. 6; and James E. Hesser, email "CADC," 2022 August 26. For more on STARCAT, see B. Pirenne et al., "A Distributed Clients/ Distributed Servers Model for STARCAT," R.J. Hanisch, J.V. Brissenden, and J. Barnes, eds., *Astronomical Data Analysis Software and Systems II, ASP Conference Series, Vol. 52*, 1993, pp. 95–99.

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16 "The Canadian Space Astronomy Data Centre," 1986 May 6; Dennis Crabtree, "Report on the CSADC," 1986 August 25; "Data Centre Status Report," undated but likely early 1986; Andrew Woodsworth, letter to Remo Ruffini, 1987 January 29. The effect of the *Challenger* disaster on HST is discussed in Gainor, *Not Yet Imagined*, pp. 42–44.

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26 *A Nation Goes Online*, pp. 83–92.

27 *A Nation Goes Online,* pp. 92–130; Thompson, *Internet in Nova Scotia*, p. 24. Woodsworth served as Project Manager for CA*net until 1990.

28 Ceruzzi, *History of Modern Computing*; New Media Institute, "History of the Internet."

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30 "Canadian Astronomy Data Centre, Newsletter No. 5," *Cassiopeia* No. 58 (March 1988) pp. 36–37; James E. Hesser, email "CADC," 2022 August 26.

31 "Canadian Astronomy Data Centre, Newsletter No. 5," *Cassiopeia* No. 58 (March 1988) pp. 36–37. See also Canadian Astronomy Data Centre, Newsletter No. 6," *Cassiopeia* No. 59 (June 1988) pp. 32–34. In his 2017 OHI with Durand and Woodsworth, Crabtree said the word "Space" was taken out of the data centre's name to avoid any suggestion that it was associated with the Canadian Space Agency, which began operations a few months later in 1989 (p. 5).

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35 The story of HST’s spherical aberration and the repairs is told in the first three chapters of Gainor, *Not Yet Imagined*.

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37 Gainor, *Not Yet Imagined*, 44; OHI with Crabtree, Durand, and Woodsworth, p. 10.

38 The contract to build DADS originated with Ford Aerospace, which was sold to Loral in 1990. Riccardo Giacconi, *1991 STScI Annual Report*, Baltimore, MD, 1992, pp. 2, 22–24; 1992 Institute Visiting Committee Report, p.4; Second Decade Committee, “The Hubble Data Archive,” 8–10; Rudolf Albrecht, OHI by author, 2015 November 9, pp. 13–16; Giacconi, *Secrets of the Hoary Deep*, p. 234; Crabtree, Durand, and Woodsworth, OHI; author conversation with Daniel Durand, 2022 August 27. Durand noted that at one point, CD-ROMs were accessed from “juke boxes” originally developed for use in Japanese bars. Data archives for HST are discussed in Gainor, *Not Yet Imagined*, pp. 310–316.

39 Robert E. Williams, *Annual Report to AURA Board of Directors: Space Telescope Science Institute*, STScI, Baltimore, MD, March 1995, pp. 1, 33; Second Decade Committee, “The Hubble Data Archive,” p. 9; N. Hill et al., “Generation and Display of On-line Preview Data for Astronomy Data Archives,” from D.R. Crabtree, R.J. Hanisch, and J. Barnes, eds., *Astronomical Data Analysis Software and Systems III, ASP Conference Series, Vol. 61, 1994*, pp. 15–188; OHI with Crabtree, Durand, and Woodsworth, p. 15; and James E. Hesser, email “CADC,” 2022 August 26. HST carries five different instruments at any time plus its fine-guidance sensors, which were also used for research purposes and were changed out along with other instruments during five Shuttle servicing missions from 1993 to 2009. Not counting the fine-guidance sensors and an instrument that corrected HST’s spherical aberration, 11 different instruments operated on HST.

40 See Ceruzzi, *History of Modern Computing*, and Christopher Gainor, “The Hubble Space Telescope in Cyberspace,” *Quest: The History of Spaceflight Quarterly*, vol. 24, no. 2 (2017) pp. 4–12.

41 Robert E. Williams, *Annual Report to AURA Board of Directors: Space Telescope Science Institute*, STScI, Baltimore, MD, March 1997, 10, 15; Second Decade Committee, “The Hubble Data Archive,” p. 10; Dennis Crabtree, “Recalibration of Archival HST Data,” *Cassiopeia* No. 90 (March 1996), 6; Daniel Durand et al., “HST in the Clouds: 25 Years of HST Processing,” from Nuria P. F. Lorente, Keith Shortridge, and Randall Wayth, eds., *Astronomical Data Analysis Software and Systems XXV, ASP Conference Series, Vol. 512*, 2017, Astronomical Society of the Pacific, pp. 351–354; Felix Stoehr et al., “The HST Cache,” from D. Bohlender, D. Durand, and P. Dowler, eds. *Astronomical Data Analysis, Software and Systems XVIII, ASP Conference Series, Vol. 411*, 2009, pp. 155–158; OHI with Crabtree, Durand, and Woodsworth, pp. 18–20. The work done at ST-ECF before 2010 has since been done at the European Space Astronomy Centre (ESAC).

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53 See Canadian Space Agency news releases, “Canada to build key component of NASA’s next giant space telescope,” 2004 September 16; “Canadian Space Agency ‘Eyes’ Hubble’s Successor: Canada Delivers its Contribution to the World’s Most Powerful Space Telescope,” 2012 July 30; Vincent McDermott, “Gateway to the Universe: How the James Webb Space Telescope is cutting through visible light with a Canadian Edge,” *SkyNews*, November/December 2022, pp. 40–43. For background on early Canadian involvement in what became JWST, see Simon Lilly, *The Next Generation Space Telescope (NGST), Submission to the Long Range Planning Panel*, 1998 November 27.

Light Speaks to Us. 1.

by Gilbert St-Onge (RASC, CDADFS, SAM, FAAQ) and Yves Tremblay (CDADFS)

Thanks to Pierre Bastien (Scientific Reviewer), département de physique Université de Montréal, OMM, CRAQ

Abstract

Many amateur astrophotographers use narrowband filters dedicated to capturing the emissions around specific wavelengths of the electromagnetic spectrum to enhance the appearance of their images of the sky.

It must be noted that these filters primarily reveal certain emission properties of the chemical elements they isolate. For example, by using these filters, we can learn about the properties of abundance, distribution, and intensity, maybe even of the variability and evolution of these emission lines in these nebulae. Since not all celestial objects have the physical properties necessary to display these emission lines, it may sometimes be useless or even ineffective to use such filters. However, these filters are very interesting for certain kinds of "detective work," such as that presented in this document.

Résumé :

Bien des astrophotographes amateurs utilisent des filtres à bande étroite dédiés à la détection des raies d'émission de certains éléments chimiques du spectre électromagnétique, pour rehausser l'apparence de leurs images du ciel. Il faut savoir qu'au premier plan, ces filtres nous révèlent certaines propriétés des émissions des éléments chimiques qu'ils isolent. Par exemple, en utilisant ces filtres, nous pouvons mesurer l'abondance, la distribution, l'intensité et peut-être même la variabilité, donc l'évolution de ces raies d'émissions dans ces nébuleuses. Comme tous les objets du ciel ne présentent pas les propriétés physiques nécessaires à l'apparition de telles raies d'émission, il peut parfois être inutile, voire inefficace, d'utiliser de tels filtres. Cependant, ces filtres sont très intéressants pour certains travaux de détection, tels que celui présenté dans ce document.

Introduction

In 2004, Gilbert St-Onge and Lorraine Morin studied—in low resolution in OIII, Hα, and SII emission domains—the Dumbbell Nebula (Messier 27 / NGC 6853) in the constellation Vulpecula (DSS Plate Finder coordinates $\alpha = 19^h\ 59^m\ 36.36^s$, $\delta = +22°\ 43'\ 15.7''$). This paper is a follow-up of their publication available at https://astrosurf.com//stog/Travaux-Recherches-%c9tudes/m27_filtres/m27.htm.

A planetary nebula appears telescopically as a small nebula enveloping a star from which it originates. Specific physical conditions in planetary nebulae allow for the presence of emission (bright) lines in their spectra, such as the intense oxygen [OIII] doublet at 500.7 nm and 495.9 nm or of hydrogen alpha, Hα, at 656.3 nm.

Literature states that confirming a source is indeed a planetary nebula implies that its spectrum must display the above-mentioned double lines of OIII and Hα, and that they must be in emission, i.e. above the continuum level. The 500.7 nm [OIII] line must be prominent in the spectrum, probably followed by that of Hα at 656.3 nm, then by the second OIII line at 495.9 nm. Other emission lines, generally less intense, are also mentioned, such as Hβ, Hα, oxygen [OI], neutral HeI or simply ionized helium HeII, simply ionized sulfur [SII], or simply ionized nitrogen [NII]; however, we did not use filters matching these emission lines.

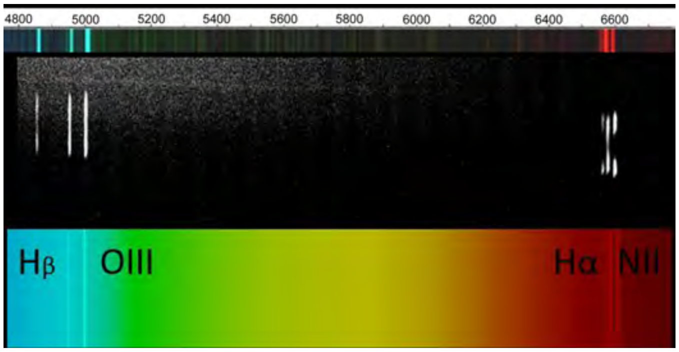

Figure 1 — Top: Raw spectrum of Messier 57.

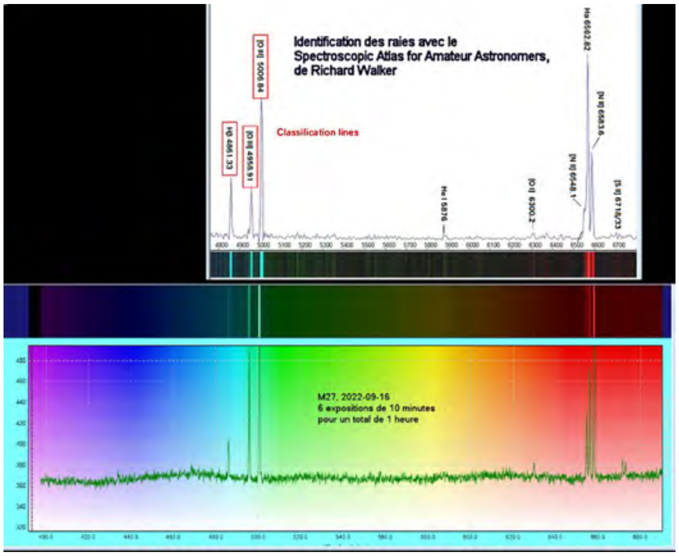

Figure 2 — Calibrated spectrum of Messier 27.

(The numbers above the spectra are given in ångström (Å))

Figure 1 shows the spectrum of the Messier 57 planetary nebula in Lyra, imaged on 2019 April 7. Figure 2 shows the spectrum of the Messier 27 planetary nebula in Vulpecula, imaged on 2022 September 16. Both images were obtained by Damien Lemay from his Rimouski (Québec) observatory. C11 Edge telescope on Losmandy Titan mount, LhiresIII

300 lines/mm diffraction grating spectrograph, SBIG STL 8300 camera, stack of 7 images of 300 seconds each with MaximDL, Integrated Spectrographic Innovative Software (ISIS), and. Basic Astronomical Spectroscopy Software (BASS).

These two planetary-nebula spectra (of M57 and M27) correspond closely to what is mentioned in the literature (e.g. Osterbrock and Ferland 2006), both displaying spectra dominated by emission lines, mainly those of Hα, OIII, Hβ, SII and NII.

Observations

Based on these two spectra, we ran observations of the Messier 27 (NGC 6853) planetary nebula using filters that isolate emission bands from Hα and OIII as well as an "IR 72 Is" filter whose bandwidth is approximately 740 nm (70%) to approximately 1000 nm (30%). Other images were taken without any filter, corresponding to a bandwidth of approximately 400 nm to ~1000 nm.

Our main objectives were to:

- Confirm Messier 27's morphology, as established in 2004, with these filters, during our first observing run of this nebula.
- Seek a possible improvement of the model, based on higher-resolution images taken in 2022.
- Implement a program to detect planetary nebulae under specific conditions (separate publication).

Confirm Messier 27's Morphology

We can see, in Figure 3b, the orientation we gave to our description of planetary nebula Messier 27. (Observations were made with a Celestron 9.25-inch Schmidt-Cassegrain telescope at *f*/6.3.)

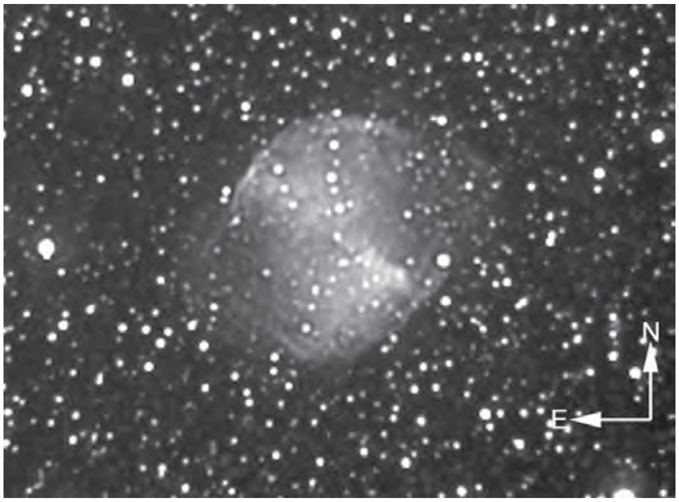

Figure 3a — Messier 27 imaged by St-Onge and Morin in 2004, with a bandwidth of approximately 400 nm to 1000 nm.

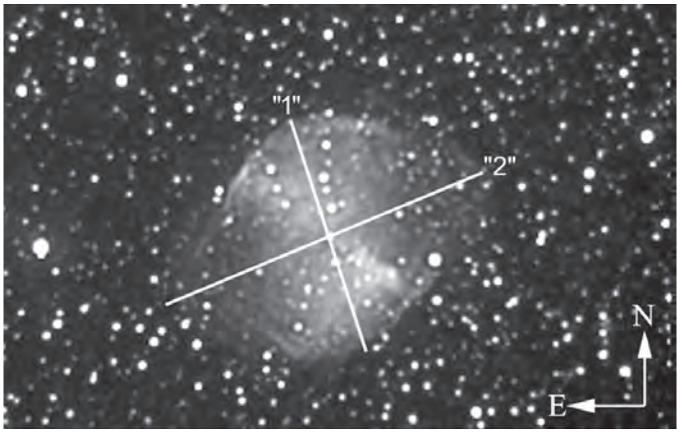

Figure 3b — Annotated image showing two perpendicular axes.

Region 1 is the brightest visible part of the nebula and has a bipolar morphology comparable to that of an hourglass, whose long axis ends in thinner and more intense curved regions. This section of the nebula is tilted almost 20° with respect to the North Celestial Pole (position angle of approximately 340°). Region 2 (~SE/NW) also shows lobes, but these are not as bright.

First Observation Results (2004)

On this occasion, we took 10-minutes total exposures per filter, under a good-quality sky, away from the pollution of big cities, using a C9.25 telescope at *f*/6.3 and a grade-1 St7Xme CCD camera.

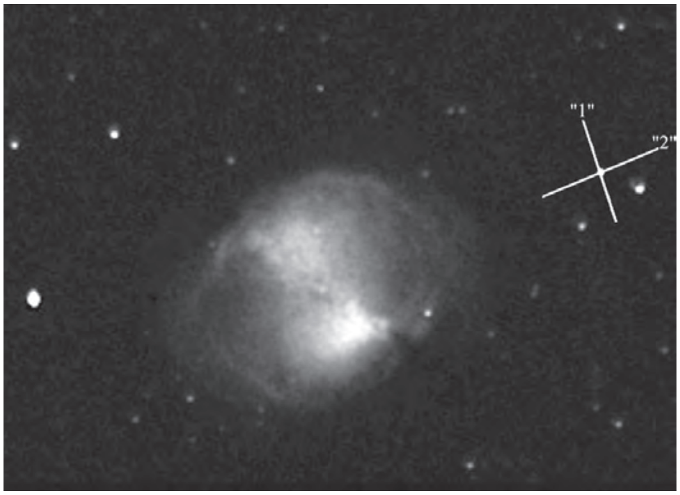

Figure 4 — M27 imaged in 2004 with an O III filter (495.9 nm and 500.7 nm wavelengths).

Doubly ionized oxygen [OIII] is detected everywhere in the nebula and is quite intense on axis 1. It seems to float, like an oxygen-ion haze, over the entire surface of the main axis 1. Remember that the OIII line at 500.7 nm is generally dominant in planetary nebulae.

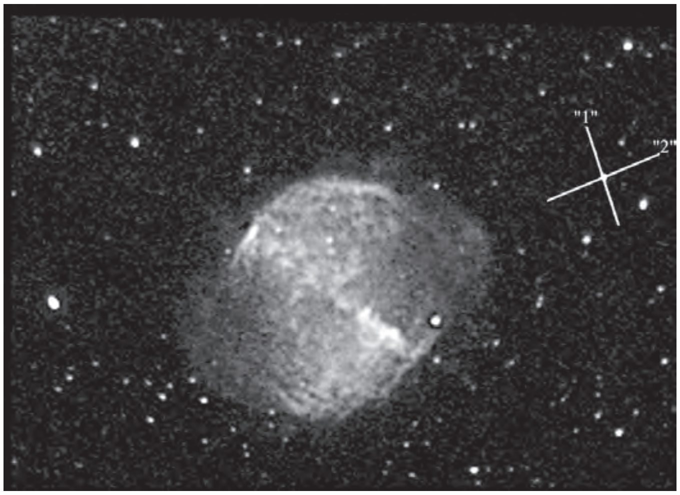

Figure 5 — M27 imaged in 2004 with an Hα filter (656.3 nm wavelength).

This shows Hα emission—one of the most important elements detected in planetary nebulae—being present on the whole surface of the nebula along axis 1. Its surface is much more detailed and covered with multiple intersecting nodes of varying intensity and surface. A large bright wall crosses the whole nebula from north-east to south-west. At the north and south extremities, large intense arch-shaped structures are visible, resembling bow shocks; they are quite intense in Hα.

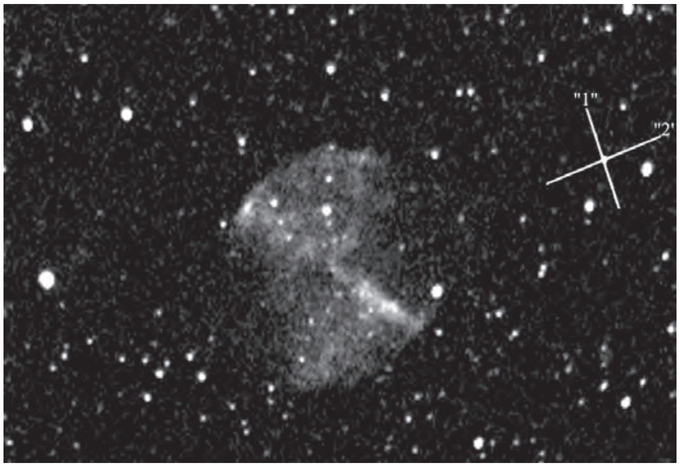

Figure 6 — M27 imaged in 2004 with an SII filter (671.6 nm and 673.1 nm wavelengths).

This shows the SII (sulphur lines), is much less intense than in the previous two figures. We can see that the transverse wall (NE–SW) is dominant; the rest of the hourglass shape of the main nebula (axis 1) is less intense and imprecise.

This filter allows the detection of near-infrared elements (793 nm to approximately 1100 nm), representing the continuum spectrum. We can see that the signal of this image is very weak, even with 10-minute exposures, in agreement with literature that says that these nebulae have visible surfaces consisting almost exclusively of emission elements; these are not reflection nebulae.

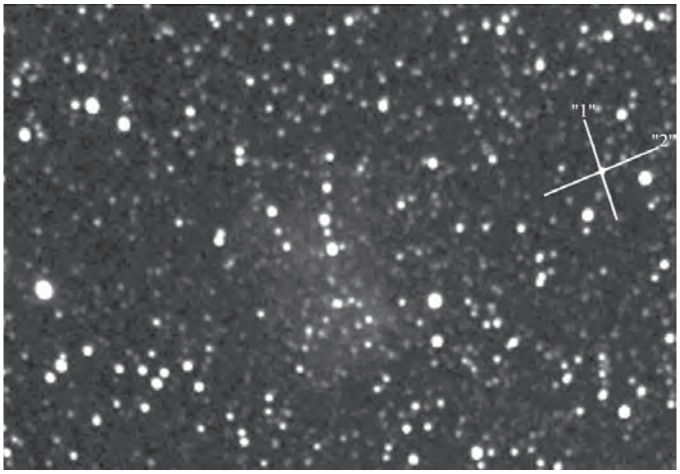

Figure 7 — M27 imaged in 2004 with an "IR 72 Is" filter (bandwidth of approximately 793 nm to approximately 1100 nm).

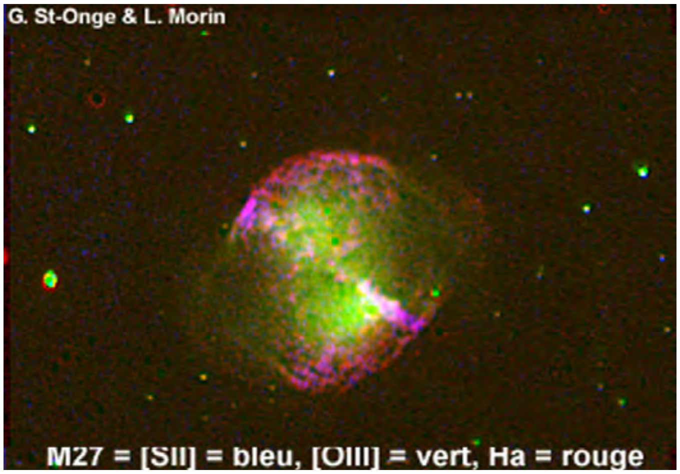

Figure 8 — shows our Messier 27 results for the model for our 2004 observations.

The three images of the emission elements studied here have been combined to better see how they are distributed on the surface of this planetary nebula. *The SII is blue, OIII is green, Hα is red.

Seek a Possible Improvement of the Model

New Observation Results (2022)

In 2022, we wanted to validate our 2004 observations, but this time from Montréal suburbs under a sky contaminated by big-city lights and by all other constraints brought by the nearby presence of a large city. The new images were produced at a longer focal length (2 m), using a C8 $f/10$ telescope located in Dorval (western suburb of Montréal). Filters were the same as in 2004, except for the "IR 72 Is" filter, which was used only for M57.

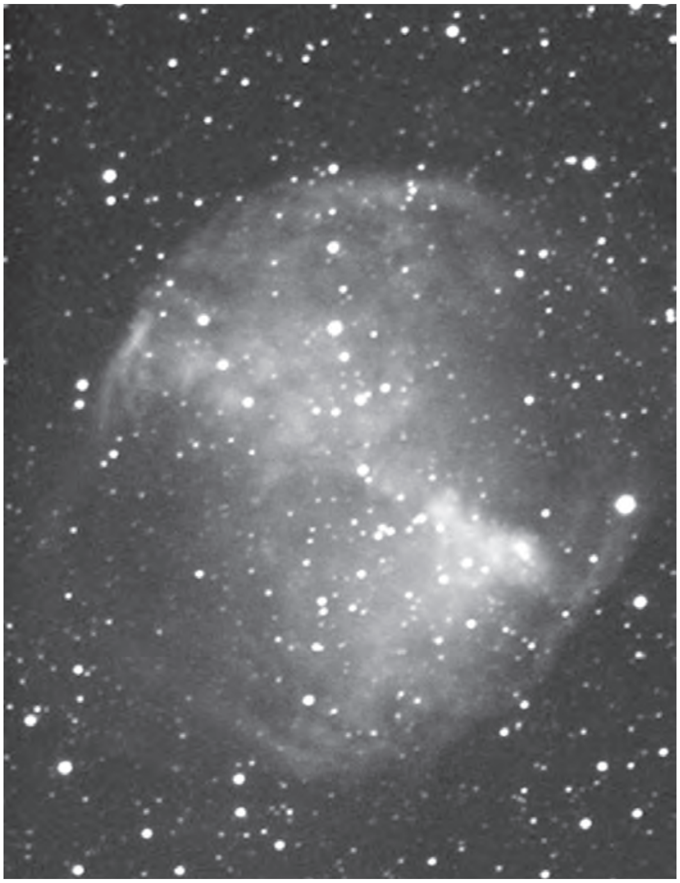

Figure 9 — The planetary nebula Messier 27, in visible light (no filter; ≈ 400 nm to ≈ 1000 nm), captured with a C8 Schmidt-Cassegrain telescope at ƒ/10 and an ST7 XMe grade 1 CCD.

Figure 9 is one of the resulting images from the 2022 Dorval observations (program ended 2022 August 5). For this image no filter was used, so we have a bandwidth of ≈ 400 nm to ≈ 1000 nm, under a suburban sky (western suburbs of Montréal). This very large bandwidth includes all the emission lines presented above in previous figures. All the intersecting nodes and the transverse wall are well detected, as well as the more intense arched structure to the north and south of the nebula, whose morphology is in the shape of an hourglass on the north/south "axis 1."

Although oxygen seems to be distributed over virtually the entire surface of the planetary nebula, there are several regions of different intensity, mainly darker compact structures distributed over a large dark and curved (arc-shaped) region that crosses the nebula from east to west, well aligned with the nebula's central star easily identifiable in this figure.

In the foreground, we can clearly see the large transversal wall, rather bright in Hα, and the arc-shaped regions to the north and south of the great hourglass-shaped nebula. Many nodes are visible, more clearly in the northern part of the nebula. We can also see the large dark curved region that crosses the nebula from east to west, that is darker to the south of the central star.

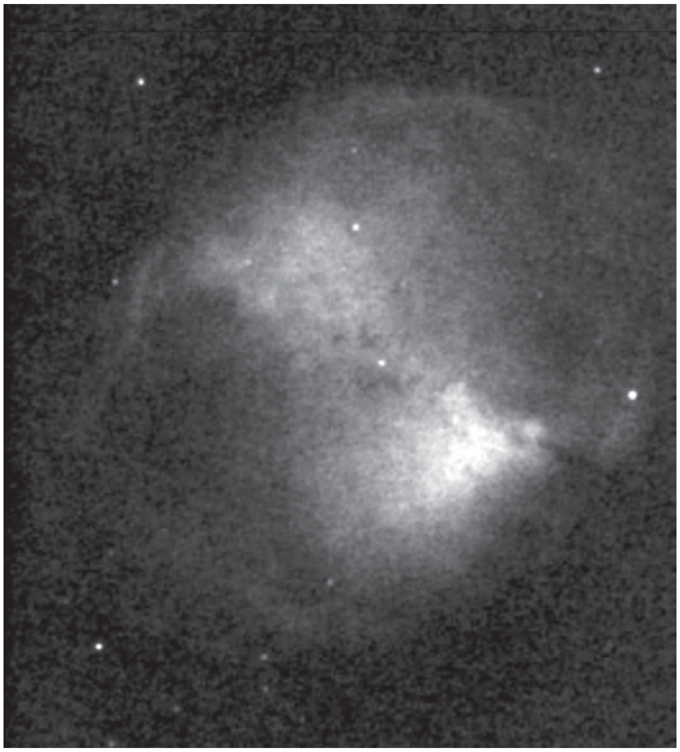

Figure 10 — The distribution of OIII in M27.

Darker in OIII, this structure seems to overflow on each side of the brighter, hourglass-shaped nebula. It can also be detected in the dimmer regions to the east and west, and is wider in OIII than in Hα. This dark region is also detected in unfiltered images where its morphology is closer to what is observed in Hα

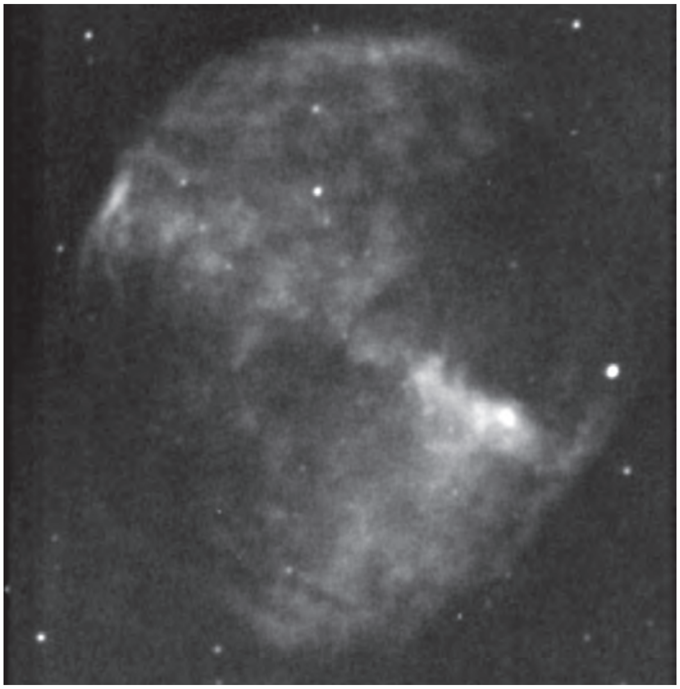

Figure 11 — The distribution of Hα in M27.

Continues on page 26.

Steve Tambosso captured this beautiful landscape with the Milky Way stretching above at Lundbreck Falls in southern Alberta. Steve says, "I shot this image at almost midnight on 2019 August 4, using my Canon 5DS R with a Sigma 14-mm 1.8 lens on a Sky-Watcher tracking mount on my Manfrotto tripod. The foreground was exposed with the tracking mount off for a single four-minute exposure at ISO 1000 at ƒ/2.8. The tracking mount was on for the single three-min exposure of the Milky Way sky, also at ISO 1000 and ƒ/2.8." The two images were then layered and processed in Photoshop.

The Dumbbell Nebula is a great target for astrophotographers, and Steve Leonard captured this fantastic image of it using composite RGB and narrowband image data. The inner core is from RGB data, and the outer nebulous region is from the narrowband data. Steve says he acquired the data (both RGB and HOO) separately and "processed to get an RGB image of the bright nebula core (and RGB stars) and an HOO image that included the outer nebulosity. A blended composite image was then generated from the RGB and HOO images, with the nebula RGB core coming from the RGB image and the outer nebulosity coming from the HOO image, with the hue of the outer HOO portion adjusted to match the inner RGB portion. All image data was captured under Bortle 8/9 skies."

Katelyn Beecroft imaged a favourite winter target: the Horsehead and Flame Nebulae. Katelyn says, "This duo is easily among my very favourite targets to image and process. There is so much going on between the bright Hα nebula, the beautiful dark structures, and even the cute reflection nebula (NGC 2023) found below them. This image is mostly RGB data (8h 45min) with Hsym added in, which is from imaging with the L-Extreme filter (6h 45min). I love the pop in the reds that the L-Extreme gives." Katelyn used an Askar FRA400 telescope with an ZWO ASI533MC camera on an HEQ5 mount, which was guided using the ASI120mm mini and ZWO 30-mm ƒ/4 guidescope.

For February, what else is more iconic than the Heart Nebula? John Ceko imaged the nebula (also known as IC 1805) using a WO Redcat 51 telescope on an EQ6R Pro mount. He used an ASI183 MC Pro camera together with an L-Extreme. John took 178, 120-sec subs. The final image was processed with PixInsight, Lightroom, and Photoshop.

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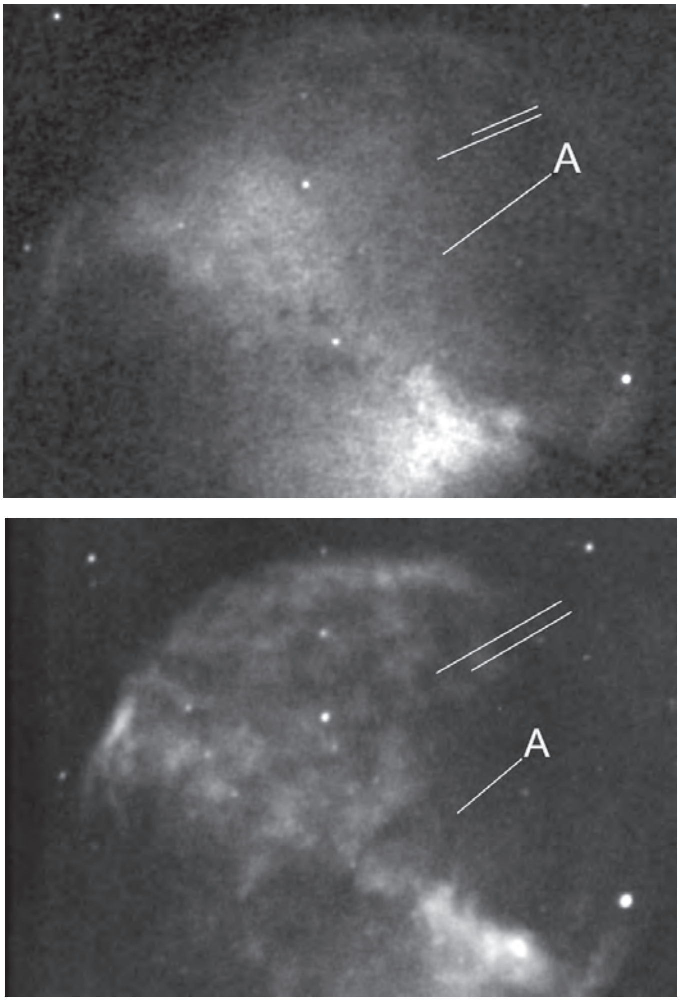

Figures 12 / 13 — OIII (top) and Hα (bottom) seem to show a curved, darker structure (marked "A") that crosses M27 from east to west (axis 2).

OIII is dominant in the heart of the great hourglass-shaped nebula, while Hα is more present at the northern and southern ends of this great structure (axis 1).

We also note that the dark "A" region (see Figures 12 and 13) contains several small compact areas that are darker in OIII in Figure 10 but are mostly dominated by Hα in Figure 11 and 14.

This shape is more familiar and the stars allow us to better locate and understand the abundance ratio of OIII and Hα across the nebula. We can also clearly see the line of the great bright transversal wall, dominated mainly by Hα.

Discussion and Conclusion

It is therefore possible to identify a planetary nebula by other means than its spectrum.

We have been able to confirm, through these observations, the fact that planetary nebulae are important sources of doubly ionized oxygen (OIII) and Hα emissions that can be imaged using appropriate filters. It is therefore possible to use these conditions to our advantage to optimize our images of these planetary nebulae. We also think that it is possible to isolate the signature of each of these emission lines by differential imaging.

To conclude this first step, we can validate our observations by comparing them with those of another planetary nebula, namely M57, the Ring Nebula in Lyra. These images were

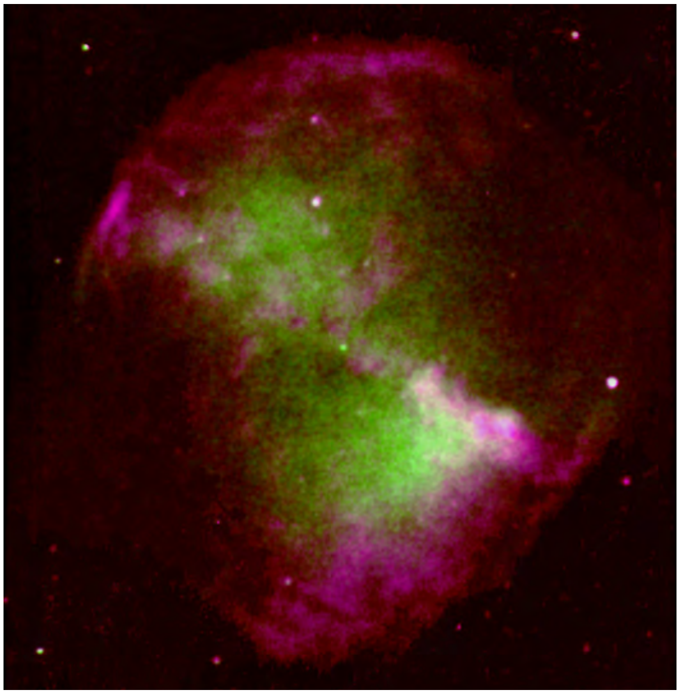

Figure 14 — Shows the overall distribution of OIII (in green) and Hα (in red) in M27.

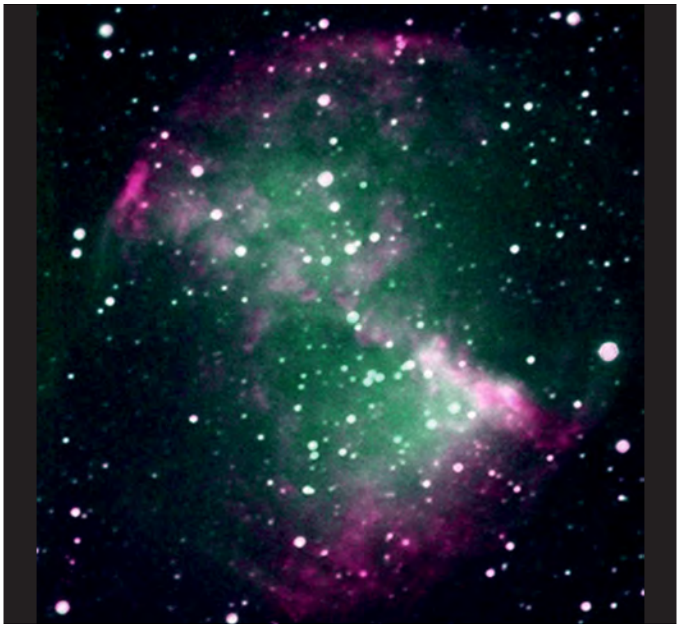

Figure 15 — This image of M27 shows the general spread of OIII (in green) and Hα (in red), superimposed on an unfiltered image (bandwidth from ≈ 400 nm to ≈ 1000 nm).

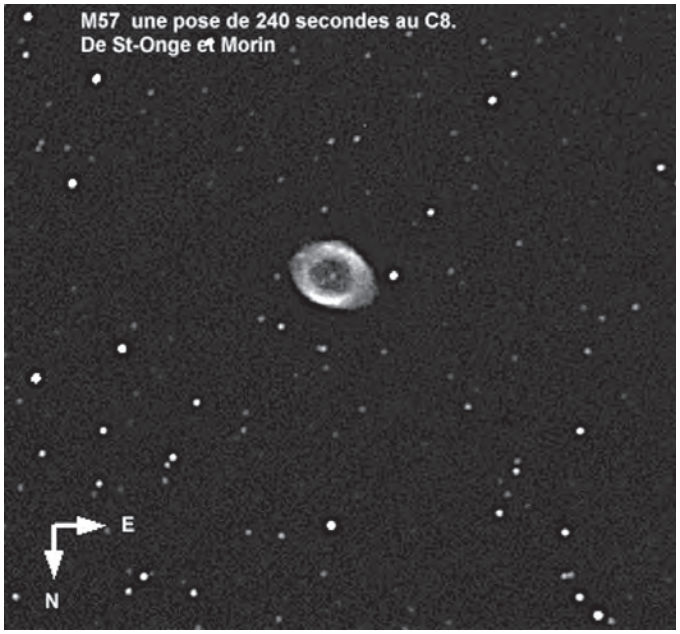

Figure 16 – An unfiltered image, exposed 240 seconds, that shows the total sensitivity range of our detector, viz. ≈ 400 nm to ≈ 1000 nm.

taken in the early 2000s by Gilbert St-Onge and Lorraine Morin, and confirm the results presented above.

This image (figure 17) is the result of a single 1080-second exposure with an $H\alpha$ filter, sensitive to the 656.3 ± 5 nm line, that lets us see M57's $H\alpha$ emission. We see that few stars in this region emit in the hydrogen alpha line; even M57's central star is practically absent. This is consistent with our 2022 $H\alpha$ images of Messier 27, where the central star is almost undetectable (see Figure 11).

M57's appearance is very different from that seen on other images: we only see a very diffused, pale disk in the background sky.

This filter only lets through the continuous spectrum ("continuum"), and only one element, in low, nonsignificant emission, can be detected, viz. doubly ionized sulfur (SIII) at 953 nm. We notice two stars in the gas ring (toward the left), and the absence of the nebula's originating star in the centre of the ring. Inside the ring, we detect only a hint of a faint star, down and a little to the left.

As discussed above, these objects are major sources of emission in OIII and in $H\alpha$ spectral lines. Based on these indications, we have set up a small observation program for imaging planetary nebulae from suboptimal observing locations. With that in mind, we have observed globular cluster M15 in Pegasus, which contains the planetary nebula Pease 1 (K648), near the heart of the cluster. A second paper will discuss this specific program. ✶

Figure 17

Figure 18 – This image results from a single 900 s exposure with an "IR 72 Is" filter, sensitive from ≈ 740 nm to ≈ 1000 nm.

We express thanks to Damien Lemay (Rimouski Astronomy Club, RASC, FAAQ, AAVSO), author of the Messier 27 and Messier 57 spectra used in this article, to Gerald MacKenzie and Dominique Tessier MacKenzie (RASC Montréal Centre) for reviewing the translation, and to Pierre Paquette (RASC Ambassador, Montréal Centre) for revision.

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Research Note / note de recherche

Finding Unknown Asteroids to Strengthen Planetary Defence: Best Project Award at the 2022 Canada-Wide Science Fair

by Arushi Nath, Toronto Centre

Editor's note: Arushi Nath is remarkable 13-year-old who has been long interested in astronomy. She, along with her 16 year-old brother Artash, have been active members of Toronto Centre for several years, providing interesting, in-depth talks. The following is a discussion on her award-winning research about detecting unknown asteroids.

The success of the NASA Double Asteroid Redirection Test (DART) Mission in slamming a kinetic impactor on moonlet Dimorphos of asteroid Didymos on 2022 September 26 and changing its orbit has put the planetary defence on world news.

The challenge of planetary defence intrigues me. Roughly 66 million years ago, an asteroid at least 10–kilometres wide may have led to the extinction of dinosaurs. If humans do not want to suffer the same fate, then we need to be well-informed and prepared to handle any threats of an asteroid colliding with Earth.

For the past two years, I have been using science and technology as a tool to solve some of the hard problems in planetary defence, starting from detecting unknown asteroids and moving on to tracking their orbit and getting information about their size and their rotation rate.

On 2022 May 19, my project "Strengthening Planetary Defence: Detecting Unknown Asteroids using Open Data, Math, and Python" won the Best Project Award (Innovation) at the Canada Wide Science Fair (CWSF) 2022 organized by Youth Sciences Canada. In addition, it won four other awards: a Gold Medal; the Excellence in Astronomy Award from The Royal Astronomical Society of Canada; the Top of the Category Award in Curiosity and Ingenuity; and the Youth Can Innovate Award. Over 350 finalists from regional science fairs across Canada participated in this prestigious 60th annual Canada Wide Science Fair (CWSF) hosted virtually in Fredericton, New Brunswick, from 2022 May 13–19.

My project on detecting unknown asteroids had five main steps: getting night-sky images using robotic telescopes, querying open datasets to find known objects, eliminating

Figure 1 — Arushi with awards won at the 2022 Canada-Wide Science Fair (CWSF).

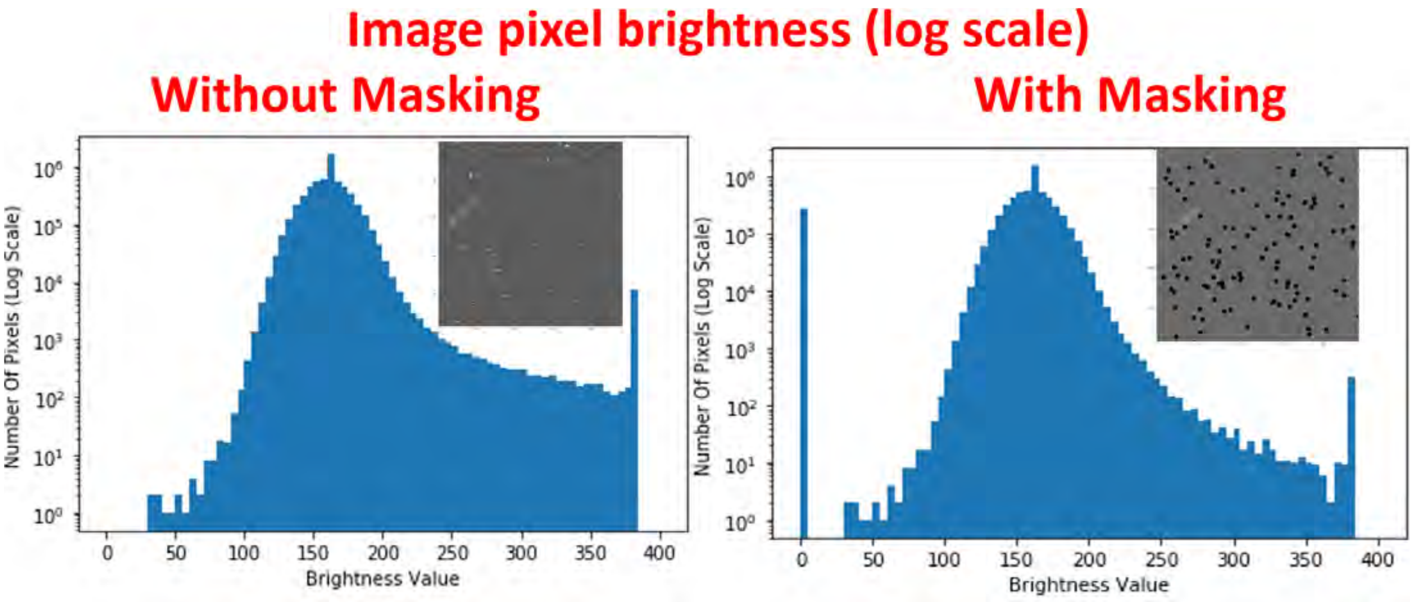

Figure 2 — Change in pixel brightness values before and after masking of known objects.

known stars, eliminating known asteroids, and finally finding unknown asteroid candidates.

As it is difficult to image the night skies from an urban light-polluted city such as Toronto, robotic telescopes located in remote regions under dark skies were used, with telescopes located in Australia, Canada, Chile, and Spain, I obtained hundreds of images of the night sky. I selected these robotic telescopes as they were located at different latitudes in order to get full-sky coverage and could be used free of charge by students for a limited time. Using robotic telescopes requires knowledge of the telescope, such as its aperture, its camera, filters to be used, exposure time to be used, and calibration of darks and flats.

I then wrote algorithms in Python to query available open datasets of night skies to find known objects in my images, namely known stars and known asteroids. These datasets are provided by NASA, the European Space Agency, and a host of other organizations. To find known stars, I started with the USNO-B1.0 all-sky star catalogue of the US Naval Observatory. But it was not able to correctly identify all the stars in my images. Later, I discovered the GAIA Early Data Release (EDR3) star catalogue of the European Space Agency, which was able to reference all the known stars in my images. To find known asteroids in my images, I turned to the Horizons Database of the NASA Jet Propulsion Laboratory, which had an exhaustive list and details of all known asteroids, including those recently submitted to the Minor Planet Database run by the International Astronomical Union (IAU).

To map known objects given in tabular databases to images of the night skies requires several steps, starting with plate solving. Plate solving is about identifying which part of the night sky was imaged and its field of view. Plate solving of images uses the meta information provided in the Flexible Image Transport System (FITS) header of the images, including focal length of the telescope, right ascension and declination coordinates, pixel size of the camera, and the pixel scale. As stars do not move in the time frame of our observations, but asteroids move across the image, the time of the observation in Universal Time Coordinated (UTC) is also needed.

I used Python libraries to project the celestial coordinates onto the pixel coordinates of my images. To improve the accuracy of these star and asteroid positions on my images, I developed a centroiding algorithm. The algorithm assumed that stars were circular, and brightest in the centre while becoming dimmer as they moved toward the edge. The key was finding the radius of these circular-assumed objects so that I could use my middle-school math skills to find their area and create custom-sized masks to hide known objects in my images. The bigger stars had higher-radius masks, while the smaller-sized stars had lower-radius masks around them. These made it easier to

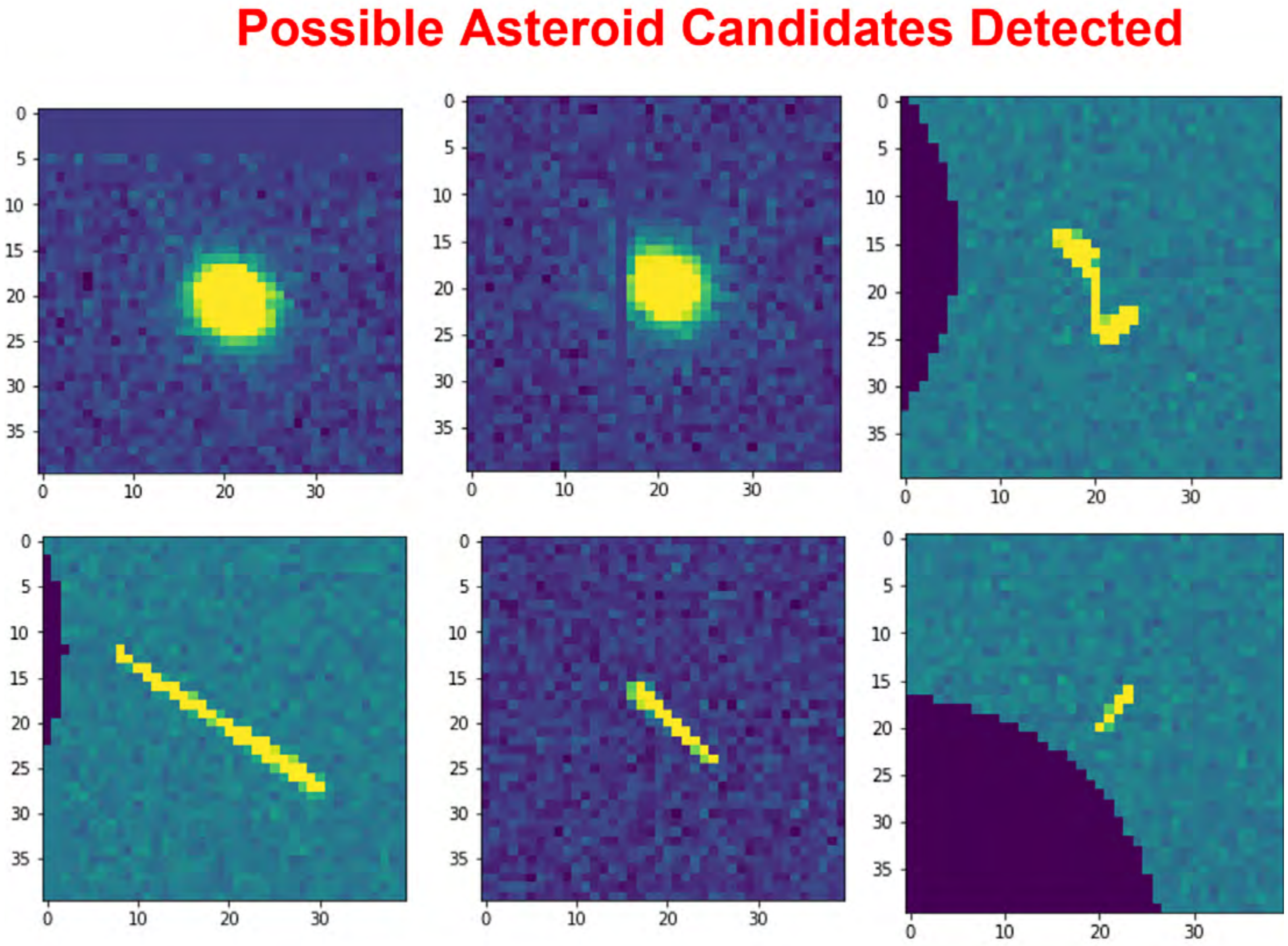

Figure 3 — Possible asteroid candidates detected after removing known objects.

eliminate them. The remaining objects were possible unknown asteroid candidates or noise.

Filtering out the noise was essential. Noise could appear on the image because of dirt, hot pixels, meridian flip, or telescope drifting during long observations. While noise is normally a few uniformly bright pixels scattered around the image, asteroids are pixels with varying brightness clumped up together. My algorithm used the standard deviation tool to get the spread of pixel brightness and eliminated objects with smaller spreads (more uniform brightness) that are more likely to be noise. The remaining objects were classified as possible asteroid candidates.

I detected three preliminary asteroids. I reported this information by creating a Minor Planet Center report for my images. It was very satisfying to have developed a project that could bring together robotic telescopes, open data, math, and programming to reveal unknown objects in the night sky. I have made my code and methodology open-source on GitHub to crowdsource planetary defence. I have also been delivering training and workshops related to my project on different platforms, including at the monthly meetings of The Royal Astronomical Society of Canada (RASC), the RASC 2022 General Assembly, the Global Innovation Field Trip (GIFT) events, and the NASA Youth SpaceApps. I want to encourage other youth to apply their technical skills and passion for solving "hard" problems related to space and other sectors.

Winning the top award: the Best Project Award (Innovation) in my very first participation at the Canada Wide Science Fair 2022 was an amazing experience. I am glad that the more than 800 hours I invested in this project prior to my participation were well rewarded by winning the top award. I am motivated to take this project to the next level and provide citizen science support to the ongoing NASA DART Mission to measure changes in the Didymos asteroid system before and after the impact. Stay tuned! ✶

More information:

Plankton Wars and Planetary Defense take best project awards at this year's CWSF. https://youthscience.ca/plankton-wars-and-planetary-defence-take-best-project-awards-at-this-years-cwsf/

Skyward

Remembering Dear Friends

by David Levy, Kingston
& Montréal Centre

Constantine Papacosmas

As I get older and older, the list of people who depart gets longer and increases with a greater frequency. But now I find myself writing, for the third month in a row, about the loss of someone who meant a lot to me, and without whom I do not know how I will continue my own journey through the night sky.

Constantine Papacosmas introduced himself to me the first night I entered the old observatory of the Montréal Centre of The Royal Astronomical Society of Canada. The young observer had just completed a truly fabulous 8-inch reflector that we used once or twice. At that time, he was brilliant, creative, and inspiring. Within a few years we had become great friends, and we spent a lot of time together. One afternoon while walking down a hill to my junior high school classes, a car passed me, then slammed on its brakes about 300 metres away. Putting the car in reverse, the driver screeched backward until it reached me.

"Hello David!"

It was Constantine.

You might have read a few months ago the story of how I got my own 8-inch reflector, Pegasus. It was a loaner scope. By the time I had returned from college, Constantine had suggested that my parents buy me the telescope. We gathered in our living room, and my parents listened carefully as Constantine explained why they should make such an expensive purchase for me—and not for any of my siblings. He correctly persuaded them that I was never about to lose my passion for the night sky.

By the end of that day, my parents agreed to buy the telescope for $400, (which would, in 2022, amount to $3,761). More importantly, that afternoon gave Dad a chance to form a genuine bond with Constantine that he never forgot.

The April 2023 *Journal* deadline
for submissions is 2023 February 1.

See the published schedule at
rasc.ca/sites/default/files/jrascschedule2023.pdf

Figure 1 — Left to right: the author, Constantine Papacosmas, and Bill Strople at a Stellafane meeting.

In 1978, while resting in our home, Dad walked in and inquired how Constantine was doing. I had had a mild falling out with him, but I simply replied we hadn't been in touch for a while. Dad had something to say about that.

"You can count on the fingers of one hand the number of close friends you have had since your youth. You just cannot afford to lose those precious friends."

The minute he left the room, I telephoned Constantine, and we picked up where we had left off.

By 1984, my dad was dying from Alzheimer's disease. He could barely recognize Mom, let alone me.

But he remembered Constantine.

The two began talking.

"Constantine, do you know what is happening to me?"

"Yes, I am sorry, but I am afraid I do know."

"Constantine, I can't live like this. I wish … I wish I were dead."

Constantine told me that story many years later.

Those of us who knew the older Constantine may not appreciate the skill, the intelligence, the humour, and the talent of the younger amateur astronomer. But they remembered him well enough to present him with the Centre's highest medal for excellence, the Charles Good Award. His clock that I received shortly before his death now tells Montréal time. It is the Constaclock.

Farewell, Constantine, and thank you for enriching my nights under the stars.

Carl Jorgensen

> *"When sorrows come, they come not single spies,*
> *But in battalions." (Hamlet 4.5.76-77)*

This column begins with a delightful quotation from Hamlet, where King Claudius reflects on the deaths of Hamlet's father and Polonius, as well as the madness of Ophelia. In this lonely period of my own life, the one constant I have is being able to continue doing the stargazing that I love so much. In recent months, the losses of Don Machholz, Constantine Papacosmas, and Wendee have tested the strength of observing the night sky as never before. But I must add to this the passing of my closest friend from my youth, Carl Jorgensen, on October 18. Of these four transitions that occurred late this year, two of them—Don and Carl, both died from COVID. This is strong evidence that we are nowhere near being done with this dreadful illness.

Our lifelong friendship began in November of 1963. I had just returned from a 14-month stay at the Jewish National Home for Asthmatic Children in Denver. At the observatory of The Royal Astronomical Society of Canada in Montréal, Isabel Williamson introduced "young Carl Jorgensen" to "young David Levy," and our friendship never wavered over 59 stargazing years after that.

We both especially enjoyed observing shooting stars. In the late summer of 1965, Carl and I were counting Perseid meteors (that all seemed to radiate from the constellation of Perseus) when Carl began to sing to himself the lyrics of a newly released song. Carl went on and on under that clear sky.

"Carl," I asked, "what are you singing?"

"Bob Dylan's new song, 'Like a Rolling Stone.'"

"How long is this song supposed to last?"

"About six minutes."

"Carl, you've been singing it for over half an hour."

By the next time Carl and I met for observing, I had become a staunch Dylan fan as well.

In March 1976, those of us who liked comets were still reeling from the failure of Comet Kohoutek to live up to expectations. Another comet, found by Richard M. West, was supposed to be in the predawn sky, and Carl drove me out to see it. As we drove into a darker sky south of Montreal, I looked out past Carl's window and saw a magnificent comet rising in the east. Carl reacted to my exclamation: "OK, we'll find a spot. Set up the telescope and try to find it."

"Carl, just look to your left!"

Figure 2 — The picture is of Carl Jorgensen and his eldest daughter, Christine, in front of the old Isabel K. Williamson observatory. Photograph by the author.

Carl glanced out his window, and nearly drove the car off the road. What an unforgettable morning that was.

Carl enjoyed a lifelong interest in double stars. His favourite (and mine) was a beautiful triple star in the constellation of Cepheus. Known as Struve 2816, it is a magnificent triple sun. It is easy to find and wonderful to watch.

It is particularly evocative now.

"Doubt that the stars doth shine," Hamlet might have complained, but I think that even he would enjoy being with Carl to enjoy the sight of that lovely star. ✶

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* 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.*

Astronomical Art & Artifact

A Complementary Mode of Doing Science, a Complementary Mode of Doing History—Restaging Astronomical Experiments, Part One

by R.A. Rosenfeld, FRASC, RASC Archivist
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Abstract

The first part of this study sets the background for introducing the practice of restaging historical astronomical experiments as a promising research method open to amateurs.

We in the developed world have the impression that we're in a period (perhaps at its tail end) when usable astronomical equipment has never been more reasonably available to the amateur community, in quality ranging from decent to superlative. It is a condition our predecessors could only have dreamed of enjoying

Those impressed by the available equipment and its potential may also notice a paradox, that despite the availability of such capable gear, few amateurs are making—or aspiring to make—scientific contributions. Seventy or a hundred years ago the model for emulation was the amateur astronomer who participated in making science happen, rather than the amateur astronomer who was content to be a scientific tourist, even if a very accomplished one. It's a curious change, with no clear cause. What is clear is the substantial unrealized potential to actively contribute to science.

Restaging historic scientific experiments is an under-utilized, and under-appreciated approach to doing science, which can involve nothing more than the typical amateur equipment of today, or of the past. Many amateurs are unaware of this approach, which can result in real scientific contributions, and an enhancement to education and public outreach. This is described in the forthcoming part of this study.

Science and the Amateur Scene

In a period which has sometimes been dubbed the "golden age" of amateur astronomy, the 19th to the earlier 20th century,[1] a productive subsection of avocational amateur astronomers actively contributed to science through harvesting and reducing data, and some of the most respected leaders within the stargazing community suggested that this was something to which all should aspire (Smyth 1844, 366–369; Webb 1859, 9).

Looking back to that golden age and comparing it to the present, a marked qualitative change seems discernible in the roles of amateur astronomers.[2] The model of the scientifically contributing amateur as an aspiration for all is currently devalued and replaced by either an education and public outreach (EPO) model, or a passive tourist model, relegating amateurs to consumers of the night sky.[3] It could be argued that none of these modes are intrinsically baneful, but any stark imbalance in their representation within a culture of amateur astronomy is unsatisfactory, and potentially deleterious to that culture; the closer it approaches to being an astronomical monoculture, the duller, more undynamic, and boring it becomes. The richest amateur experience would involve practising all three modes, as time and opportunity allow.

In light of this change in the conception of what it means to be the highest expression or best embodiment of the amateur astronomer, one would like to see numbers stating the proportion of scientifically contributing amateurs to the general population of amateur astronomers, and to look for variations in that proportion over the last two centuries. Unfortunately, reliable, hard numbers for such a comparison spanning the "golden age" of amateur astronomy to the present are not to be had. What is available is an estimation of those numbers for the "present" era, that is, ca. 2000, published by Andreas Gada and colleagues over two decades ago (Gada et al. 2000).

The estimates of Gada et al. are useful, because they give a sense of scale not otherwise available. From their figures I take the median number of amateur astronomers of all types in North America to have been 325,000. And the median number of their class of "Master" astronomers—those with professional levels of skill—which I will take as a stand-in for scientifically contributing amateurs, comprised 750. Therefore 0.23% of amateurs fall into that class. In rounded figures, the population of North America in 2000 numbered 430,000,000 people. If 325,000 of them could be classed as amateur astronomers of some sort, then they accounted for but 0.076% of the population, a minuscule number. And, more exiguous yet, 0.000174% of the total North American population are scientifically contributing amateur astronomers. It is entirely possible that these proportions were varied much in the last century or so, even as prevalent models of amateur astronomy have drifted. That in itself would be sobering, as it implies that the room for growth proportion of amateur astronomers among the general population is static, and largely invariable. The same would apply to the proportion of amateur astronomers who contribute to science; it may never be more than

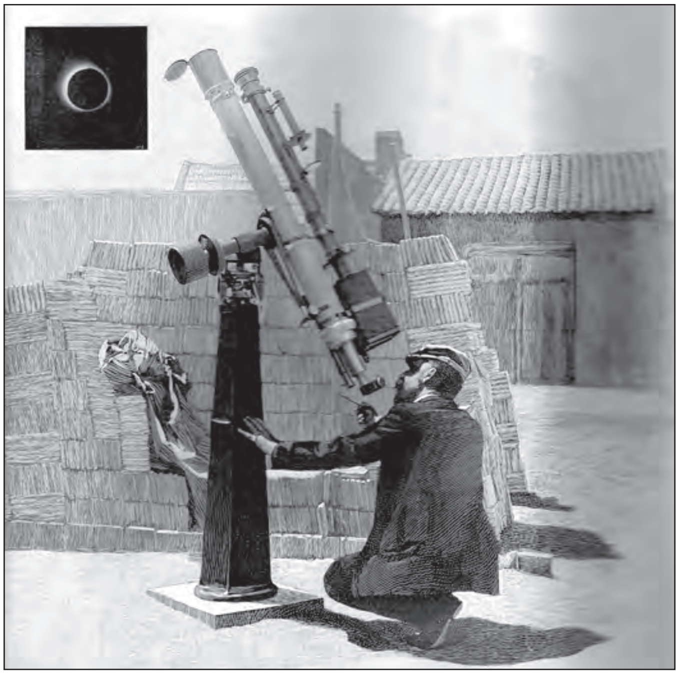

Figure 1 — Solar eclipse, 1900 May 28, Spain. Dramatic celestial events, such as eclipses, offer exciting opportunities to try replicating earlier observations to clear up ambiguities in historical reports, clarify current misunderstandings about how observations were made, or discover necessary experimental steps omitted from accounts. Reproduced courtesy of the Specula astronomica minima.

0.23% of all amateurs. And, at the other end of the amateur spectrum, there may be hard limits to the proportion of people in a given population in a given culture who will venture into amateur astronomy, and limits to the appeal of EPO missionizing by amateurs of all stripes to the population at large.

The story of the cultural shift from amateur astronomer (i.e., avocational scientist) to stargazer is complex, and in some respects still puzzling. Before turning to the possible causes, an influential cultural exception should be noted. The British Astronomical Association (BAA), founded in 1890 as an umbrella organization with sections covering diverse observational disciplines marked by a shared ethos, has provided a nearly constant example of an amateur institution committed to supporting its members in becoming real amateur scientists (while the BAA observing sections remain strong, in recent years the BAA seems to be making a bit more room for consumers of science, perhaps in the hope that once in the tent they may in time become active amateur scientists). The "RASC" in 1868–1869, and again immediately after its refounding in the early 1890s, started out along similar lines with generous help from BAA members in the second period, but all too quickly it transitioned to a mainly passive mode, with occasional flickerings and flares of active scientific resurgence being few and far between.

Figure 2 — The abbé Chappe d'Auteroche (1722–1769) on his 1761 transit of Venus expedition, taking altitude observations of lightning ("Experiment on natural electricity"). Not all historical experiments are good candidates for restaging, particularly if they contravene modern health and safety regulations. The exercise of informed judgement is never out of place. Reproduced courtesy of the Specula astronomica minima.

Tom Williams has cast welcome light on why BAA-style astronomy didn't become more prevalent in the United States, despite some promising starts in the 1910s and 1920s (Williams 2000a; 2000b). Instead, a few specialist, more narrowly focused societies formed to cater to those American amateurs who wanted to produce useful science, such as the American Association of Variable Star Observers (1911–), the American Meteor Society (1911–), and the Association of Lunar and Planetary Observers (1947–, founded by American RASC member Walter H. Haas) (Williams & Saladyga 2011; Haas 1993; Taibi 2017). The Canadian story has yet to be told, but some of Dr. Williams's analysis would likely apply here as well. For causes he points to geographical separation, possible generational conflict, territoriality, concomitant undermining, and a lack of influential media support at a critical juncture, all conspiring to make organizing scientifically inclined amateurs difficult in the early years. Additional factors deflecting amateurs from becoming scientists were the rise of the amateur telescope making (ATM) movement and the need of its devotees for physical space for their craft, and the willingness of the planetaria sprouting on the American urban landscape to provide that space. The first produced many people more interested in making telescopes than in using them—ironic, given that the foreword to the ATM "bible" is Harlow Shapley's clarion call to amateur telescope makers (ATMs) to turn their creations "advantageously for science" (Shapley 1933)!—and the second drew those ATMs from being potential producers of science to being unwaged EPO staff for planetaria. The lure of the latter would be irresistible to a young amateur at the time of the first space age.

What of the present? There are three technological developments that have had a profound effect on the nature of amateur astronomy in the last three or four decades: the availability of very capable astronomical equipment at relatively low prices; the digital astrophotography revolution; and suites of powerful information processing, analysis, and dissemination software.

The principal efficient causes of the availability of relatively inexpensive but good to superb quality amateur equipment were the increasing shift of its manufacture to China and Taiwan, where wages were much lower than in the U.S., and the fairly rapid improvement in techniques, and quality control in those manufactories (Harrington 2007, 80–81; Dickinson & Dyer 2008, 41, in regard to APOs). These changes began to be noticed in the 1990s (but the recent combination of worldwide pandemic(s), rise in geo-political tensions, and accelerating climate change resulting in supply-chain disruptions, increased costs of production and delivery, and diminishing discretionary budgets, may have spelled the end of the era of plentiful quality equipment at budget prices).

At the risk of repeating a commonplace, the revolution in amateur digital astrophotography has been striking. The advent and widespread adoption of digital photography (CCD and CMOS sensors, in dedicated astronomy cameras, DSLRs, and videocams) for the amateur market has given amateur astrophotographers capabilities undreamed of before ca. 2000 (Hughes 2013, 3, 95–100, 1313–1314, 1439–1448; Covington 2018, 19–20). It has placed professional capabilities in amateur hands, and made wonders of imagery achievable from light-polluted areas. This was not just a triumph of available hardware and optics; something else was needed.

The final efficient cause was the complementary availability of the software to process the images, and communicate them, computerized telescope and camera control, digital planetaria, databases, and the various platforms for all this.

Never before has so much advanced hardware and software been so inexpensively available for amateurs to contribute to astronomical science with their own equipment. But that hasn't happened. The overwhelming majority of self-identified "amateur astronomers" remain passive tourists of the night sky. It's a puzzle why that is so. There *are* amateurs who have taken advantage of their fine equipment to contribute to science (e.g. AAVSO DSLR Manual; SAS; Hubbell 2013). Other amateurs have taken another (but equally valuable) route in joining a mediated crowd-science platform to do science by working with data and images captured by professional facilities. As with the revolution in astrophotography, digital crowd science has been made possible through the ready availability of continuously developing hardware and software (Lintott 2019). Both groups of scientifically contributing amateurs have found the experience extremely rewarding (e.g. van Arkel 2011). There are just not enough of them.

Restaging historic scientific experiments with typical amateur equipment of today, or of the past, is another way for amateurs to take part in meaningful investigations, which can result in real scientific contributions, and can enhance education and public outreach. I don't presume to offer this as a proposal that will radically increase the proportion of scientifically contributing amateurs among the amateur population at large. It does increase the available paths to contribute scientifically, and that makes it of value, even if it only increases the proportion by 0.01%.

The second part of this study will look at the role of restaging historical experiments as a surprisingly productive research tool in the history of science over the past 40 years, and as a tool for doing new science with old science.

Acknowledgements

This research has made use of NASA's Astrophysics Data System.

Endnotes

1 With respect to double stars, 1870–1950 has been called "a golden period for discovery" (Argyle 2012a, 11; 2012b, 325–326). Identifying an era as "golden" is, of course, a value judgement. There seems a plethora of eras labelled "golden" in astronomy, such the as "1950s...marked the beginning of the golden age of astronomy" (Percy 2013), or the current renaissance in amateur spectroscopy (Eversberg 2010), or the "new golden age of cataclysmic variable star astronomy" (Shears 2018), or the "golden age of large surveys" (Rodriguez 2017). For Rod Mollise the golden era of amateur astronomy was ca. 1957–ca. 2010, whereas Stuart Parkerson argues that the "Golden Age of Amateur Astronomy" is now, and it is still unfolding (Mollise 2016; 2022; Parkerson 2018). No "multi universe" is required for all these "golden eras" to be concurrently true, even those argued for by Mollise and Parkerson. It really is a matter of perspective.

2 I term it "qualitative" because I lack the data to establish it, or disprove it quantitatively. Hence it's an impression.

3 Dickinson 1990 makes the case for the last option. A problem with the way this is formulated is that the classic *and present* usage of the term "naturalist" after which he has coined the expression "naturalist of the night" refers to field naturalists (professional and amateur) who make scientific contributions to biology (e.g. Stokesbury et al. 2009). This is brought home

when one opens something like the *Oxford Dictionary of Biology*, only to find that major contributing scientists like Darwin and Wallace are referred to as "naturalists" (ODB 2015a; 2015b). The implication is obvious; if the term is to mean anything at all, the true "naturalist of the night" can only be an active member of the AAVSO, the BAA, or something similar!

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Binary Universe

Hello *Aurora*

by Blake Nancarrow (Toronto Centre)
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I feel blessed to have seen aurora borealis many times in my life and lucky to have photographed the northern lights on occasion. But I suppose it is a bit like an addiction, a desire, the need to see them again. And that makes me want good software tools to notify me and keep me apprised of and ready for favourable conditions. For people who have never seen aurora, this might create opportunities, a chance at making that first observation to the life list.

Of late I have been using an app on my Android phone called *hello aurora*, version 2.5.

Head over to the hello-aurora.com site to learn more about the tool and to find links for Android or iOS if you want to try it out. You can use it freely.

What's Happening Right Now

On launching the app, the user sees the "now" screen (Figure 1) This shows the immediate state of auroral activity for your custom location or that detected by the GPS sensor of your mobile device. Unfortunately, the upper part of this screen did not work for me. The screen snap I have included is from the developer's samples. It shows the "chance now" percentage rating along with the "aurora strength," a quick verbal summary, and a magnetometer line graph. These data are updated every few minutes, so you are able to have current information at your fingertips. All these help you know if you should fire up the car and grab the camera and tripod.

The "real-time space data" section below (Figure 2) contains tiles for the Bz, Bt, solar speed, and density values. The small analogue circular gauges allude to the strength of the various measures. If more of the circle is filled, your chances are good.

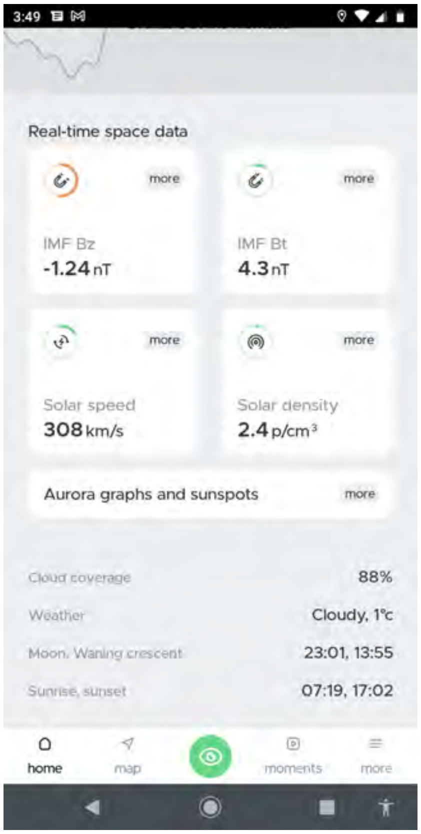
One may tap the "more" buttons to learn about these indicators. For example, the Interplanetary Magnetic Field – Bz information panel explains that you'll have a greater chance of seeing aurora when the Bz direction is negative. It also includes an assessment of the current value.

At the bottom of the screen, you will see local weather conditions including cloud coverage and Moon brightness. And finally, you will note the toolbar for accessing other features within the app.

By the way, I was pleased to see the dark background in screen snaps on the product websites. That will prove handy when

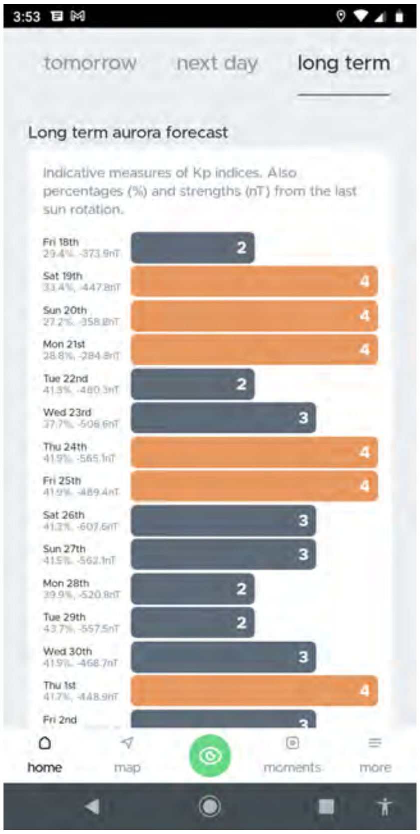
Minor substorm expanding and partly cloudy. You might see aurora by eye.

Figure 1 — The hello aurora *"now" display (top-half) showing real-time indicators (dark mode active).*



Cloud coverage 88%
Weather Cloudy, 1°c
Moon, Waning crescent 23:01, 13:55
Sunrise, sunset 07:19, 17:02

Figure 2 — The lower portion of the "now" screen including weather predictions.



Long term aurora forecast

Indicative measures of Kp indices. Also percentages (%) and strengths (nT) from the last sun rotation.

Figure 3 — The "today" screen shows Bz and Bt tiles along with a Kp indices bar chart.

we want to maintain our dark adaptation while out of doors. Sadly, I could not enjoy this feature as I'm trapped in an older version of the Android OS. Up-to-date devices should work fine.

Later Today and Beyond

Swiping left or right, or tapping the relevant label at the top of the screen, switches displays.

The "today" screen (Figure 3) shows similar tiles as the first screen but what is to happen in the next hour or so. Below is a very useful Kp bar graph showing predicted levels for the next three to six hours.

Below the Kp chart is a tile entitled "last sun rotation record." This unique feature helps you learn about active sunspots that may rotate into position that might in turn generate aurora in Earth's atmosphere.

Swipe left again. The "tomorrow" screen shows the Kp indices, the Sun rotation information, and your predicted weather conditions again but further into the future. The "next day" screen, same deal, just another 24 hours out.

Another unique feature of *hello aurora* is the long-range predictive screen (Figure 4). In the "long term" display, you will find a vertical-oriented Kp-index chart stretching out two weeks or more. This might be helpful if you won't be able to get to a dark-sky site or the club observatory for a few days.

Show Me

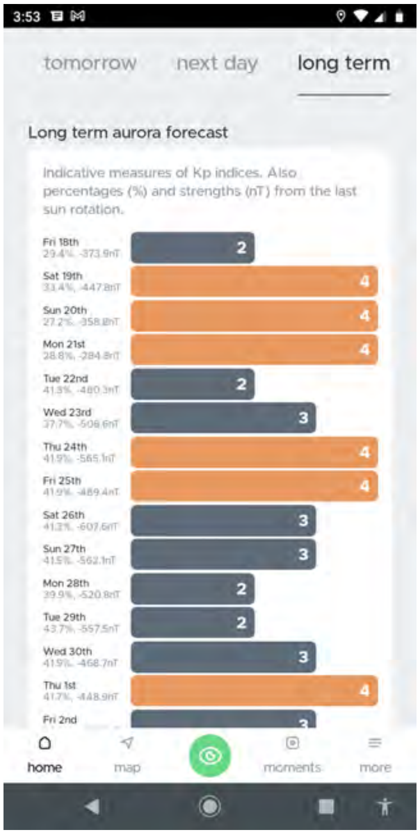
If you examine the bottom toolbar, it shows five icons. I've already discussed the informative screens of the "home" mode in the app.

The "map" mode switches you, not surprisingly, to a terrestrial map wherein you might see aurora near you location (Figure 5). You can swipe to pan, and pinch to zoom.

The display can show total, high, medium, and low cloud cover and the conditions of roadways! *If* you are viewing the northern lights from Iceland. Yep. Iceland.

The author Jérémy Barbet has tapped into his local sources. I asked him if he might utilize the excellent data (astronomy-specific no less) available from Environment Canada. Barbet said while he currently wasn't drawing from Canadian sources, the weather was specific to our country. I don't anticipate him indicating road conditions for all of Canada! That said, he does retrieve magnetometer data from CARISMA.

The green eyeball and "moments" buttons allude to the social and sharing aspect to *hello aurora*. If you imaged the northern lights, you can share your photo along with an assessment.



Indicative measures of Kp indices. Also percentages (%) and strengths (nT) from the last sun rotation.

Figure 4 — Do future trip and weekend planning with the "long term" Kp indicates.

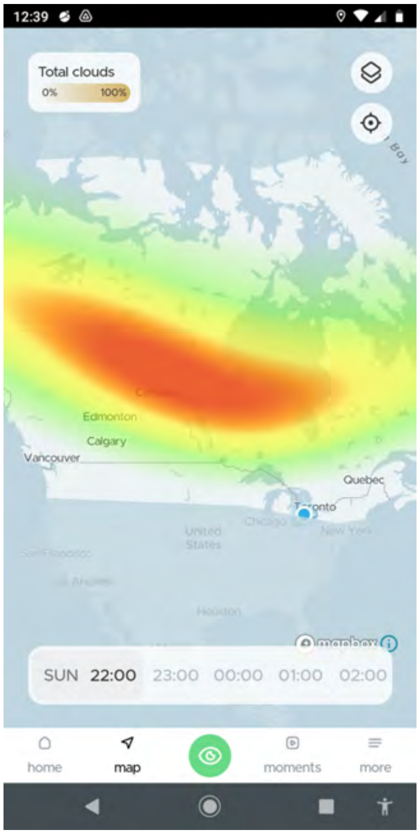


Figure 5 — Check for intense aurora in your area with the "map" display.

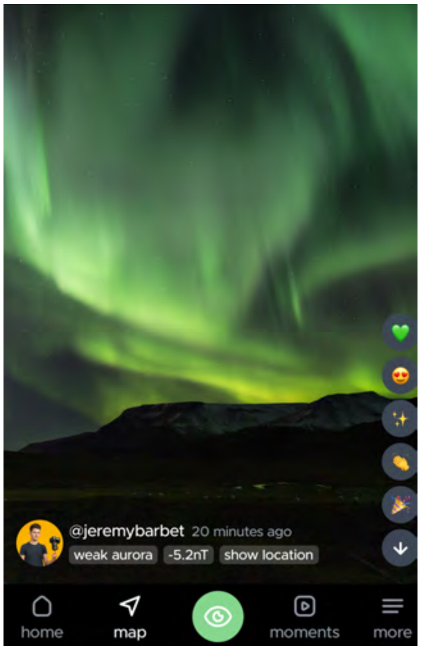


Figure 6 — The hello aurora app allows for shared photos and social interactions.

You'll need to create an account and use your GPS detected location to share. You can examine a shared photo (figure 6) and react to and rate it.

The app can also alert you with location-specific notifications.

Preferences

Via the "more" button in the toolbar, you can control various settings in the app. This includes the location for the notifications, setting up your favourite observing sites, logging in, etc.

Good Help

As mentioned, within the app there exist help panels to explain some of the technical aspects to aurora hunting. On the website, I found both good instructional how-to notes and a good FAQ. The software author responded to my questions and invited me to ask more.

Bottom Line

Overall, it's not bad. I like the *hello aurora* app. I'm mildly irked with a couple of things, and I am hopeful that it will improve over time. Both the Android and iOS crews like the app. The Android store rating shows as 4.2 out of 5 stars with 201 reviews and over 10,000 downloads. The Apple store is more positive: 4.7 with 14 ratings. One reviewer said that he liked that it was not science-heavy; rather it was simple, used good graphics, and featured an intuitive interface. I agree.

It certainly is useful in its free state. There are in-app purchases you can make although I do not understand the levels. On my Android, it shows buttons for $1.59, $6.99, $13.99, and $18.99. The Apple Store says you can get a Pro Account for $1.99, Beginner $0.99, Supporter $3.99, Premium $11.99, and Sponsor $7.99. Somewhere I found the statement that with a subscription plan, "you will get your shared photos, stats, on your profile and advanced settings." I'm still confused. Regardless, one can pitch in. I might throw Barbet a few bucks because I think this is a keeper.

Bits and Bytes

Robert Hurt taught me how to zoom quickly in FITS Liberator 4! I was used to the Adobe mouse-key technique in old FL3. He shared the new popular methods: scroll with the mouse roller wheel or pinch/unpinch on the touchpad. How about that?✶

Blake's interest in astronomy waxed and waned for a number of years but joining the RASC in 2007 changed all that. He is a member of the national observing committee. In daylight, Blake works in the Information Technology industry.

CFHT Chronicles

Volcanoes, Cosmic Webs, and GEMS: What a Way to End 2022

by Mary Beth Laychak, Director of Strategic Communications, Canada-France-Hawaii Telescope (mary@cfht.hawaii.edu)

Another year has come and gone with lots of exciting science at CFHT. Before we dive into our science highlights, a quick volcano note. At the time of writing this column, December 2022, Mauna Loa is erupting for the first time in 38 years. In the two weeks since the start of the eruption, the County of Hawai'i established a lava viewing site along the "old Saddle Road"; 17,000 vehicles passed through the road during the first week. The Maunakea Observatories (MKO), County of Hawai'i, and everyone on island is watching the lava slowly progress toward the Daniel K Inouye Highway aka Saddle Road that bisects the island. The MKOs are working with everyone involved on contingency plans in case lava causes a closure of the Saddle Road.

Impacts to observing have been day-to-day based on wind and other weather conditions. What will the conditions be when this column is published? Only Mauna Loa knows the answer to that.

Weak Gravitational Lensing Reveals Dark Matter Maps of the Cosmic Web

Next up: Exciting science from one of our former French resident astronomers, Jean-Charles Cuillandre and the UNIONS team.

Scientists at CEA Saclay (Commissariat à l'énergie atomique et aux énergies alternatives) in France used data from the international science collaboration UNIONS (Ultraviolet Near Infrared Optical Northern Survey) to generate a reference catalogue of 100 million gravitationally lensed distant galaxies, one of the largest datasets ever created. The new catalogue is based on thousands of deep images of the northern sky

Figures 1 and 2 — Images of the Mauna Loa eruption taken from the Maunakea Access Road by CFHT engineer Tom Benedict

captured by MegaCam, CFHT's digital camera built at CEA. Three new publications present dark-matter-mass maps of the cosmic web, showing how the high-density regions in these maps help measure the still poorly known properties of dark matter.

A new milestone has been reached for weak gravitational lensing with the release of one of the largest galaxy catalogues to date. This catalogue contains precisely measured shapes of 100 million galaxies, which trace the slight deformations caused by the gravitational lensing of light travelling throughout the cosmic web of dark matter that permeates the Universe. Modern cosmology requires careful handling of the error budget and comparing catalogues produced through complementary approaches is part of the process. Two versions of the shape catalogue, obtained with different, independent methods, have just been released internally to the Ultraviolet Near Infrared Optical Northern Survey (UNIONS) science collaboration. UNIONS is a large imaging survey of the northern sky in the optical and near-infrared, co-led by Jean-Charles Cuillandre, CEA Saclay/Université Paris-Saclay. Three telescopes based in Hawai'i are used to conduct this ambitious survey started in 2017: CFHT, Pan-STARRS of the University of Hawai'i, and the Japanese Subaru telescope.

The key cosmology observations were captured at CFHT with the wide-field imaging camera MegaCam, built by CEA 20 years ago. MegaCam with its one-square-degree field of view (four times the size of the full Moon) and 375 million pixels was the largest optical astronomical camera in the world when it saw its first light. Since then it has been surpassed by only four other wide-field cameras (three of which are engaged in UNIONS) and remains at the forefront of science. The scientists who produced this new catalogue are now inviting all UNIONS members to utilize this dataset to conduct new science projects.

UNIONS expands upon the Canada-France Imaging Survey (CFIS), a large program at CFHT. Starting in 2017, CFIS utilized 346 nights of observation time with the goal of addressing some of the most fundamental questions in astronomy: the properties of dark matter and dark energy, how the galaxy cluster structure seen in the Universe today grew from galaxies, and how the Milky Way assembled.

"The superb observing conditions at CFHT on Maunakea led to the unprecedented collection of galaxies over a very large area of the sky culminating in this truly unique catalogue," said Cuillandre. "MegaCam's sensitivity in the blue end of the spectra and CFHT's outstanding delivered image quality in the optical play a critical role in UNION's goal to survey the northern sky in those wavelengths."

Under the lead of Martin Kilbinger, one of the two catalogue versions was created over a four-year period by the CosmoStat laboratory (CEA/IRFU/DAp). To process UNIONS data from CFHT, an entire processing pipeline was developed, called ShapePipe. ShapePipe has so far processed a total area sky area of 3,500 square degrees, using more than a million CPU hours and producing 500 terabytes of data; the final weak-lensing data containing 100 million galaxies has a size of 18 gigabytes. The software is modular and has high-perfor-

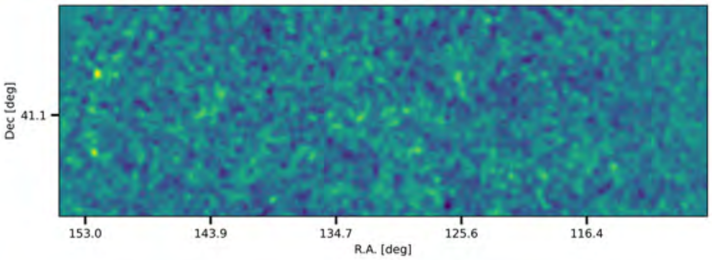


Figure 3 — A dark-matter map of the projected cosmic web reconstructed from UNIONS weak-lensing data. This patch located in the Lynx constellation is 275 deg2, which is less than one tenth of the total area observed by UNIONS so far (final coverage will reach 5000 deg^2 over the northern sky). Yellow peaks show locations of overdensities corresponding to galaxy clusters, while blue regions correspond to underdense areas, called voids.

mance computation capabilities. It combines state-of-the-art third-party methods with in-house methods developed by CosmoStat. Due to its modular architecture, it is easy to test and implement new algorithms, and can be applied to other weak-lensing surveys. A technical article led by Samuel Farrens, detailing the software, has been submitted to the peer-reviewed *Astronomy & Astrophysics* journal. CosmoStat has made the code public.

Two science projects led by CosmoStat members and alumni, under the supervision of Kilbinger, using UNIONS weak-lensing data have been published. First, Guinot et al. (A&A article in press) carry out careful testing and validation of the ShapePipe catalogues, and present dark-matter maps and mass profiles of galaxy clusters observed by the ESA satellite mission *Planck*. This demonstrates the very high quality of UNIONS lensing data, at par or even better than other large surveys, such as the Kilo-Degree Survey (KiDS) or the Dark Energy Survey (DES), while the sky coverage of UNIONS is still only partial (goal: 5000 square degrees).

As a second astrophysical application, Ayçoberry et al (submitted to A&A) examine weak-lensing peak counts as a method to measure cosmological parameters. These peaks trace high-density regions in the cosmic web, the properties of which are very sensitive to the underlying cosmological model. The publication introduced a novel method to explore spatial variations of the lensing calibration and assesses a variety of uncertainties and systematics that can impact cosmological inference.

In the near future, the UNIONS observations will provide essential support to the European space telescope *Euclid*. This ESA satellite mission will map the cosmic web over the entire accessible sky at an unprecedented resolution to measure the properties of the mysterious dark energy.

"UNIONS' unique collaboration and observing strategy made the development of this new catalogue possible," said Todd Burdullis, QSO Observations Specialist at CFHT.

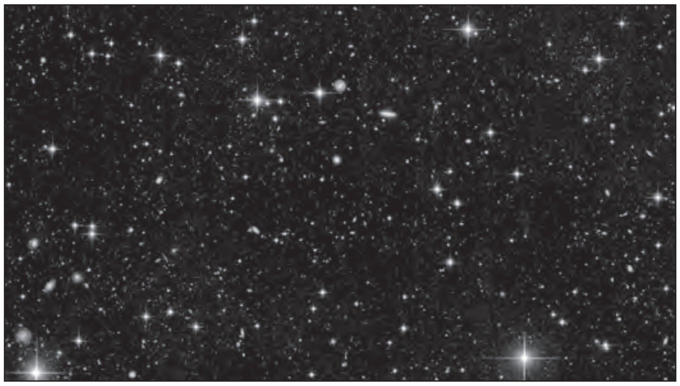


Figure 4 — A typical image from CFHT-MegaCam for UNIONS: the sky area covered here is only 0.2 deg2 (1/25,000 of the whole survey) but it already shows many thousands of the typical distant galaxies (the tiny blobs) used to trace the dark matter.

"MegaCam's efficiency in completing large programs like UNIONS continues to create legacy catalogues and archival data, expanding our understanding of the Universe."

Gems

December 2022 brought the return of one of our favourite outreach activities: GEMS or Girls Engaged in Math and Science. Cancelled in 2020 and 2021 due to the pandemic, the program aims to highlight STEM for fifth-grade girls. Usually, the students learn about spectroscopy with CFHT, making their own spectrographs and exploring different elements. This year's event was entirely outside, making our standard spectroscopy session difficult, too much high-precision cutting, taping, colouring, and minimal power outlets.

Figure 5 — Dinosaur relaxing on the shore just before impact from "Comet GEMS."

Instead, CFHT resident astronomers Nadine Manset and Heather Flewelling talked to the girls about comets, asteroids, and impact cratering. They set up stations outside where the students could experiment with creating their own impact craters in a variety of media—flour, sand, and water. Nadine and Heather used plastic dinosaurs (not to scale) to demonstrate how the Chicxulub impact affected dinosaurs and their ecosystem. Reports are that the students had a wonderful experience. ✶

Editor's Note: The Mauna Loa eruption stopped in early December.

Mary Beth Laychak has loved astronomy and space since following the missions of Star Trek's Enterprise. She is the Canada-France-Hawaii Telescope Director of Strategic Communications; the CFHT is located on the summit of Maunakea on the Big Island of Hawaii.

Dish on the Cosmos

The Case of the Missing Supernova Remnants

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

In this column, I wish to share a mystery that my colleagues and I have been working to solve. We are not seeing the number of supernova remnants that we should see here in the Milky Way Galaxy. However, new radio observations with the Australia Square Kilometre Array Pathfinder (ASKAP) offer an opportunity to find these missing remnants. If we don't find them, we will have to rethink some of our ideas about the relics supernova explosions leave behind.

Dr. Roland Kothes is an astronomer at the Herzberg Astronomy and Astrophysics Research Centre in Penticton, B.C., which is part of the National Research Council Canada. Dr. Kothes has been studying supernova remnants for most of his career. He pointed out a mystery to me: if we use radio observations to search for the leftover signatures of historic explosions, we can only find about half the number of supernova remnants we expect.

A supernova usually occurs when a high-mass star ends its life. After exhausting all possible sources of energy generation through nuclear fusion, the supernova occurs when the star collapses. The core of the star undergoes a compression into an ultradense form of matter called neutronium made almost entirely of neutrons, where the rules of quantum matter prevent further collapse. This object becomes a neutron star and the conversion from regular matter with protons and electrons into the neutronium releases a burst of neutrino particles, which blows off the outer layers of the star in a supernova explosion. Supernovae are some of the strongest explosions that we know about, with the explosion releasing the same amount of energy in a few milliseconds as our Sun will release over its lifespan of about ten billion years.

These dramatic explosions detonate into the space of the Milky Way. While we often regard the space between stars and planets as a vacuum, it is filled with very-low-density gas and dust, which makes up the interstellar medium (ISM). The supernova explosion drives an intense shock wave through the ISM, destroying dust grains and ionizing gas into a hot plasma with some particles moving near the speed of light. Since these plasmas are connected to the galactic magnetic field, the fast-moving particles bend in the magnetic field and create a specific signature of radio light called synchrotron emission. The regions, known as supernova remnants, are traced out by the synchrotron emission and are visible in radio maps of the sky as bubbles of radio light, tens of parsecs across.

Supernova remnants aren't the only "bubbles" in the sky. We also see these spherical shells in ionized regions around massive stars. Before those stars undergo supernova explosions, their intense radiation fields ionize the gas around them. While intense compared to sunlight here on Earth, these ionized regions are relatively cool compared to the shock-heated gas of a supernova explosion. This leads to a major point of departure between these two types of bubble features concerning the grains of dust in space. Where a supernova remnant destroys the dust grains inside of it, an ionized gas region leaves the grains intact. We can distinguish between supernova remnants and ionized regions since only ionized regions show the infrared emission from dust grains.

We can predict the number of ionized regions and supernova explosions we should be seeing in our galaxy. We believe that we understand how stars evolve if we know their initial mass. This confidence leads to blithe statements like the one above that massive stars end their lives in supernovae, specifically stars eight times the mass of the Sun and heavier. Slightly less well, we also know how many stars of each mass form per year. We think that 1 supernova-producing star forms in our galaxy every 50 years and that this rate has been relatively constant for hundreds of millions of years. Thus, we expect one supernova explosion every 50 years. Finally, we estimate that a supernova explosion will be visible as a radio remnant for about 50,000 years, which means that we should see about 1000 supernova remnants here in the Milky Way.

In our surveys, we only see about 400 remnants, which raises two main possibilities. First, we might be missing remnants that are actually there. Our previous work may not have been sufficiently sensitive or have high enough resolution to see remnants that are there. Alternatively, some factor in our estimates above may be wrong. The most obvious solution is that the lifetimes of the remnants are shorter, so we should see fewer, but there may be other explanations.

Roland Kothes is trying to understand where these missing supernova remnants are found. A graduate student, Brianna Ball, and I are collaborating with Roland to try to find these missing remnants. We are taking advantage of new data from the new ASKAP telescope, which is just commencing on a massive survey of the southern radio sky. ASKAP has several unique design features, but the key advantage for this study is ASKAP's wide field of view. ASKAP can capture an image 40 deg2 of sky at the same time, the size of 200 full Moons. ASKAP also uses the techniques of radio interferometry, so the images are comparatively high resolution. The work being developed here is just a small portion of the science being done by two collaborations using ASKAP: the Evolutionary Map of the Universe (EMU) and Polarisation Sky Survey of the

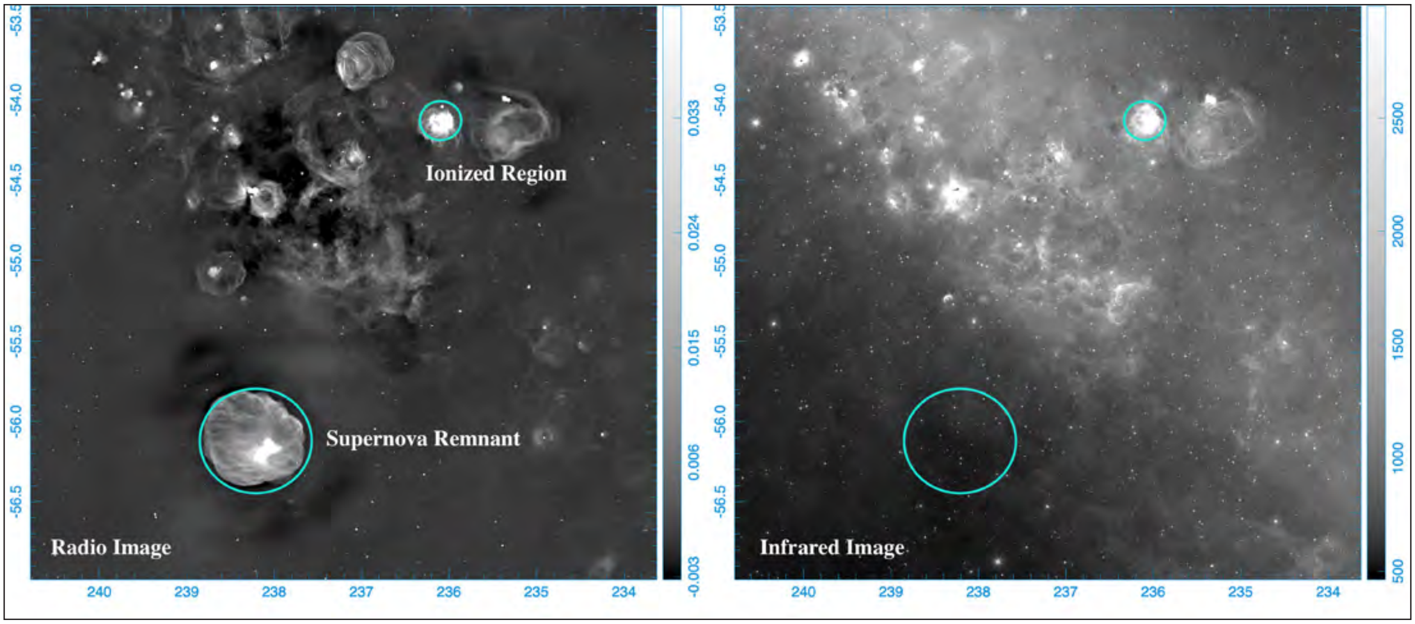


Figure 1 — Map of part of the southern sky in radio (left) and infrared (right) light. The two circles indicate different types of radio emitter, with the ionized region visible in both the radio and the infrared whereas the supernova remnant is visible only in the radio.

Universe's Magnetism (POSSUM). Yes, all the surveys using ASKAP have names of Australian animals.

Figure 1 shows two pictures of the same region of the sky. The left panel shows the radio image from ASKAP and the right panel shows the infrared view of the same sky. The circles highlight two regions. The ionized region is visible in both images because the warm plasma gives off radio emission and the dust is bright in the infrared. Since the supernova remnants destroy the dust inside of them, they are invisible in the infrared. By finding bubbles in the radio image that are not present in the infrared, we can identify new supernova remnants.

Working with the ASKAP and EMU collaborations, Brianna Ball has been leading the discovery of new remnants using these images over this field. So far, she has found over 10 new remnants, which helps bring the expected numbers in line with predictions. However, it isn't quite enough to close the gaps between expectations and observations. It has become clear that part of the answer is that, even with these new observations, some regions are just so confusing that we cannot identify all the SNRs. However, the ASKAP collaborations are just starting on a set of major radio surveys that will expand the area covered beyond this one map to cover the entire sky visible from Australia. If the expanded observations continue to reach the conclusion that we are not seeing the predicted numbers of remnants, we will have to reconsider some of our assumptions in the estimate. ✶

Erik Rosolowsky is a professor of physics 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.

John Percy's Universe

Tycho Brahe and the Development of Observational Astronomy

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

Of the "famous five" (Western) astronomers of the Renaissance, Tycho Brahe gets short shrift. Nicolaus Copernicus has a revolution named after him. Galileo Galilei was celebrated by a 148–country International Year of Astronomy in 2009. Johannes Kepler and Isaac Newton have laws of motion named after them. Tycho tends to be remembered for more colourful stuff.

Tycho Brahe (1546–1601), born Tyge Ottesen Brahe, was a Danish nobleman. In his youth, he lost half of his nose in a duel with his cousin after too much drinking. He wore a prosthetic nose for the rest of his days—brass for everyday, gold or silver for special occasions. He was a very busy astrologer and alchemist as well as an astronomer, but that was par for the course in those days. Although he was a faithful husband as far as we know, he was denied a formal church wedding to his beloved Kirsten, mother of his eight children, because she was a commoner. His tame elk fell down a flight of stairs in a drunken stupor and died. In later life, Tycho squabbled with the Danish powers-that-be, and self-exiled to Prague. There was an unsubstantiated rumour that he died by poisoning—possibly by Kepler, no less. His body was later exhumed—not once but twice—just to check. Most likely he died of some urinary problem. A few days before his death, he had attended a royal banquet, where he desperately had to urinate, but etiquette did not allow him to get up and leave the room to do so until the king had risen and departed.

Now, I am delighted to learn that the Toronto Consort, one of my favourite musical groups, is presenting "Celestial Revolutions: The Life and Times of Tycho Brahe" on 2023 May 3–4, at 8 p.m. in Toronto's Jeanne Lamon Hall (www.torontoconsort.org). The Toronto Consort is Canada's leading ensemble specializing in Renaissance and early Baroque music. A film of the concert will be released on May 5 for viewing on EarlyMusic.tv. Rental price is $15.99 for 72 hours. It promises "an exploration of his fascinating life and times," and I'm sure it will succeed, just as Toronto's Tafelmusik Baroque Orchestra's Galileo Project did in 2009. There is much to be gained by viewing historical figures within their own times and culture, not in ours, and much to be gained by linking science and the arts.

Tycho had close connections with the most powerful families in Denmark and had ample resources to lead a typical aristocratic life. At age 12, he entered the University of Copenhagen to study law and politics, but became increasingly interested in astronomy, even though it was not on his curriculum. Broadly educated, and a Renaissance man (literally), he would have learned about Aristotelian physics, and was quite aware of the work of Copernicus. He observed a solar eclipse on 1560 August 21, and a conjunction of Jupiter and Saturn on 1563 August 23. He was puzzled that the prediction of the eclipse was out by one day, but even more so when two different predictions of the conjunction, using two different models—the Ptolemaic and the Copernican—differed by three weeks. Surely, astronomers could do better!

As he travelled to centres of learning across Europe, he met astronomers, learned more about astronomy, and he began gathering, improving, and using the best astronomical instruments that he could find. Back home in 1567, he made a life decision to become an astronomer. He was granted an honorary canon position in Roskilde, which left him lots of time for astronomy, as well as for the necessary duty of casting horoscopes for nobility, and thereby for the state. Astrology was part of politics!

On 1572 November 11, he made a remarkable and unexpected discovery. A new star (stella nova—hence our astronomical terms nova and supernova) appeared in Cassiopeia. Chinese astronomers had been observing such events for centuries, but they were generally unknown to European astronomers—in part because Aristotelian physics held that the stars were perfect and unchanging. Unlike other observers of the star, Tycho followed up; he continued to observe the star for many weeks. Its lack of diurnal parallax confirmed that it was indeed a fixed star, and not something in the atmosphere. This discovery was a powerful blow to Aristotelian physics. Modern astronomers have been able to interpret and use his careful observations and records to reconstruct the star's brightness variations, and conclude that it was a Type Ia supernova—"Tycho's supernova." At maximum brightness, it rivalled Venus.

By this point, Tycho's scientific reputation, combined with his ample resources and connections, made him one of the most distinguished and powerful people in the country. His patron King Frederick II, concerned that he might move elsewhere, awarded him lordship of the island of Hven, previously Crown Land, and the funds to build a major observatory. Uraniborg was named after the muse of astronomy. Construction began in 1576. Tycho acquired or built the best possible instruments—armillaries and quadrants—and used them, with great care, to make systematic, sustained observations of the Sun, Moon, planets, and stars, often with his younger sister Sophie as assistant. To make his instruments less affected by wind and vibration, he built a satellite observatory—Stjerneborg, the

Figure 1 — Tycho using the six-foot Mural Quadrant at Uraniborg, assisted by his team of observers, instrument-builders, scribes, computers, students, and his faithful dog. From Astronomiae Instavratae Mechanica (Wandsburg, 1598).

castle of the stars—next door, below ground, with the instruments resting on bedrock. The organization of Uraniborg, with its state-of-the-art instrumentation, quality control, specialized staff, recorders, computers, a printing press, dozens of students in training, visiting scholars, and a team approach has much in common with research institutes today (though few, if any, include an alchemy lab!). And patrons must be satisfied, just as granting agencies must, today. Tycho regarded his team as his familia—his second family. But he did not work in isolation; he exchanged visits with or communicated actively with other scholars from all over Europe.

In November 1577, he began observing a bright comet as it made its way across the sky. Comets were believed to be atmospheric phenomena—hence they could be as changeable as Earthly things were. But Tycho showed that the comet had no diurnal parallax, and must lie beyond the Moon, out where the planets moved. It was celestial. The comet's position and motion cast serious doubt on the reality of the imaginary crystalline spheres, which some thought were the means by which the planets moved in their orbits. He also noted that the tail of the comet always pointed away from the Sun.

Throughout these times, he was also building up a catalogue of the precise positions of 777 stars. These formed the reference points for observing the positions and motions of the planets—and for new stars, as well as comets. He also advanced the understanding of the complex apparent motions of the Moon. But the "bread and butter" of his observing program was long-term observations of the motions of the planets, particularly Mars. These later formed the basis for Kepler's Laws of Planetary Motion.

Though primarily an instrument-builder and observer, Tycho could not help speculating on the nature of the Universe that he was observing. He was aware of the Copernican Sun-centred model, as well as the Ptolemaic Earth-centred one. He was strongly influenced by Aristotelian physics, which maintained that our world was made up of the "four elements"—earth, water, air, and fire. But the Sun, Moon, and planets were made of quintessence (the "fifth essence" or element) which was perfect and unchanging, and could move in ways that the lazy, ponderous Earth could not. In his Tychonic model, the planets orbited the Sun, which, along with the Moon, orbited the Earth. This preserved some of the geometric advantages of the Copernican model. And if all motion was relative, could not the Earth be placed at the centre, where Holy Scriptures would have it? This model remained popular for many decades, especially among diehard geocentrists. In developing this model, he was also influenced by his own observation that the stars did not show annual parallax, as they should if the Earth was moving. That turned out to be due to the immense distances of the stars, not due to a stationary Earth.

Tycho was immersed in a culture that believed there were connections between Earth, humanity, and the heavens—which was, of course, the basis of astrology. The planetary motions that he observed, the comet, and the new star must surely have implications for humans and for humanity. He was especially interested in medical astrology and alchemy. As the king's astronomer, he was expected to provide horoscopes to interpret these observations, and their implications.

We should also remember that Tycho worked within a European culture. Significant astronomy had been done in Asia and elsewhere, by scholars such as Ulugh Beg (1394–1449) with his fine observatory in Samarkand.

Tycho's patron Frederick II died in 1588. When his successor Christian IV came of age, it was clear that he had little interest in astronomy. Other nobles were jockeying for position in the new regime. Tycho's enemies, jealous of his generous funding in the past, denied him access to both funds and status. Some of them fumed about his lack of a formal church marriage. He was also accused of occasionally neglecting his courtly duties, or of lording it over the residents of Hven, both of which were partly correct. He tried to appeal to these enemies and to the king through diplomacy, to no avail.

Unwanted in Denmark, he found a new patron in Prague—Rudolph II, the Holy Roman Emperor. He was appointed Imperial Court Astronomer. Among other things, his commoner wife and children were finally accorded noble status. Assisted by a young Kepler, he set out in 1600 to publish the results of his observations, but died the following year, so he did not live to see his magnum opus The Rudolphine Tables, published in 1602.

Tycho's observations lived on. Indeed, he defined what astronomers call "observing" today. His planetary observations—especially of Mars—formed the basis for Kepler's Laws and for much subsequent knowledge of the Solar System geometry and motions. The fortuitous appearance of the 1572 supernova and the great comet of 1577–1578, and his careful observations of them, showed how such observations could support or challenge astronomical and physical theory. He pushed his instruments to their limits but, within a generation, they were supplanted by telescopic ones. However, his attention to precision, observation, recording, and publication of his results live on in the methodology that astronomers use today.

Reference

An excellent, well-illustrated overview of Tycho's life and work is Tycho Brahe and the Measure of the Heavens, by John Robert Christianson, Reaktion Books, 2020. See also wikipedia for a good summary. ✶

John Percy FRASC is Professor Emeritus, Astronomy & Astrophysics and Science Education, University of Toronto, and a former President (1978–1980) and Honorary President (2013–2017) of the RASC.

Obituary

Jay Myron Pasachoff (1943–2022)

by John R. Percy, FRASC

Jay Myron Pasachoff, astronomer, eclipse chaser, world traveller, educator, mentor, prolific author, and Honorary Member of the RASC, died at his home in Williamstown, Massachusetts, on 2022 November 20, at the age of 79, of lung cancer. He and his work were known and appreciated by millions of professional and amateur astronomers, educators, students, and the general public around the world.

Jay was born in Manhattan on 1943 July 1, the son of Samuel Pasachoff, a surgeon, and Anne (Traub) Pasachoff, a teacher, but moved to the Bronx at a young age. After graduating from the prestigious Bronx High School of Science, he entered Harvard University. His obituary in the New York Times details how he chose a career as an astronomer, though he had already been an amateur telescope maker and observer in high school. He intended to major in math, but he also enrolled in a freshman seminar in astronomy, taught by solar-eclipse expert Donald H. Menzel. A few weeks into the semester, there was a total solar eclipse visible off the coast of Massachusetts. Menzel borrowed a DC-3 aircraft, and took his class to watch it. Pasachoff was hooked. He completed his A.B., A.M., and Ph.D. at Harvard, with a doctoral thesis on the fine structure of the solar chromosphere. After a postdoctoral fellowship at Caltech, he took a position at Williams College in Williamstown, Massachusetts, a top-ranked liberal arts college. There, he served as Field Memorial Professor of Astronomy, Chair of the Department of Astronomy, and Director of the historic Hopkins Observatory until his death. He taught at Williams for 50 years.

Jay was best-known (at least in the media) for observing and studying 75 solar eclipses, 36 of them total, quite possibly a record. He preferred the label eclipse preceder to eclipse chaser. Since solar eclipses can occur anywhere on Earth, expeditions to observe them require long and meticulous planning and logistics, and generous support—which Jay received from the National Science Foundation, NASA, the National Geographic Foundation, and other agencies. Since Williams College does not have graduate programs, Jay did not have access to graduate research assistants. Instead, he engaged undergraduates—literally hundreds of them—in his research. This was a life-changer for many of them, introducing them to the challenge and excitement of doing real science, often in exotic places, and sparking their passion for astronomy. Perhaps he was guided by his own profound experience as a freshman at Harvard.

The purpose of all of this was to better understand the complex physics of our Sun's chromosphere and the faint million-degree corona. These can be observed in the few minutes of a total solar eclipse. Even after new ground-based and space-based methods for solar observation became available, Jay promoted and advanced the tried-and-true use of eclipses for these purposes.

Though media coverage of his death emphasized his work on the Sun and solar eclipses, his contributions to astronomy education, outreach, and communication were equally remarkable. I first got to know him in the 1970s, when we co-organized an International Astronomical Union (IAU) conference on astronomy education in Williamstown, and we co-edited the conference proceedings. At this conference, I met kindred spirits from all over the world. Jay's interest in international astronomy education meshed naturally with his globe-trotting research. So too did his interest in public education. Total solar eclipses, being one of Nature's greatest and rarest spectacles, generate intense public interest—and serious misconceptions and safety concerns. Jay served as President of IAU Commission 46 (Education and Development) from 2003 to 2006, and as President of the IAU Working Group on Solar Eclipses from 2006 to 2022. In all, he held three dozen IAU commission or working group memberships during his career, plus many more leadership positions in other scientific and educational organizations.

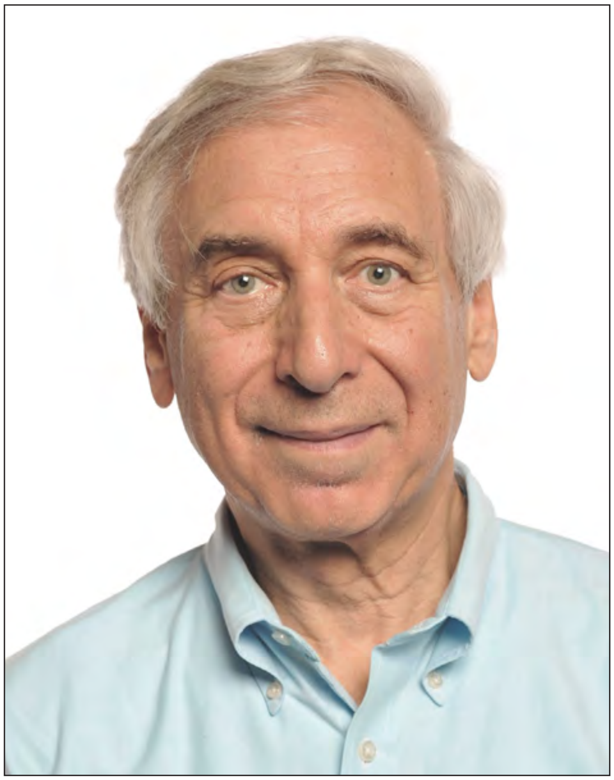


Figure 1 — Jay Myron Pasachoff (1943–2022), astronomer, educator, prolific author, and Honorary Member of the RASC. Source: Williams College.

He was a prolific author/co-author of textbooks at the college level (several editions of The Cosmos: Astronomy in the New Millennium, with Alex Filippenko) and at the high school and junior high school level as well. Many of the school textbooks were co-authored with his wife, historian and biographer Dr. Naomi Pasachoff—herself a prolific author. For the public, he wrote The Complete Idiot's Guide to the Sun, the updated fourth edition of the Peterson Field Guide to the Stars and Planets, the Peterson First Guide to Astronomy, and the Peterson Field Guide to Weather (co-authored with Canadian meteorologist Jay Anderson). Eclipse chasers have a vested interest in understanding the weather! Not surprisingly, Jay wrote or co-authored several books about the Sun. He also co-authored two books on art with Roberta J.M. Olson, reflecting his deep interest in that subject. He was aware that astronomical phenomena such as eclipses had aesthetic and emotional value, as well as scientific value. He repeatedly co-taught a course on rare books, of which he had many. He promoted astronomical history, heritage, and biography, and wrote countless short articles on these and other varied topics.

Jay's was a strong and eloquent voice in a fundamental debate about the purposes of teaching astronomy. Was it more important to teach and learn about basic topics like the cause of the seasons and of Moon phases (Jay referred to these as "16th-century astronomy")? Or to teach and learn about contemporary astronomy, challenging though it was for teachers who have so little background in astronomy and astronomy teaching? The answer, of course, is "some of both." Jay urged teachers not to neglect the contemporary. In his textbook writing, he tried to inspire and empower teachers at all levels to do so.

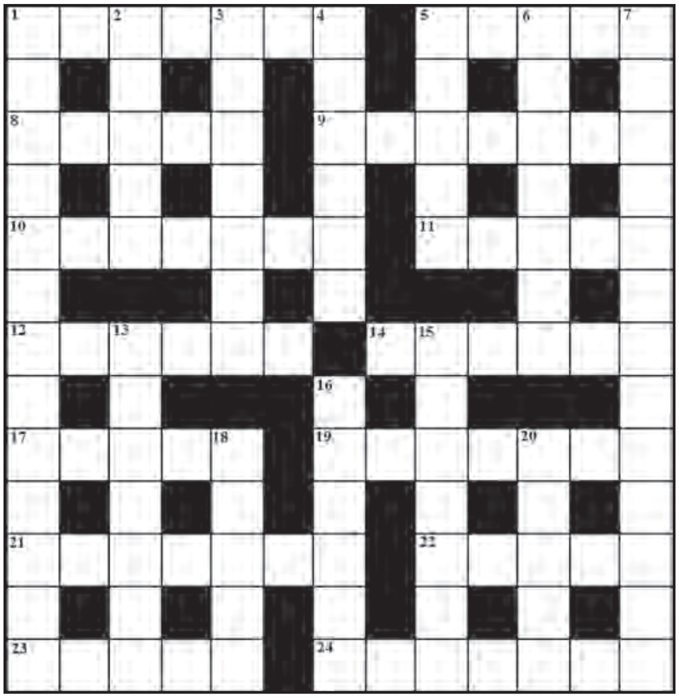
His many awards and honours include the Education Prize of the American Astronomical Society, the Klumpke-Roberts Award of the Astronomical Society of the Pacific for excellence in promoting public understanding and appreciation of astronomy, Fellow of the Royal Astronomical Society, as well as Honorary Member of the RASC, which is restricted to 15 members at any one time. Minor Planet (5100) Pasachoff is named in his honour, and (68109) Naomipasachoff is named in Naomi's honour.

He leaves his wife Dr. Naomi (Schwartz) Pasachoff, daughters Eloise and Deborah, a sister Nancy Kutner, and five grandchildren. ✶

John Percy FRASC is an active Professor Emeritus in Astronomy & Astrophysics, and in Science Education at the University of Toronto, and a former President (1978-1980) and Honorary President (2013-2017) of the RASC. He was a colleague and friend of Jay Pasachoff for over four decades.

Astrocryptic

by Curt Nason



ACROSS

1. Bum turned in a soda before he dove under a big dog (7)
5. Grissom had little energy or spirit in the Martian crater (5)
8. Active region loses nothing to a long flower in Africa (5)
9. Stage of confusion between little extraterrestrial and Earth (7)
10. An acute angling of ad toon Sam (7)
11. Upland area designated for a backstop in Chicoutimi (5)
12. April storms lead to one isle of Jupiter's winds (6)
14. Judge bangs it right in loose asteroid material (6)
17. A most peculiar collection of particles (5)
19. Gases up at the Square (7)
21. Confuse a lion with it pointing away from the Sun (3,4)
22. The last Greek at the first Olympic game, strangely enough (5)
23. Apollo president had set sights on Pluto's moon first (5)
24. Lyra's plucker eventually washed up shore (7)

DOWN

1. No contest I'll solve about a stellar figure (13)
2. It makes sense to record an NGC supplement (5)
3. Magellan, for example, also visited the rocky planets (7)
4. Double star compiler would oddly take in the entire sky (6)
5. Ancients soundly surmised such a star was a comet (5)
6. Planet 5 was a powerful uplifter (6.1)
7. A blast arrives from cataclysmic ones (8,5)
13. Firebird went south by the time Glen got there (7)
15. Get back together about a moving one in Ursa Major (7)
16. Asteroid where a survey ended with nothing (6)
18. Shepherd rides on the back of Charles' Wain (5)
20. A cubic metre of matter in an Easter egg (5)

Answers to previous puzzle

Across: **1** CIVIL TWILIGHT (2 def); **8** ALGORAB (Al(go R)ab); **9** TANIA (anag+a); **10** DELOS (2 def); **11** LEPORIS (Le(por)is); **12** ACAMAR (a ca(ma)r); **14** SCALES (2 def); **17** ENTROPY (an(n)ag); **19** MACHO (hid); **21** HULST (H+anag); **22** ADAMANT (an(T)ag); **23** REGIOMONTANUS (anag);**24** SISSY (2 def); **25** STETSON (stet+son)

Down: **1** CHANDRASEKHAR (anag); **2** VOGEL (an(G) ag); **3** LARISSA (anag+rev); **4** WOBBLE (anag); **5** LIT UP (2 def); **6** GENERAL (anag); **7** THARSIS MONTES (anag); **13** ANTILOG (anag); **15** COMPACT (2 def); **16** DYNAMO (anag); **18** ORTHO (anag); **20** CHAIN (2 def)

The Royal Astronomical Society of Canada

Vision

To be Canada's premier organization of amateur and professional astronomers, promoting astronomy to all.

Mission

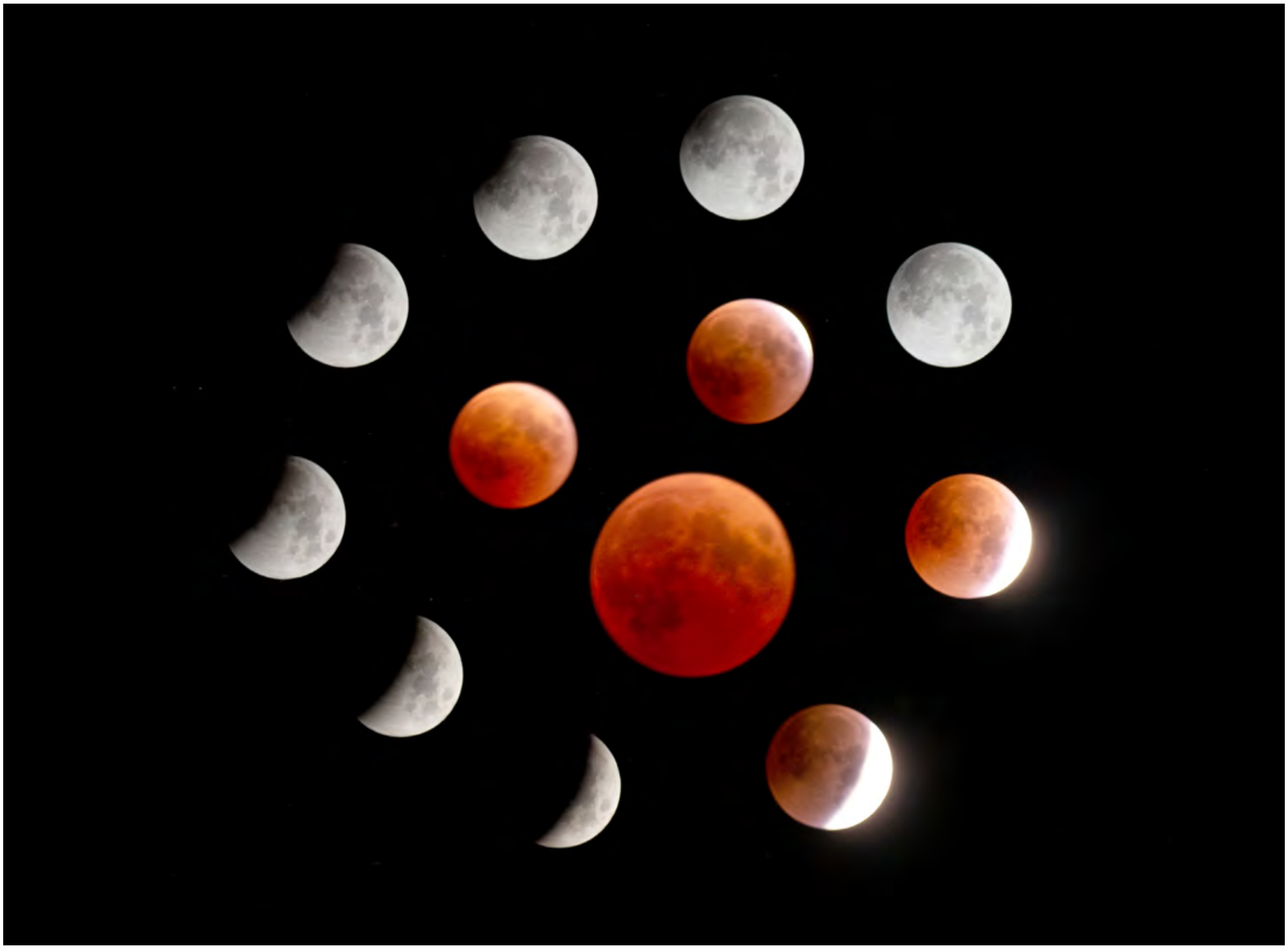
To enhance understanding of and inspire curiosity about the Universe, through public outreach, education, and support for astronomical research.

Values

- Sharing knowledge and experience
- Collaboration and fellowship
- Enrichment of our community through diversity
- Discovery through the scientific method

Great Images

by Andrea Girones



Andrea Girones captured the 2022 November 8 eclipse on a cold, windy morning at Britannia Beach in Ottawa. She used single shots with a RedCat51 telescope and a Nikon D750 DSLR tracked on a Sky-Watcher Star Adventurer tracking mount. Images were combined in Photoshop.

Journal

Shawn Nielson took this image of a favourite duo: the Perseus Double Cluster from Kitchener, Ontario. Shawn says, "I like the Double Cluster with its pretty coloured stars … just [the] right appearance." He used a Starfield Optics 8″ astrograph telescope, a Starizona Nexus reducer/corrector at ƒ/3, a QHY268M CMOS camera, and a filter wheel with Optolong LRGB filters on a Sky-Watcher EQ6 mount on a Skyshed Pier. Acquisition was done using NINA 2.0 and the final image was processed in PixInsight. Total exposure was 3.5 hours using LRGB.