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Journal

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PROMOTING ASTRONOMY IN CANADA

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Meteor Outburst in 2022?

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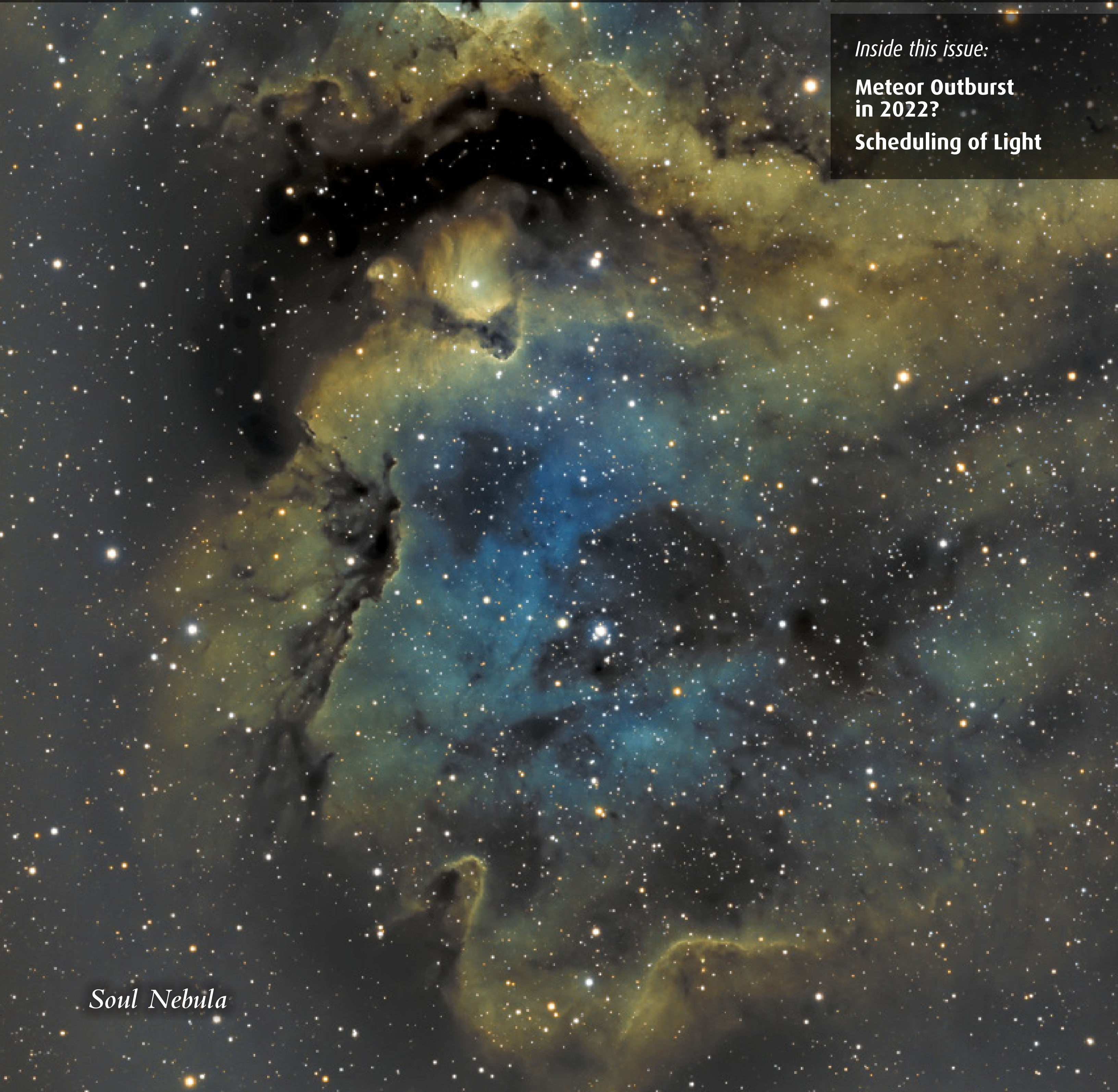

Soul Nebula

The Best of Monochrome.

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

Semaj Ragde captured this image from the tower of the Bastille during a violent uprising on July 1789, long before cameras were invented. It shows the waxing crescent Moon on an extraordinarily clear night, caught using eyepiece projection. (See inside back cover.)

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Société Royale d'Astronomie du Canada

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Ed Mizzi captured a beautiful region of the Soul Nebula in Cassiopeia from his backyard observatory in Waterdown, Ontario. He used a ZWO AS183 mono camera on a Skywatcher Esprit 100 mm APO, f/5.5 mounted on a Skywatcher EQ6-R. He used PHD and SG Pro and processed it in the Hubble Palette using PixInsight and Photoshop in Ha, OIII and SII for a total of 30 hours.

Errata:

In the February 2021 issue, the caption to Figure 6 on p. 19 incorrectly reads "Arthur Griffin" — it should have read "Jack Grant."

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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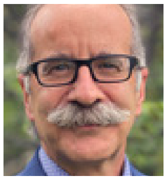
President's Corner



by Robyn Foret, Calgary Centre
(arforet@shaw.ca)

Looking back at 2020, interest in astronomy has blossomed as evidenced by overwhelming attendance at virtual events and the depletion of inventory at almost all telescope dealers and manufacturers.

While texts abound on the topic, it is images of celestial objects that inspire the newcomer, and technology has placed the means to capture data and create imagery in urban and rural settings like never before.

As with any science, astroimaging begins with knowledge and is honed with experimentation and peer review. The RASC offers programming that addresses these nicely. Starting with knowledge, www.youtube.com/c/RASCANADA/videos is a great place to start, specifically in The Insider Guide to the Galaxy series of tutorial videos for Introductory and Intermediate Astrophotography. Other guides on instruments, imaging tools, and other resources abound.

Once you have enough information to jump in, the RASC Astroimaging Certificate Program is where to go next. Start here https://rascastroimaging.zenfolio.com/ to see the kind of images that are expected to earn certificates. It's advisable to set realistic goals for yourself and to use our imaging community to help you along the way.

While there is no required order for the three available certificates, those are described here www.rasc.ca/astro-imaging-certificate. Astroimager – Wide Field is a great place to start as it introduces you to many types of astronomical imaging.

The Astroimager – Solar System will hone your skills of tracking, focusing, stacking, and image processing. You will need to master all of these to reach the required level of detail and quality demanded by this Certificate.

The Astroimager – Deep Sky, like the Solar System Certificate, also depends on your ability to master tracking, focusing, stacking, and image processing.

While submissions for these certificates are accepted from RASC members only, the membership dues pale in comparison to your astroimaging set-up, and the peer review offered by the dedicated and experienced Astroimaging Committee members is invaluable. Some will achieve the certificate on their first submission, but others will receive great critique and tips on what needs tweaking.

One more resource worth mentioning on this topic is the RASC's Robotic Telescope. While capturing your data and processing it with your own hands is required for the aforementioned certificates, the RASC has made available image data from its Robotic Telescope. Image sets from our 16-inch telescope in the Sierra Nevada mountains are available for purchase. Visible-light targets have 8 hours of exposure and narrowband targets have 20 hours of exposure. More info is offered here: http://secure.rasc.ca/StoreCat?Category=RT%20DATA

A final word on what may be the greatest astroimager ever: The *Hubble Space Telescope*. Hubble has brought new insights and stunning imagery to scientists and the public at large in unprecedented quality and quantity. To learn more about Hubble, be sure to check out the official memoirs of the space telescope in the new book, Not Yet Imagined: A Study of Hubble Space Telescope Operations by our own Past President, Dr. Chris Gainor, available as a free download at www.nasa.gov/connect/ebooks/not-yet-imagined.html. Congratulations, Chris. ✶

News Notes / En manchette

Compiled by Jay Anderson

No werewolves, but the full Moon still disturbs sleep

For centuries, humans have blamed the Moon for our moods, accidents, and even natural disasters. But new research indicates that our planet's celestial companion impacts something else entirely—our sleep.

In a paper published January 27 in *Science Advances*, scientists at the University of Washington (UW), the National University of Quilmes in Argentina, and Yale University report that sleep cycles in people oscillate during the 29.5–day lunar cycle. In the days leading up to a full Moon, people go to sleep later in the evening and sleep for shorter periods of time.

The research team, led by UW professor of biology Horacio de la Iglesia, observed these variations in both the time of sleep onset and the duration of sleep in urban and rural settings—from Indigenous communities in northern Argentina to college students in Seattle. The pattern's ubiquity may indicate that our natural circadian rhythms are somehow synchronized with—or entrained to—the phases of the lunar cycle.

"We see a clear lunar modulation of sleep, with sleep decreasing and a later onset of sleep in the days preceding a full Moon," said de la Iglesia. "And although the effect is more robust in communities without access to electricity, the effect is present in communities with electricity, including undergraduates at the University of Washington."

Using wrist monitors, the team tracked sleep patterns among 98 individuals living in three Toba-Qom Indigenous communities in the Argentine province of Formosa. The communities differed in their access to electricity during the study period: One rural community had no electricity access, a second rural community had only limited access to electricity—such as a single source of artificial light in dwellings—while a third community was located in an urban setting and had full access to electricity. For nearly three-quarters of the Toba-Qom participants, researchers collected sleep data for one to two whole lunar cycles.

Study participants in all three communities showed the same sleep oscillations as the Moon progressed through its 29.5-day cycle. Depending on the community, the total amount of sleep varied across the lunar cycle by an average of 46 to 58 minutes, and bedtimes see-sawed by around 30 minutes. For all three communities, on average, people had the latest bedtimes and the shortest amount of sleep in the nights three to five days leading up to a full Moon.

When they discovered this pattern among the Toba-Qom participants, the team analyzed sleep-monitor data from 464 Seattle-area college students that had been collected for a separate study. They found the same oscillations.

The team confirmed that the evenings leading up to the full Moon—when participants slept the least and went to bed the latest—have more natural light available after dusk: the waxing Moon is increasingly brighter as it progresses toward a full Moon, and generally rises in the late afternoon or early evening, placing it high in the sky during the evening after sunset. The latter half of the full Moon phase and waning Moons also give off significant light, but in the middle of the night, since the Moon rises so late in the evening at those points in the lunar cycle.

"We hypothesize that the patterns we observed are an innate adaptation that allowed our ancestors to take advantage of this natural source of evening light that occurred at a specific time during the lunar cycle," said lead author Leandro Casiraghi, a UW postdoctoral researcher in the Department of Biology.

Whether the Moon affects our sleep has been a controversial issue among scientists. Some studies hint at lunar effects only to be contradicted by others. De la Iglesia and Casiraghi believe this study showed a clear pattern in part because the team employed wrist monitors to collect sleep data, as opposed to user-reported sleep diaries or other methods.

More importantly, they tracked individuals across lunar cycles, which helped filter out some of the "noise" in data caused by individual variations in sleep patterns and major differences in sleep patterns between people with and without access to electricity.

These lunar effects may also explain why access to electricity causes such pronounced changes to our sleep patterns, de la Iglesia added.

"In general, artificial light disrupts our innate circadian clocks in specific ways: it makes us go to sleep later in the evening; it makes us sleep less. But generally we don't use artificial light to 'advance' the morning, at least not willingly. Those are the same patterns we observed here with the phases of the Moon," said de la Iglesia.

Regardless, the lunar effect the team discovered will impact sleep research moving forward, the researchers said.

"In general, there has been a lot of suspicion on the idea that the phases of the Moon could affect a behavior such as sleep—even though in urban settings with high amounts of light pollution, you may not know what the Moon phase is unless you go outside or look out the window," said Casiraghi. "Future research should focus on how. Is it acting through our innate circadian clock? Or other signals that affect the timing of sleep? There is a lot to understand about this effect."

Compiled with material provided by the University of Washington

Parker Solar Probe takes family portrait

The *Parker Solar Probe* was wheeling around the Sun last June 7—the fifth in its series of 24 planned close approaches to our star—when its Wide-field Imager for Solar PRobe (WISPR) captured the planets Mercury, Venus, Earth, Mars, Jupiter, and Saturn in its field of view. Its proximity to the Sun not only puts NASA's *Parker Solar Probe* in position to grab unprecedented information on the nascent solar wind and solar activity, it also affords the spacecraft some unique (and pretty cool) views of our Solar System.

WISPR's job is to take images of the solar corona and inner heliosphere in visible light, as well as images of the solar wind, shocks, and other structures as they approach and pass the spacecraft. The imager was doing just that last June, at the closest approach (or perihelion) of its orbit, when its field of view swept away from the edge of the Sun and toward the planets beyond. It's an interesting perspective: Mercury, the innermost planet, appears farthest away from the Sun.

"Imagine being able to stand on the Sun and gaze toward the stars," said Nour Raouafi, *Parker Solar Probe* project scientist at the Johns Hopkins Applied Physics Laboratory in Laurel, Maryland. "It's just awe-inspiring to see so many worlds in our Solar System—including our own planet—in the same portrait. We often think of viewing our Solar System from the outside in, and this allows us the unique opportunity to see it from the inside out. It's a view few spacecraft can provide, and *Parker Solar Probe* has given us an entirely different perspective on our place in space."

The spacecraft was approximately 18.7 million kilometres from the Sun's surface, and about 158 million kilometres from

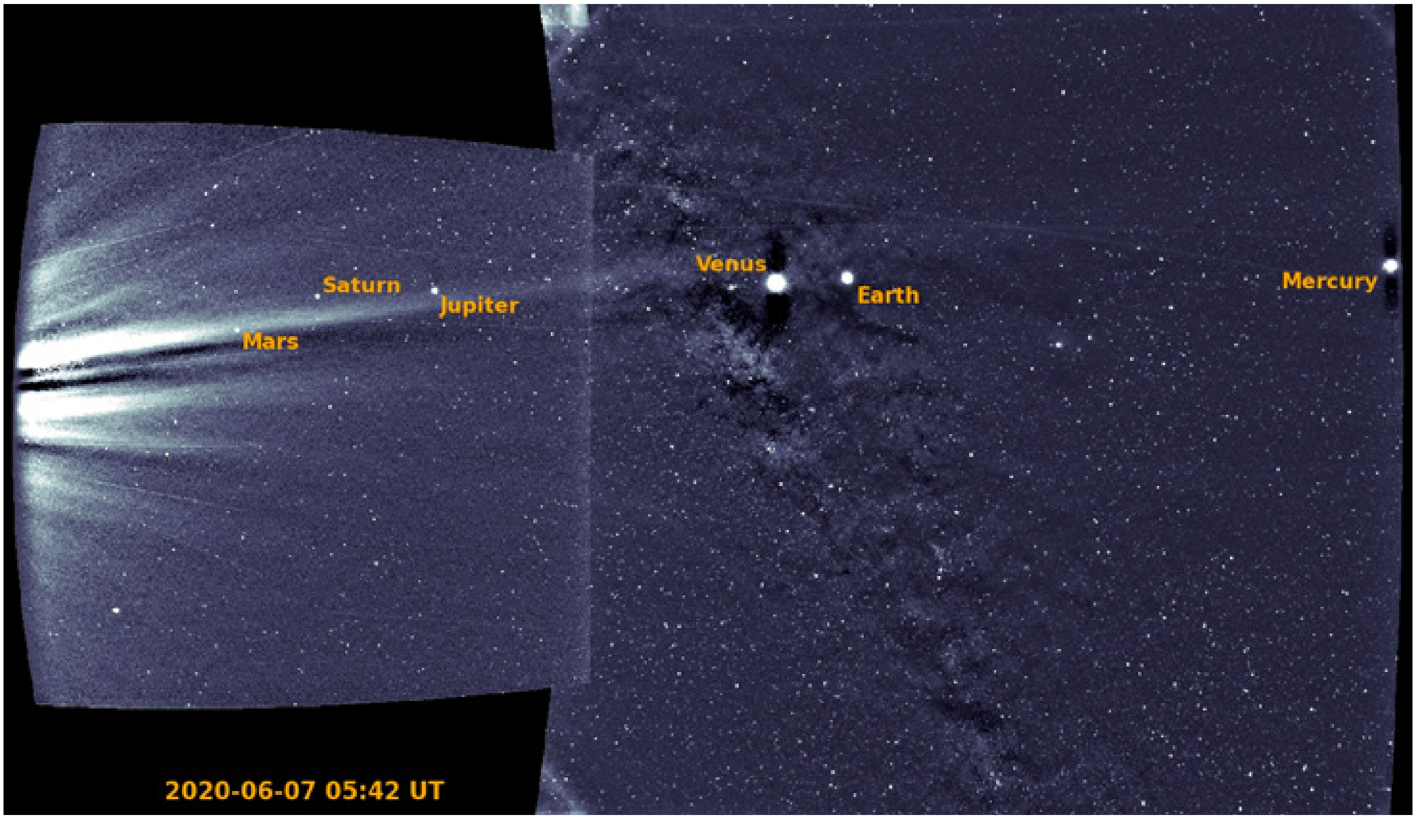


Figure 1 — The Parker Solar Probe was approximately 18.7 million kilometres from the Sun's surface, and about 158 million kilometres from Earth when it took this. Image credit: NASA/Johns Hopkins APL/Naval Research Laboratory/Guillermo Stenborg and Brendan Gallagher

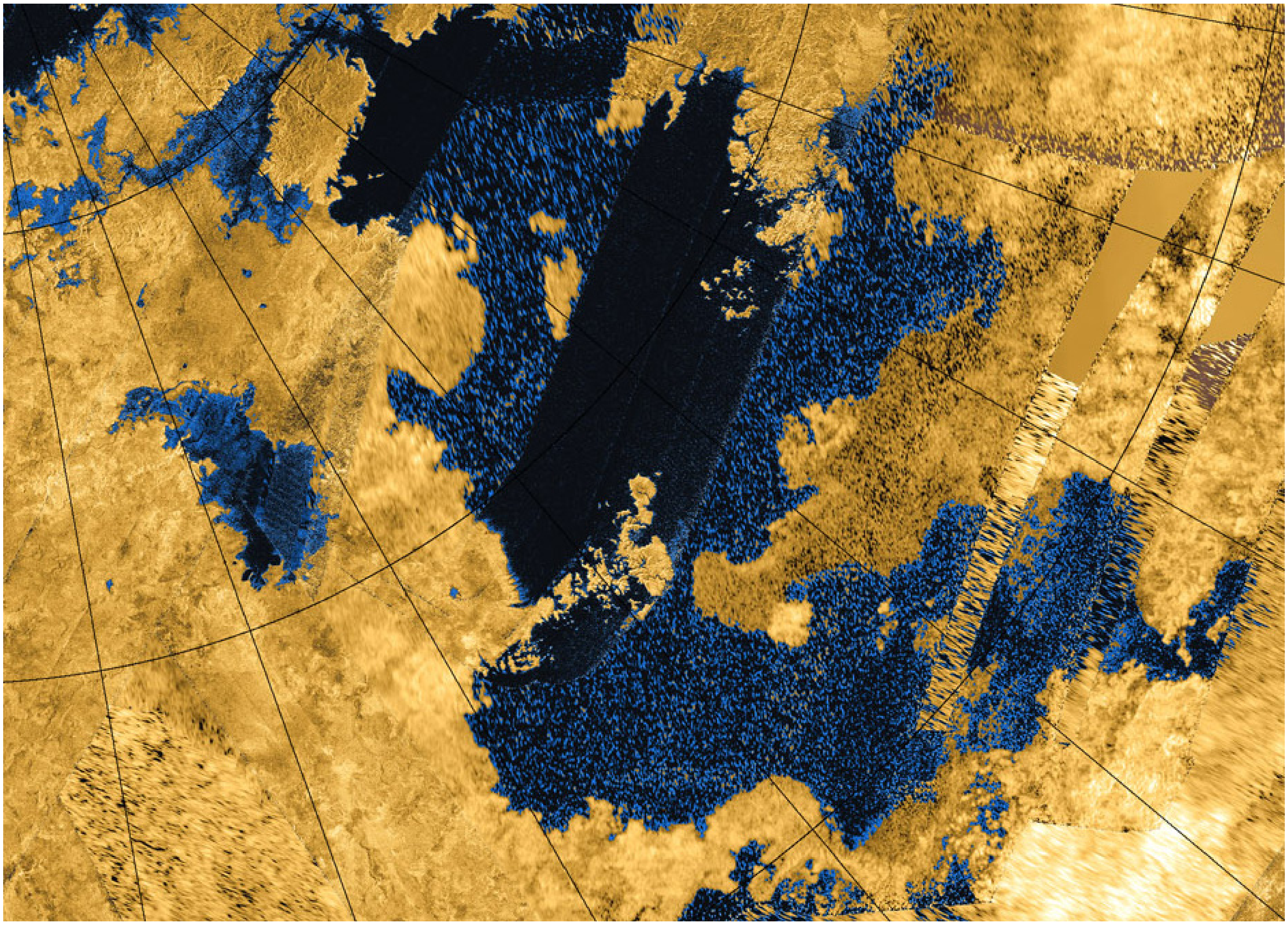


Figure 2 — This colourized mosaic from NASA's Cassini Mission *shows a view of Titan's Kraken Mare, its largest sea. The liquid in Titan's lakes and seas is mostly methane and ethane. The data were obtained by* Cassini's *radar instrument from 2004 to 2013. In this image, the north pole is just beyond the upper left corner. The view extends down to 50 degrees north latitude. Liquids appear blue and black depending on the way the radar bounced off the surface; land areas appear yellow to white. Image: NASA*

Earth, when WISPR gathered the images. *Parker Solar Probe* has since completed two additional close approaches—the latest on January 17—that brought it within a record 13.5 million kilometres of the Sun's surface.

Compiled with material provided by NASA.

Deep diving in a methane sea

Far below the gaseous atmospheric shroud on Saturn's largest Moon, Titan, lies Kraken Mare, a half-million square kilometre sea of liquid methane. Cornell astronomers have estimated that sea to be at least 304 metres deep near its centre—enough room for a potential robotic submarine to explore.

"The depth and composition of each of Titan's seas had already been measured, except for Titan's largest sea, Kraken Mare—which not only has a great name, but also contains about 80 percent of the moon's surface liquids," said lead author Valerio Poggiali, research associate in Cornell Center for Astrophysics and Planetary Science (CCAPS).

At 1.6 billion kilometres from Earth, frigid Titan is cloaked in a golden haze of gaseous nitrogen. But peeking through the clouds, the moonscape has an Earthlike appearance, with liquid methane rivers, lakes, and seas, according to NASA.

The data for this discovery was gathered on *Cassini*'s flyby of Titan on 2014 August 21. The spacecraft's radar surveyed Ligeia Mare—a smaller sea in the Moon's northern polar region—to look for the mysteriously disappearing and reappearing "Magic Island," which was an earlier Cornell discovery.

While *Cassini* cruised at 20,900 km/h nearly 970 km above Titan's surface, the spacecraft used its radar altimeter to measure the liquid depth at Kraken Mare and Moray Sinus, an estuary located at the sea's northern end. The Cornell scientists, along with engineers from NASA's Jet Propulsion Laboratory, had figured out how to discern lake and sea bathymetry (depth) by noting the radar's return time differences on the liquid surface and sea bottom, as well as the sea's composition, by ascertaining the amount of radar energy absorbed during transit through the liquid.

It turns out that Moray Sinus is about 85 metres deep, shallower than the depths of central Kraken Mare, which was too deep for the radar to measure. Surprisingly the liquid's composition, primarily a mixture of ethane and methane, was methane-dominated and similar to the composition of nearby Ligeia Mare, Titan's second-largest sea.

Earlier scientists had speculated that Kraken may be more ethane rich, both because of its size and extension to the Moon's lower latitudes. The observation that the liquid composition is not markedly different from the other northern seas is an important finding that will help in assessing models of Titan's Earth-like hydrologic system.

Beyond deep, Kraken Mare also is immense—nearly the size of all five Great Lakes combined.

Titan represents a model environment of a possible atmosphere of early Earth, Poggiali said.

"In this context," he said, "to understand the depth and composition of Kraken Mare and the Moray Sinus is important because this enables a more precise assessment on Titan's methane hydrology. Still, we have to solve many mysteries."

One such puzzle is the origin of the liquid methane. Titan's solar illumination—about 100 times less intense than on Earth—constantly converts methane in the atmosphere into ethane; over roughly 10-million-year periods, this process would completely deplete Titan's surface stores, according to Poggiali.

In the distant future, a submarine—likely without a mechanical engine—will visit and cruise Kraken Mare, Poggiali said.

"Thanks to our measurements," he said, "scientists can now infer the density of the liquid with higher precision, and consequently better calibrate the sonar aboard the vessel and understand the sea's directional flows."

Compiled with material provided by Cornell University

When it comes to some white dwarfs, one plus one equals one

White-dwarf stars are the endpoints of stellar evolution for stars lighter than about 10 solar masses. In cases where evolution of a binary-star system leads to the formation of a pair of white dwarfs, the emission of gravitational waves will extract energy from the system and the two components will gradually spiral in toward each other. Eventually the pair will collide and merge, usually creating a Type Ia supernova that disrupts the entire system.

If at least one of the partners has a very large mass, more than eight times that of the Sun, the merger can lead to the formation of a neutron star. This new star may have a mass in excess of the Chandrasekhar limit—1.4 solar masses—that determines whether the object will become a supernova, or gradually cool to a benign white dwarf. In most cases, binary white-dwarf systems will form a supernova.

Now, a team of astronomers led by Lidia Oskinova of the University of Potsdam, Germany, used ESA's *XMM-Newton* X-ray telescope to study IRAS 00500+6713, an object originally discovered in 2019. At the time, astronomers reported that the object has very high wind speeds and was too bright, and therefore too massive, to be an ordinary white dwarf. Oskinova and her team suggest that the object is a new type of white dwarf that survived the merger of two earlier white dwarfs and a supernova explosion that failed to disrupt the system. The analysis of the optical spectrum of the central star revealed that it is hot, hydrogen and helium free, and drives an extremely fast wind, with a record breaking speed of 16,000 km/s, all signs of a white dwarf of unusual character.

The research team conducted deep X-ray imaging spectroscopic observations of IRAS 00500+6713, detecting both the central star and the nebula. X-ray spectra revealed large neon,

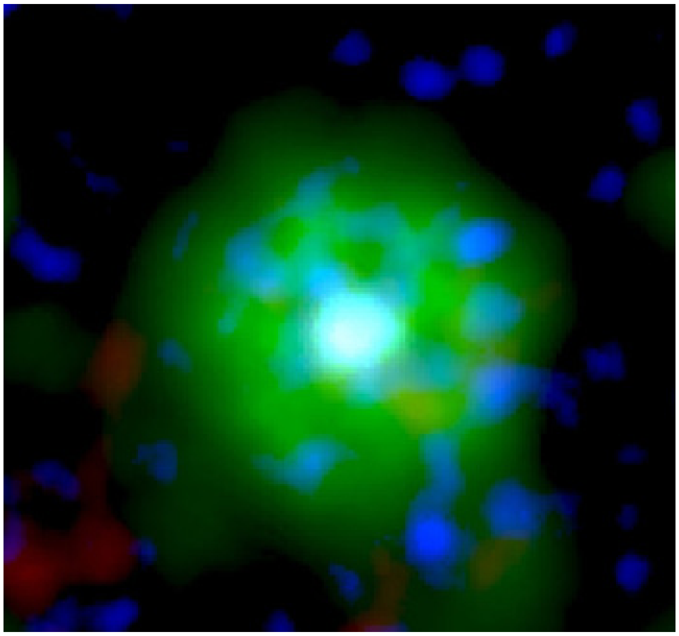


Figure 3 — A new type of star that has never been seen before in X-ray light. The adaptively smoothed image shows that X-ray emission uniformly fills the whole extent of the nebula. The nebula is mostly composed of neon, seen as green in the image. Image: ESA/XMM-Newton, L. Oskinova/Univ. Potsdam, Germany

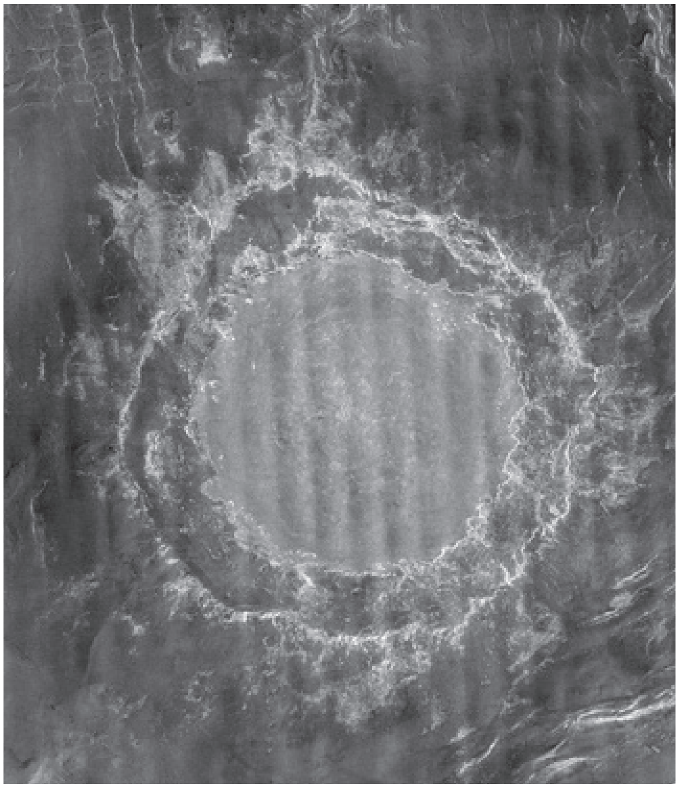


Figure 4 — This **Magellan** *image mosaic shows Mead Crater, the largest (275 kilometres in diameter) impact crater known to exist on Venus. It is named after the cultural anthropologist Margaret Mead. Image: NASA*

silicon, and sulfur enrichment, leading the team to conclude that the new star resulted from a merger of two types of dwarf: a heavy ONe (oxygen-neon) and a lighter CO (carbon-oxygen) white dwarf, supporting earlier identification of a super-Chandrasekhar mass. In addition, the research team identified the surrounding nebula as a supernova remnant. Modelling suggested that the heavier white dwarf pulled material from the lighter, eventually leading to a supernova explosion that failed to disrupt the system, allowing it to evolve into the heavy white dwarf seen in X-rays. The object has a high rotation speed, preventing it from further collapse.

Oskinova and her team hypothesize that IRAS 00500+6713 will likely collapse into a neutron star within the next 10,000 years with a second supernova to mark the occasion.

Compiled in part with material provided by ESA, the University of Potsdam, and Nature.

Thick-skinned Venus resists crustal movement

At some point between 300 million and 1 billion years ago, a large cosmic object smashed into the planet Venus, leaving a crater more than 280 kilometres in diameter. A team of Brown University researchers has used that ancient impact scar to explore the possibility that Venus once had Earth-like plate tectonics.

For a study published in *Nature Astronomy*, the researchers used computer models to recreate the impact that carved out Mead crater, Venus's largest impact basin. Mead is surrounded by two clifflike faults—rocky ripples frozen in time after the basin-forming impact. The models showed that for those rings to be where they are in relation to the central crater, Venus's lithosphere—its rocky outer shell—must have been quite thick, far thicker than that of Earth. That finding suggests that a tectonic regime like Earth's, where continental plates drift like rafts atop a slowly churning mantle, was likely not happening on Venus at the time of the Mead impact.

Evan Bjonnes, a graduate student at Brown and the study's lead author, says the findings offer a counterpoint to recent research suggesting that plate tectonics may have been a possibility in Venus's relatively recent past. On Earth, evidence of plate tectonics can be found in huge rifts called subduction zones, where swaths of crustal rock are driven down into the subsurface. Meanwhile, new crust is formed at mid-ocean ridges, sinuous mountain ranges where lava from deep inside the Earth flows to the surface and hardens into rock. Data from orbital spacecraft have revealed rifts and ridges on Venus that look a bit like tectonic features but Venus's thick atmosphere makes it hard to make definitive interpretations of fine surface features.

Mead is a multi-ring basin similar to the huge Orientale basin on the Moon. Previous work showed that the final position of the crater rings is strongly tied to the crust's thermal gradient—the rate at which rock temperature increases with depth. The thermal gradient influences the way in which the rocks deform and break apart following an impact, which in turn helps to determine where the basin rings end up.

Bjonnes's work showed that for Mead's rings to be where they are, Venus's crust must have had a relatively low thermal gradient. That low gradient—meaning a comparatively gradual increase in temperature with depth—suggests a fairly thick Venusian lithosphere.

"This tells us that Venus likely had what we'd call a stagnant lid at the time of the impact," said Evan Bjonnes. "Unlike Earth, which has an active lid with moving plates, Venus appears to have been a one-plate planet for at least as far back as this impact."

Alexander Evans, an assistant professor at Brown and study co-author, said that one compelling aspect of the findings from Mead is their consistency with other features on Venus. Several other ringed craters that the researchers looked at were proportionally similar to Mead, and the thermal gradient estimates are consistent with the thermal profile needed to support Maxwell Montes, Venus's tallest mountain.

Compiled with material provided by Brown University. ✷

Will Comet 73P/Schwassmann-Wachmann 3 Produce a Meteor Outburst in 2022?

by Joe Rao

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Abstract

Comet 73P/Schwassmann-Wachmann 3, a member of the Jupiter family of comets, broke into several fragments in the autumn of 1995. A dramatic increase in the comet's intrinsic brightness was then seen, suggestive of a massive expulsion of dust. Orbiting the Sun about every 5.4 years, the comet has continued to disintegrate since its initial disruption. Dozens of fragments have since been identified in subsequent near-Earth passages. Three independent studies have investigated the prospects of Earth's passage through its trail of freshly ejected material, which could lead to a meteor shower. One study showed that Earth will fail to interact with the ejected material, while the other two suggest a direct interaction with the trail, thus possibly producing an outburst of meteor activity at the end of May 2022.

Using an N-body integrator, we found that all three studies are plausible. However, the occurrence of a meteor shower/outburst requires a rather unique set of circumstances: One that assumes a larger-than-normal preponderance of the particles are subsequently ejected at sufficiently high velocities to overcome the effects of solar-radiation pressure. Such material would tend to migrate forward of the comet's direction of motion around the Sun, ultimately colliding with Earth. We find that any detectable meteor activity would reach a maximum on 2022 May 31.21 UTC, with a mean radiant position of α=208.35° δ=27.45° (J2000.0).

Key words: *Comets: individual (73P/Schwassmann-Wachmann 3) – meteors, meteoroids*

1. Introduction

Meteor observing is usually a slow and meditative pursuit, but occasionally it can turn dramatic. Most meteor showers are fairly predictable. Occasionally, a bright fireball will blaze into view, but there is always a chance of witnessing something truly new and unexpected—perhaps even when no shower was predicted at all.

And at the end of May 2022 things could turn exciting.

In the fall of 1995, comet 73P/Schwassmann-Wachmann 3, fractured into several pieces and left a trail of fragments in its wake, which the Earth might encounter during the overnight hours of 2022 May 30–31.

On that night, a meteor shower might erupt ranking with the January Quadrantids or December Geminids; annual displays that are normally the richest of the year. Yet, there is also a small chance of something extraordinary—perhaps one of the most dramatic meteor displays since the spectacular Leonid showers, which occurred around the turn of this century, with a large fraction of the meteors being bright.

Or perhaps, visually, nothing at all will be seen.

The possibility of Earth interacting with the dross of a fragmented comet may sound familiar. Indeed, most astronomy texts often make reference to the famous case regarding the splitting of comet 3D/Biela in 1842 or early 1843 and its contemporaneous association with spectacular meteor storms occurring in 1872 and again in 1885.

The question is, might there be hope for a similar performance resulting from the recent break-up of comet 73P/Schwassmann-Wachmann 3?

2. Comet 73P/Schwassmann-Wachmann 3

Diminutive Visitor

Comet 73P/Schwassmann-Wachmann 3 (hereon designated "SW 3") was the third comet found by German astronomers Friedrich Carl Arnold Schwassmann and Arno Arthur Wachmann in the early 20th century. After its discovery on photographic plates exposed on 1930 May 2 at Hamburg Observatory (Bergedorf) for the regular minor-planet survey, orbit calculations quickly revealed that the comet would pass only 0.0616 AU from the Earth on 1930 May 31.

Astronomers believe that SW 3's nucleus probably measures only around 1.3 km (0.81 mile) in diameter [1]—hardly a significant celestial body. Consequently, the comet is intrinsically quite faint. For this reason, its peak brightness in 1930 was estimated to be between magnitudes +6 and +7. SW 3 was also seen to possess a rather faint tail measuring about ½° in length. [2]

Even though SW 3 orbits the Sun about every 5.4 years, 1930 was the last time anyone saw it for quite a while. In fact, between 1935 and 1974, SW 3 came and went eight times without being observed. It finally was caught on photographs taken in Australia in 1979 (magnitude +12.5 on March 19 when 1.4359 AU from Earth), missed in 1985, and recovered again in 1990 (magnitude +9.0 on April 17 when 0.3661 AU from Earth; its best apparition since 1930).

Surprise!

Astronomers expected SW 3 to make another uneventful return in the fall of 1995. From September 8 through 13, however, radio-wavelength observations of the comet's emissions made at the Observatoire de Paris-Meudon's Nancay Radio Telescope, indicated a significant increase in hydroxide (OH^-), with peak production at $2.22 \pm 0.22 \times 10^{29}$ molecules per second. This is only a factor of 10 below the peak production rates observed for the much larger Halley's Comet during its 1986 apparition.[13]

Then, during mid-October, 1995, the Central Bureau for Astronomical Telegrams suddenly began receiving "numerous reports from observers worldwide of independent discoveries [3]" of a comet verging on naked-eye visibility that had been sighted low in the western sky during evening twilight and sporting a dust tail 1° long.

This, however, wasn't a "new" comet at all—it was 73P/Schwassmann-Wachmann 3!

This was a huge surprise, because that year the comet never came closer to Earth than 1.3114 AU on October 17. Predictively, it should have appeared no brighter than about magnitude +12; a challenging target even through large amateur telescopes. And yet there it was, shining 6.5 magnitudes brighter than anticipated—a nearly *400-fold increase* in luminous intensity! Here was a classic demonstration of how a comet can go around the Sun on numerous occasions as a staid member of the solar community, and then abruptly and unpredictably undergo some sort of violent change.

As to the cause of this tremendous outburst, the answer came on 1995 December 12–13, when observations of SW 3 made at the European Southern Observatory in La Silla, Chile, revealed "at least four separate brightness peaks in the coma. [4]" SW 3's tiny nucleus had fragmented, but unlike 3D/Biela, which simply broke in two, SW 3 apparently fractured into *four parts*.

On IAUC No. 6301, dated 1996 February 1, comet investigator Zdeněk Sekanina determined that component B broke off from the primary component C "most probably about 1995 Oct. 24" … evidently followed by a secondary splitting of component B, which gave birth to component A on, or about December 1. As for component D, it seems it might have separated from C in late November. Noted Brian G. Marsden, then-Director of the Central Bureau for Astronomical Telegrams: "There now appears to be no escape from the conclusion that the brightness outburst, which apparently occurred between Sept. 5 and 8, preceded the first breakup episode by at least six weeks."

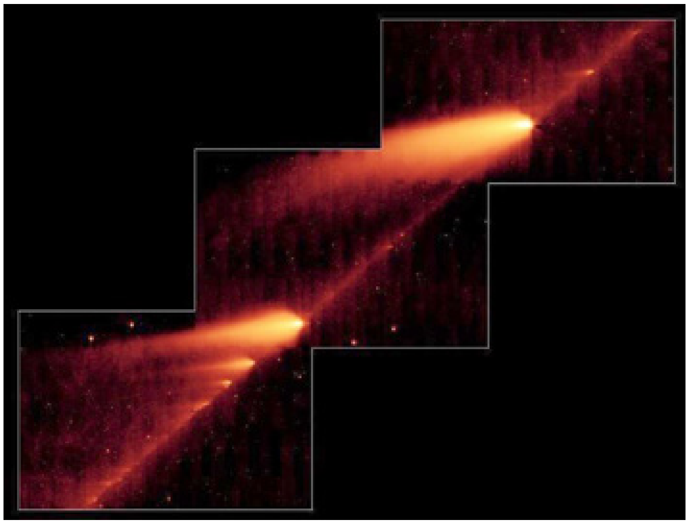

Figure 1 — Recorded on 2006 May 4–6 by the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope*, this image captures about 45 of 58 alphabetically catalogued large comet fragments. The brightest fragment at the upper right of the track is Fragment C. Bright fragment B is below and left of centre.* Spitzer's *infrared view also captures the trail of dust left over as the comet deteriorated during previous perihelion passages in 1995 and 2001. Emission from the dust particles warmed by sunlight appears to fill the space along the cometary orbit. Image credit:* ***NASA, JPL, Caltech.***

The comet was still quite bright on its next visit in the fall of 2000, when many people saw it, even though it was poorly placed for observation. Two of the fragments spotted in 1995 (known as B and C) had returned, together with a new one (E), which probably was released (but undetected) during the 1995 return. C was presumed to be the largest remnant of the original comet and was thus designated as the main object, with B (about one-third the size of C) and E appearing as individual small comets trailing more than ½° behind C.

In the spring of 2006, the disintegrating comet made its next return appearance. Initially, astronomers counted at least eight remnants: big fragments B and C, plus smaller fragments G, H, J, L, M, and N. During this apparition, some of the fragments were themselves forming their own sub-fragments.

On 2006 April 18, the *Hubble Space Telescope* recorded dozens of pieces of fragments shed primarily by B and G [5]. Between May 4 and 6, it was the *Spitzer Space Telescope*'s turn to image the comet (Figure 1); using its Infrared Array Camera (IRAC), it was able to observe 45 of 58 known fragments [6]. The main fragment, C, passed closest to Earth on May 13 at a distance of 0.0735 AU, with fragments B and E passing even closer at 0.0515 and 0.0505 AU, respectively. In all, SW 3 broke into more than 68 fragments. Perihelion was on June 9, with the comet passing the Sun at a distance of 0.9391 AU.

The comet would not return to the vicinity of the Sun until 2011 October; another unfavourable apparition.

SW 3's most recent perihelion was in March 2017. Big fragment C was still chiefly intact, but was then seen accompanied by a smaller fragment designated as BT. So, it appears that the comet was then continuing to slowly break apart, shedding new pieces with each return through the inner Solar System.

Its next perihelion will occur on 2022 August 25 at a distance of 0.9729 AU.

3. Meteors from 73P?

Shortly after SW 3 was discovered in 1930, two astronomers at Kwasan Observatory (Kyoto, Japan) calculated an orbit and from this, one (Shibata) predicted a possible meteor shower when the Earth passed close to the comet's node on June 9 [7]. The assumed radiant was located in northern Hercules, near the fourth-magnitude star Tau (τ) Herculis. The potential new meteor shower was thus christened the "Tau Herculids," (later designated #61 TAH at the IAU Meteor Data Center).

Meteoroids presumably shed by SW 3 had been sighted as meteors chiefly by Japanese observers during the final week of May into early June 1930. The observed activity, however, was very weak, producing only several possible shower members. On June 8, an announcement regarding the potential of a strong meteor shower associated with SW 3 was widely circulated in newspapers around the globe [8].

Indeed, on June 9, from Kwasan Observatory in Kyoto, Japan, an outburst of 59 meteors in one hour (9:51 to 10:51 p.m. local time) was reported. On the following night, again from the same location, 36 meteors were sighted in only 30 minutes (an event rate of 72 meteors per hour) [9].

But there is a problem in accepting that these events actually took place. The only person who claimed to see these outbursts was Kaname Nakamura, who commented that "…all of these meteors were very faint and only a few of them were as bright as 4th magnitude." However, there was a full Moon on June 11, so his observations on June 9 must have been conducted under the bright-sky conditions of a waxing gibbous Moon.

Moreover, Nakamura noted that on both nights (June 9 and 10), "…bright lunar haloes were high above the southern horizon." So, despite a nearly full Moon illuminating a moonlight-scattering layer of high-altitude cirrus or cirrostratus clouds, Nakamura still managed to somehow see a bevy of very faint meteors on consecutive nights. Even the director of the Kwasan Observatory, Issei Yamamoto, later noted that "Mr. Nakamura was practically the only observer" among staff members of the observatory.[1]

Elsewhere however, Nakamura-san's suggested meteor activity was conspicuously absent. Members of the meteor section of the British Astronomical Society failed to see a single member of the Tau Herculid stream on the nights of June 5, 7, and 9, putting the blame squarely on the bright moonlight.

Any reports of possible Tau Herculid activity in the years following 1930 has ranged from exceedingly sparse to non-existent. Some meteoroid orbits inferred from meteor streaks on photographic plates taken from 1963 and 1971 [10], which were initially identified with this stream, were later found (in 1999) to have no connection with it whatsoever.

Finally, during this past decade, minor activity from the Tau Herculids was definitely confirmed: On 2011 June 2, NASA Cameras for all-sky meteor surveillance in California (CAMS), photographed 3 members of this stream between 4h and 12.2h UTC[2]. Additionally, on 2017 May 30–31, between 23:39 and 00:45 UTC, five shower members were again captured by CAMS. Lüthen et al. (2001) [11], had forecast possible activity for both years from a dust trail shed by SW 3 in 1941 and another in 1952. Actually, both predictions were thought to be somewhat dubious since the respective miss distances were considered fairly large (0.0011 AU and 0.0013 AU, respectively).

Ingredients for a Meteor Shower

The birth, life, and death of a meteor stream is reasonably well understood, at least in broad outline. Whenever a comet comes near the warmth of the Sun, a little of its frozen nucleus sublimates, shedding clouds of dust and rubble. In time, this material spreads out along the comet's orbit, then gradually diffuses away from the orbit. An intense shower occurs when Earth passes—albeit briefly—through a thin, concentrated band of debris inside the much larger dust stream. These dense filaments are typically found relatively near the parent comet, and in most cases, they were probably shed from it only in recent centuries.

All the ejected particles, regardless of size and unless perturbed, stay closely confined to the plane of the comet's orbit—at least until, in time, the stream degrades and drifts apart. Gravitational perturbations by the planets are a major factor in shifting and eventually breaking up a meteor stream. Tracking all of these influences is what meteor-shower forecasting is about.

The old meteoroids that have had time to become widely scattered are the ones that produce the ordinary, weak annual shower. The narrow, densest part of the swarm is a ribbon whose width is poorly known; in fact, the "ribbon" may actually be a more complicated structure consisting of thin bands and sheaves.

Testing for 73P/Schwassmann-Wachmann 3

In 2004, astronomer Jérémie Vaubaillon, at the Institute of Celestial Mechanics and Computation of Ephemerides (IMCCE) in Paris, France, introduced a new type of model for the formation and evolution of comet dust trails. His ejection model is primarily based on a hydrodynamic model by Crifo & Rodionov, 1997 [12] and takes into account comets at heliocentric distances of less than 3 AU that ultimately produce clouds of dusty debris. The meteoroids are ejected in a uniform manner from the comet's spherically symmetric sunlit hemisphere. For comet SW 3, numerical simulations were performed [13] using nearly two million particle ejections from 1801 to 2006, assigned to five size bins ranging from 0.1 to 100 mm. The typical ejection (escape) velocity V is computed in the sunlit hemisphere [26] [27], as a function of comet nucleus properties (size, fraction of active area etc.), particle size, ejection sub-solar angle and heliocentric distance, using a Monte-Carlo method and leading to a range in V up to 20 m/s (±20 m/s), with V falling to 0 m/s at sub-solar angle = 90° [27 and 28]

As has been previously noted, save for a scattered few, no meteor activity of consequence associated with comet SW 3 has been reported since 1930. (Even here, there is some contention as to whether heightened activity noted in that year actually took place.) However, the nucleus fragmented in 1995 and has continued to disintegrate, producing a fresh trail of cometary material. This, combined with the Earth's orbit positioned very close to the descending node of the comet, has raised the prospects for a possible meteor outburst or perhaps even a storm similar to what happened with 3D/Biela; a possibility that should certainly be investigated.

Wiegert et al., 2005 [13] discussed the exceptionally close (0.05 to 0.07 AU) approach in May 2006 of comet SW 3 and its associated fragments relative to Earth. In that paper the authors noted that, "…a swarm of comet fragments of various sizes, ranging from kilometre sized on down, will pass near the Earth in 2006, and the possibility exists that the τ Herculid shower, typically unimpressive, could be dramatically stronger than usual."

Ultimately however, such a possibility for enhanced activity was ruled out (as will later be shown to be correct): "…partly (as a result) of the dynamics of the parent comet, which suffers frequent close encounters with Jupiter (Figure 2), and partly of the location and timing of the splitting event, which produces a distribution of meteoroids that does not approach the Earth particularly closely." (Wiegert et al. ibid)

After 2006, the next possible Earth encounter for meteor activity is in 2022, but it would not originate from meteoroids

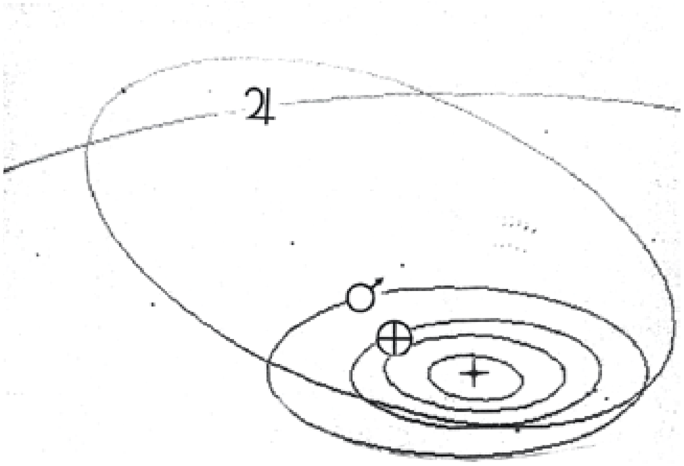

Figure 2 — Orbit of comet 73P/Schwassmann-Wachmann 3 (SW 3). It is a member of Jupiter's "comet family," a group of about 400 short-period comets with aphelia near the orbit of Jupiter. The comet's orbital period is roughly 5.4 years and it arrived at aphelion in 2019 late December, 5.213 AU from the Sun. Its close proximity to Jupiter's orbit means that occasionally it will be perturbed by that big planet's gravitational field. Since the comet's discovery in 1930, it has approached to within 0.68 AU of Jupiter in October 1953, and within 0.29 AU in November 1965. It will make a similarly close approach to Jupiter (0.29 AU) in February 2025. Image credit: Joe Rao

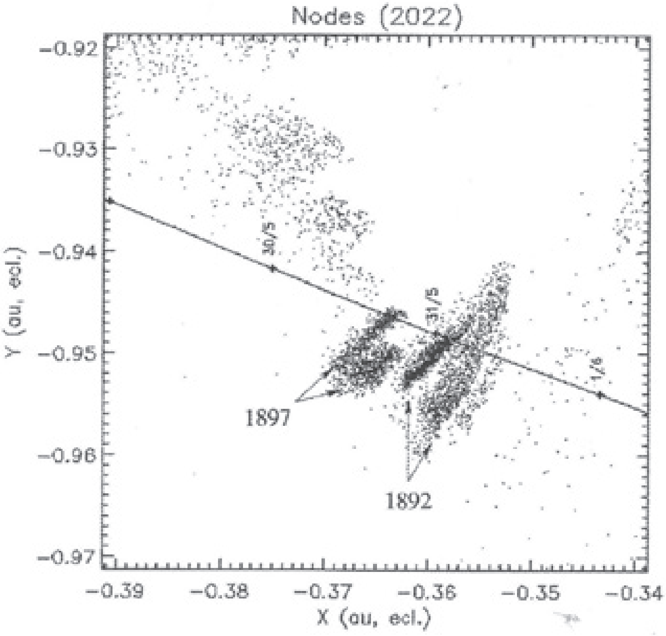

Figure 3 — The nodal crossing points of meteoroids (depicted as small dots) ejected from SW 3 at all perihelion passages back to 1801 based on the Vaubaillon model, plotted relative to the Earth's orbit for the year 2022. Only meteoroids whose descending node occurred within one week either before or after Earth's passage are shown. The relevant dust trails are marked by arrows indicating their year of origin. Earth interacts with dust ejected from 1892 and 1897, but not with the dust trail produced by the fracture of SW 3's nucleus in 1995. Image credit: Jérémie Vaubaillon.

released during the 1995 splitting of SW 3's nucleus. Rather, meteoroids released during pre-discovery apparitions in 1892 and 1897 reached the Earth at the end of May that year. A maximum ZHR (zenithal hourly rate) of 10, from these 19th-century meteoroids, is back-predicted, but, based on Vaubaillon's model, no interaction of Earth with cometary material released during 1995 is forecast for 2022 (Figure 3).

Let's Dance!

Out of curiosity, we attempted to model the meteoroid stream associated with the 1995 breakup of comet SW 3 using a different methodology. For the task of providing adequate orbital simulations for particles relating to SW 3, the computer program DANCE OF THE PLANETS [14] was chosen. It is an N-body integrator; the incremental movement of each body due to the gravitational influence of all others is continuously calculated, closely approximating the action of gravitation. One unfortunate limitation of the program is it does not take into account non-gravitational forces, an effect that accelerates or decelerates a comet's motion, changing its orbital period.

Our attempt was made solely to corroborate Vaubaillon's model prediction as to how closely SW 3 meteoroids would approach Earth. First, epoch 1995 positions of SW 3 were obtained from orbital elements developed by Kenji Muraoka, derived from 226 observations (1989 to 1996) [15]. Second, to simulate a trail of meteoroids, an additional 19 comets (the maximum possible for this software program) were generated, directed along a radius vector diametrically opposed to the Sun. Third, for the representation of the respective meteoroid "cloud" orbits, Muraoka's orbital elements from the 1995 apparition of SW 3 were copied onto the program's "CMT" files:

$\boldsymbol{T}$ = 1995 September 22.88978 UTC
$\boldsymbol{q}$ = 0.93278
$\boldsymbol{e}$ = 0.694848
ω = 198.7693°
$\boldsymbol{\Omega}$ = 69.9466°
$\boldsymbol{i}$ = 11.4239°

The only alterations made were in the respective perihelion distances (q) of the other 19 comets from the Sun. Starting with "parent comet" SW 3 at 0.93278 AU, all 20 comets were aligned within a space measuring 0.01076 AU (1.609 million km or 1 million miles); each comet separated incrementally by increasing distances from the Sun of 0.00053789 AU or 80,000 km (50,000 miles).

The speed of the orbital simulation is set using the tunable DANCE parameter "Pace" (the apparent time acceleration). Very large values can diminish simulation accuracy. "True" is real time. For heliocentric space views, the maximum pace simulated by DANCE is 240k; one minute equates to about 385 years. It was determined for adequately simulating a trail of meteoroids, the Pace should be set at a much slower unit of 1000 (where one minute equates to roughly 16 years). There is also a tunable magnification function, "Zoom," which for heliocentric space views, runs upwards to 512×. A Zoom of 1× corresponds to a naked- eye view. For our simulations, a Zoom of 64× was employed.

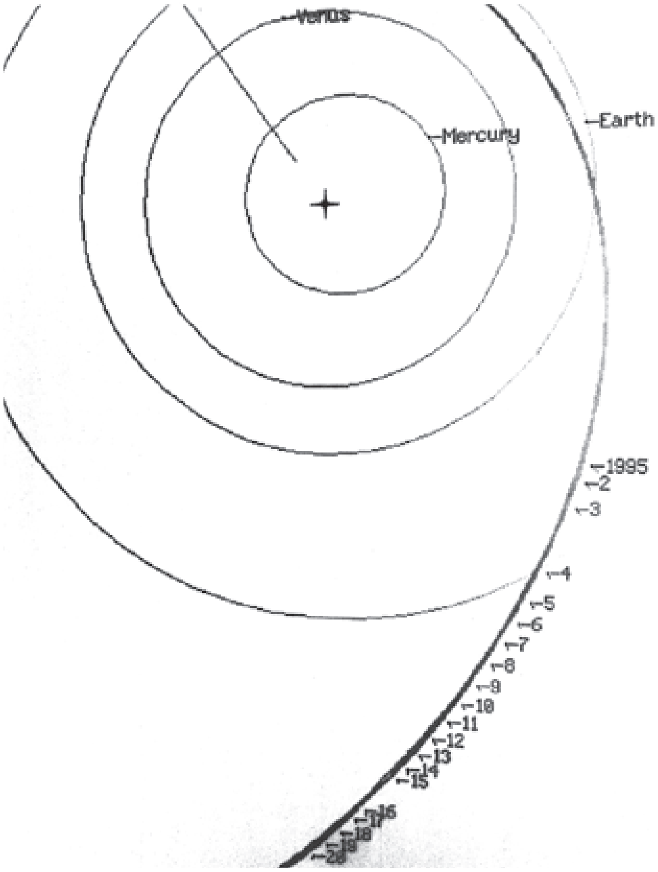

Figure 4 — Positions of Earth, SW 3, and the presumed train of meteoroids on 2022 May 31 using "Dance of the Planets" orbital simulator. Note that the orbits of the comet ("1995") and its meteoroid train appear somewhat displaced from their original 1995 orbits—the year of the breakup of the comet nucleus. Assuming meteoroids are ***trailing behind*** *the parent comet, no interaction with the Earth can take place, supporting the findings of the Vaubaillon model. Image credit:* ***Joe Rao***

So, starting from perihelion in 1995, the 20 comets were set into motion at Pace = 1000 and Zoom = 64×. Moving forward in time, the comets gradually separated from each other along their corresponding orbital paths.

Moving forward from 1995 to 2006, the "parent" comet, SW 3, and the next six comets in the presumed meteoroid trail, swept past the Earth near the comet's descending node at distances of less than 0.2 AU as shown in Table 1. r = heliocentric distance, Δ = geocentric distance.

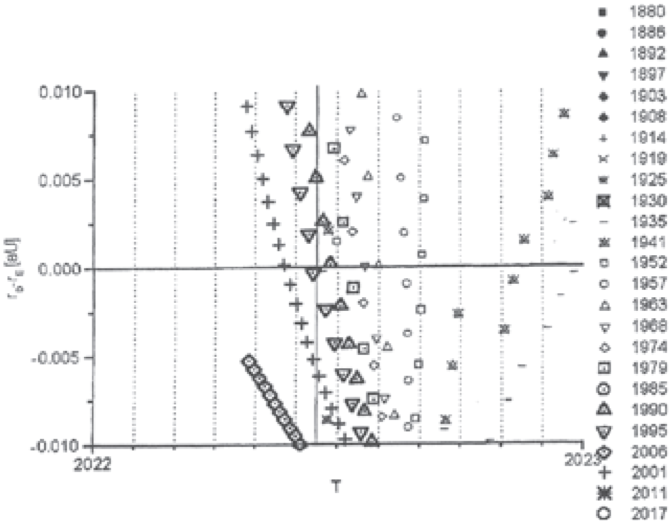

Figure 5 — Diagram from the study by Lüthen et al. 2001, depicting the distance of the particle at the node from the orbit of Earth (rD–rE) as a function of perihelion time T. The particles reaching the node at the same time as Earth are marked with the vertical line. Dust trails of particles ejected forward of parent comet SW 3 that reach perihelion in 2022 are shown. On May 31.21 UTC, Earth will pass the richly populated 1995 dust trail at a distance of only about 0.0004 AU. Image credit: **Rainer Arlt.**

Comet	UTC Date	r(AU)	Δ(AU)
SW 3	2006 May 20.27	0.960	0.184
#2	2006 May 23.60	0.961	0.132
#3	2006 May 26.95	0.961	0.084
#4	2006 May 30.29	0.962	0.053
#5	2006 June 2.69	0.962	0.069
#6	2006 June 5.96	0.963	0.113
#7	2006 June 9.39	0.963	0.164

Table 1 - SW 3's 1995 meteoroid trail proximity to Sun and Earth

In this simulation, the parent comet arrived at perigee *one week after* the actual perigee passage of the main fragment ("C") and two smaller ones ("B" and "E"). This likely can be attributed to non-gravitational forces on the fragments as they approached the Sun. Such a relatively large displacement implies that the comet is either very active or very low mass (in this case, more likely the latter as opposed to the former).

However, these values support the 2005 findings of Wiegert and his colleagues, i.e. in spite of this very close approach of the comet and its fragments to Earth, even a distance of ~0.05 AU was not close enough to produce any noticeable meteor activity.

As for 2022, once again Earth will apparently be spared from any interaction with material shed by the 1995 break-up of SW 3. Using DANCE, it was determined that Earth will arrive at the descending node of SW 3 65.9 days *prior* to the arrival of the comet and its accompanying train of meteoroids (Figure 4). So, it would seem that, as was the case in 2006, there is no possibility of an outburst or enhancement of the Tau Herculid shower, again corroborating the findings of Wiegert et al. using the Vaubaillon model.

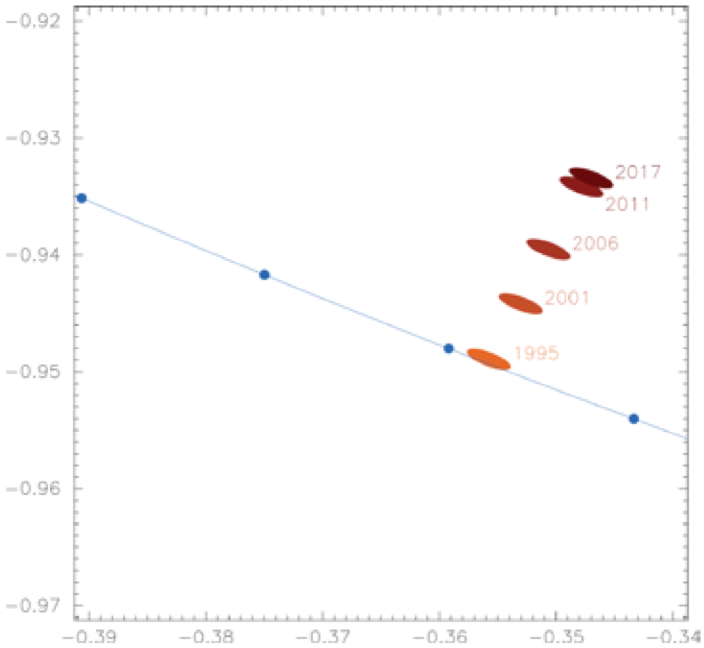

Figure 6 — Diagram, on the same scale as Figure 3, depicting the location of the intersection with the ecliptic plane of the dust trails of 1995, 2001, 2006, 2011 and 2017, as computed in Table 1 of the study by Horii et al. (2008). The continuous line represents the path of the Earth in 2022. On May 31.21 UTC, the dust trail ejected in 1995 is forecast to approach the Earth as closely as 0.00038 au. in excellent agreement with the study by Lüthen. Image credit: David Asher, adapted from a diagram by Mikiya Sato.

4. Another Solution

Our above conclusion would seemingly close the book on the prospects of observing a meteor shower created in the wake of the 1995 breakup of SW 3. Except…there is yet another possibility.

Interestingly, the first investigators to put forward a countering solution were Lüthen et al. 2001, who forecast that: "Probably the best chance to see an SW 3-id display will come in 2022, when we pass the 1995 trail at about only 0.0004 AU distance. It should read "The display is especially promising: the disintegration of P/SW 3 in 1995 should have introduced a lot of dust particles into the trail." (Figure 5).

A later independent study by Horii et al. 2008 [16] buttressed the findings of Lüthen et al. 2001, by indicating that "…the dust trail ejected in 1995 will approach the Earth as closely as 0.00038 AU; in 2022 meteors due to this dust trail is highly expected." (Figure 6)

The obvious question is, what is the cause of this discrepancy? Why does Wiegert et al. and our study show that the fragmented material released by SW 3 in 1995 clearly misses Earth in 2022, while two other studies predict otherwise?

Cometary Ejection

In the case of predictions for most meteor showers, it is assumed that the ejection velocity of material shed from the nucleus of the parent comet would be within the range between –30 and +30 m/s, where "+" is in the direction of the body's motion and "–" in the opposite direction. In the case of Vaubaillon's model, the typical ejection velocity considered for a 1-mm sized particle is +20 m/s (± 20 m/s).

In comparing the breakup of comet 3D/Biela to SW 3, the former presumably split either in 1842 or early 1843, near aphelion. That resultant splitting was slow and subtle and was not detected until nearly the end of 1845 and did not contribute to any noticeable increase in the apparent brightness of that comet. In a 1971 study, Brian G. Marsden and Zdeněk Sekanina determined that Biela split with a relative velocity between the two portions of only one metre (3.28 feet) per second [17].

In contrast, the breakup of SW 3 apparently took place in early October 1995, within just a couple of weeks after perihelion on September 22. Additionally, the breakup was accompanied by a brightness spike of more than six magnitudes, which occurred over just a fortnight in early October 1995, likely due to a sudden and massive expulsion of dust. Horii et al. noted that "…since meteoroids were ejected from the split nuclei of the comet, these meteoroids were likely to have higher ejection velocity than usual." Their study assumed an ejection velocity of –26.71 m/s, meaning that the dust was ejected in the opposite direction of the comet's motion.

But there is yet another important factor to consider.

Size Matters

That other factor is the size of the ejected particles. In the case of most of the annual meteor showers, the majority of visible meteors are caused by particles generally ranging in size from about that of a small pebble (~2 mm) down to a grain of sand (~0.3 mm), and generally weigh less than 1–2 grams.

As is important in understanding the physical break up of a comet nucleus, it is that its constituent particles are expected to vary in size from sub/micron-sized flecks of dust to multi-millimetre grains of sand and even larger pebbles and "rocks." How such large particles are spatially distributed depends in part on the spin of the comet's nucleus and the locations of its outgassing regions. Small particles (≤0.1 mm) are pushed away more rapidly by solar radiation pressure regardless of the direction they leave the nucleus, and this pressure of sunlight helps to force such dust particles to a position trailing behind the comet. Larger particles, however, are greatly unaffected by solar-radiation pressure.

In Horii et al., the effects of solar-radiation pressure *were not considered.* This, combined with negative ejection velocities, suggests that large particles from 1995 would preferentially migrate to a position *forward* of the comet, not behind, while smaller particles would be "blown out" from this part of the meteoroid trail.

Lüthen et al., also did not take solar-radiation pressure into consideration with their calculations. In exploring the prospects of meteor activity from four different meteoroid trails shed by SW 3 dating back to 1908, this study considered trails from 1941, 1952, and 1995, which were, "on orbits which radiation pressure cannot assist particles to achieve (occurring at a negative $\Delta\alpha0$[3])."

The big question of course is, how many large particles can be expected to be ejected with velocities of –26.71 m/s? Typically, not many for most meteoroid trails. Stream modeling predicts the consequences – in terms of observable meteors – for a given distribution of ejection velocities. The implication of the Horii et al. study is that the more particles are ejected at -26.71 m/s (normalized to tangential ejection at perihelion), the greater an outburst will result. Jenniskens [18] discusses ejection speeds and how they scale with meteoroid size. The required -26.71 m/s is a little on the high side, but not excessively so and moreover we can expect some meteoroids to acquire velocities in excess of the nominal value [18] [19] [30]

Put simply, the 1995 trail is rather unique, having been formed in the wake of the major 1995 disruption of SW 3. Based on current knowledge of comet ejection processes, the ejection velocity range from 73P should (just) encompass the required value, for meteoroids of visual meteor size.

Hence the reasons for anticipating a possible meteor outburst in 2022.

Compilation of Earth Passages

In Table 2 we compare the predictions of Lüthen et al. and Horii et al. for the Earth's encounter with the material shed in 1995 by SW 3 in 2022.

	Date of encounter	Time (UT)	***r*E-*r*D** (AU)	Longitude of node	Trail	***V*g** (km/s)
Lüthen	2022 May 31	4:55	0.00040	69.440°	1995	12.10
Horii	2022 May 31	4:59	0.00038	69.448°	1995	12.84

Table 2— A comparison of the predictions of Lüthen et al. and Horii et al. for the Earth's encounter with the material shed in 1995 by SW 3 in 2022.

The two independently predicted times of encounter with the 1995 trail *differ by only four minutes* and the difference in the distance between the orbit of the trail and the Earth's orbit (*r*D–*r*E) is practically negligible, only 0.00002 AU.

The entry velocity (*V*g) of the prospective meteors through the Earth's atmosphere is just over 12 km/s in both studies. To this Horii et al. note that, "…it is a disappointing point that the value of *V*g is lower than general meteor showers." As noted by Lüthen et al., "The geocentric velocity Vg (given in km/s) needs to be increased by about 4 km/s for observing purposes due to the gravity of the Earth."

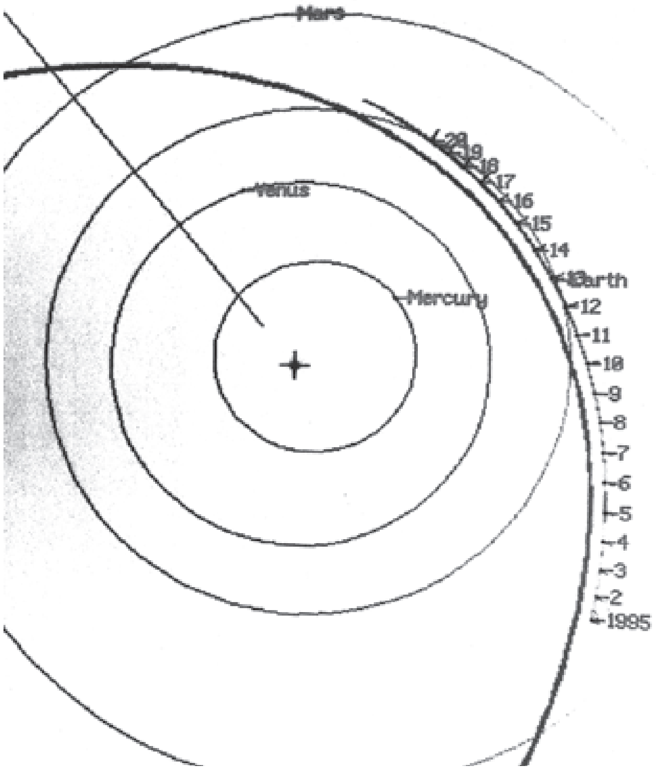

Figure 7 — Positions of Earth, SW 3, and presumed train of meteoroids on 2022 May 31 using "Dance of the Planets" orbital simulator. Assuming meteoroids are moving forward of the parent comet ("1995"), interaction with the Earth takes place between comet samples #12 and #13. A second computation was then made regarding this particular segment of the train to narrow down the time when meteoroids would be closest to Earth's vicinity. Five comet samples were found, falling within a 2.99-day time frame, which encompassed the date and time of maximum ascertained by Lüthen et al. 2001 and Horii et al. 2008. Image credit: Joe Rao

The Leonids are the *swiftest* of all shower meteors, *V*g ~72 km/sec. This is almost the highest theoretical speed for meteors belonging to the Solar System due to their head-on trajectories relative to Earth's orbit. Contrarily, meteors from SW 3 with *V*g ~12.5 km/sec, would be practically the *slowest* of all known shower meteors. This is due to the fact that they are moving in the same general direction as Earth and must overtake the Earth in their orbit in order to be seen.

Last Dance

As previously noted, the Lüthen et al [11] and Horii et al. [16] studies both suggest that in the wake of the 1995 breakup of SW 3, larger meteoric particles were ejected in the direction opposite to the comet's motion. So, while starting out behind the comet, they ultimately may have ended up moving ahead/forward of the comet because they are moving in smaller orbits. In this context, we repeated our original DANCE methodology of creating a meteoroid trail for SW 3 using orbital elements from 1995, but this time, 19 comets were directed along a radius vector *forward* to that of the Sun. Starting with the 1995 perihelion distance of SW 3, each comet was again separated incrementally by *decreasing distances from the Sun* of 0.00053789 AU or 80,000 km (50,000 miles). A Pace of 1000 and a Zoom of 64× were again utilized.

On 2022 May 31, at 05:00 UTC, Earth was positioned between comet samples #12 and #13 (Figure 7).

After the orbital elements were determined for these two cometary proxies, elements for another 18 objects were closely approximated by linear interpolation; these 20 objects would then represent that particular segment of the trail of meteoroids that would come near enough to interact with Earth.

Starting from 2022 May 1, these 20 new objects were set into motion, but this time using a much slower Pace of 100 (in which one minute equates to about 20 months).

In DANCE, when a sample comet approaches very close to a planet—in this case Earth ("E")—its orbit may be significantly modified. In this particular case, five out of the 20 comets underwent some degree of perturbation as shown in Table 3 with comet samples 16 through 20:

Pert. dist.			UTC of min.	Min. dist.
Sample	Earth radii	Date	distance	Earth radii
E-20	261	2022/5/28	06:11	229.3
E-19	260	2022/5/28	23:52	162.1
E-18	260	2022/5/29	17:06	130.1
E-17	260	2022/5/30	11:23	154.9
E-16	260	2022/5/31	05:59	229.3

Table 3 - Earth interaction with 1995 meteoroid trail from SW 3

The second column is the Earth-comet distance in Earth radii when the comet sample began to be perturbed. The fourth column is the UTC of least separation, and the fifth column the corresponding distance, again in Earth radii.

The case of comet sample #16 shows least separation occurring only 62 minutes after the mean of Lüthen et al. and Horii et al., while the nearest of these five approaches to Earth (sample #18) comes just 1.49 days prior. So, it would appear that our DANCE methodology worked quite well in simulating Earth's 2022 interaction with a meteoroid trail composed of large particles shed by the 1995 break-up of SW 3, and is in good agreement with the findings of both Lüthen et al. and Horii et al.

Intensity/Duration "Guesstimates"

It is problematic to try to predict meteor rates for a possible 2022 display of SW 3 meteors, primarily because Earth has never interacted with this particular meteoroid trail before. As noted previously, on 2017 May 30–31, between 23:39 and 00:45 UTC, five shower members from SW 3 were captured by NASA CAMS. Lüthen et al. had forecast possible activity from a dust trail shed by this comet from 1941; the miss distance (rD–rE) was considered somewhat large (0.0011 AU), yet slight activity was still recorded.

Compared to 2017, rD–rE in 2022 is reduced by about one-third to roughly 0.0004 AU. That would suggest, at the very least (from a scalability argument), a potential hourly rate for 2022 of about 14.

However, the impending interaction with the 1995 trail will likely be composed of a far-more dense concentration of debris having been discharged in the wake of the fracturing of SW 3's nucleus compared to the 1941 trail. But just *how much denser*, and what that could ultimately translate to in terms of overall meteor numbers is unknown.

A ten-fold increase would suggest rates of 140 per hour; a strong outburst similar to the annual Geminid or Quadrantid displays, while a one-hundred-fold increase would suggest 1,400 per hour; a full-fledged meteor storm.

It is probably prudent to have conservative expectations and focus on the former, lower rate possibility, although as we are about to see, we certainly cannot discount the latter possibility.

Bielids revisted?

In meteorology, "analogue forecasting," (as the technique is called), operates on the straightforward principle of making predictions by comparing current weather patterns to similar patterns (or analogues) from the past. Some call this type of forecasting pattern recognition. The question now arises: Can we use an "analogue methodology" to forecast a meteor shower?

In 1999, astronomers Robert H. McNaught and David Asher published a paper [20] concerning dust trail density and variations of ZHR for past and future Leonid meteor storms using three statistical parameters, rE-rD, $\Delta\alpha 0$, and fM^4. But the Leonid parent comet (55P/Tempel-Tuttle) is a "Halley-type" comet with a period of 33 years in a highly inclined orbit, so we cannot use this comet for a comparison to SW 3.

However as previously mentioned, there was the splitting of the nucleus of comet 3D/Biela in 1842-43, which was followed by spectacular Bielid (or "Andromedid") meteor storms radiating from Andromeda on 1872 November 27 and again in 1885. And like SW 3, 3D/Biela was a member of Jupiter's comet family, with an orbital period of 6.6 years. Since we don't have any previous data points (trail encounters) with material that was shed by SW 3 in 1995, then the next best thing is to work by analogy with different streams. In this case, Jenniskens & Vaubaillon 2007 [21] determined that the 1872 and 1885 storms were caused primarily by dust released by 3D/Biela in 1846, with only "minor contributions from dust ejected in 1839 and 1852, respectively." Thus, we decided to concentrate solely on the 1846 dust trail.

In Table 4 we compare the dust trail parameters of the resultant 1872 and 1885 Bielid storms with the upcoming situation for SW 3 in 2022.

			$\Delta\alpha 0$	rE–rD		
Year	Comet	Trail	AU	AU	f M	ZHR*
1872	3D	4 revolutions	+0.0222	+0.00119	0.249	7400
1885	3D	6 revolutions	-0.0006	-0.00032	0.285	6400
2022	73P	5 revolutions	-0.0220	+0.00039	0.240	????

** ZHR values for 1872 and 1885 are based on an analysis by P. Jenniskens*

Table 4 – Circumstances of 3d/biela dust trail encounters in 1872 and 1885 compared with the 1995 73p/SW 3 encounter in 2022

At first glance, the comparison of the 19th-century storms produced by 3D/Biela with the upcoming situation in May 2022 for SW 3 appears supportive for a strong outburst; possibly even a storm.

With similar orbits, the conversion factor from meteoroid ejection speeds to $\Delta\alpha 0$ will also tend to be similar. This is relevant since the strength of the outburst depends on the

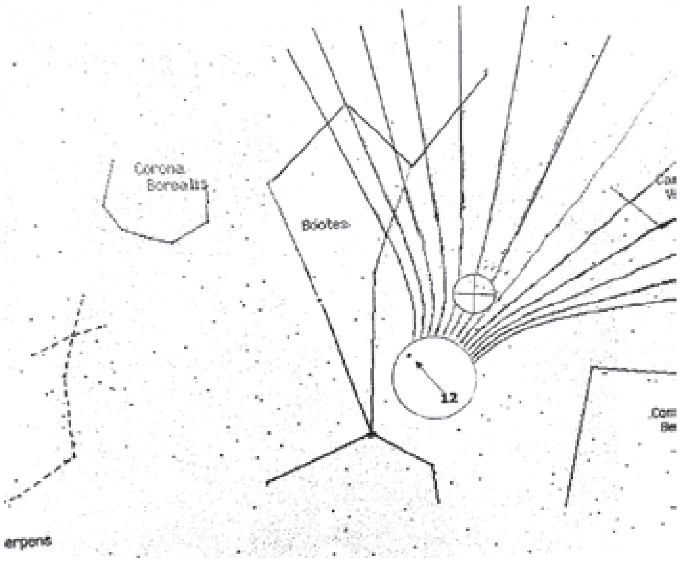

Figure 8 — Position of the radiant (using ***Dance of the Planets****) for a possible meteor outburst near 5h UTC on 2022 May 31 at α=210.17° δ= +25.03°. Rather than a small patch, it appears that the potential radiant in the constellation of Boötes could measure several degrees or more in width. An arrow points to the +4.8-magnitude star 12 Boötis. The smaller circle encompassing a cross, is a positional consensus based on our position combined with that of Lüthen et al. 2001 and Horii et al. 2008. This mean radiant position of α= 208.35° δ=27.45° is near the border of Boötes and Canes Venatici, less than a couple of degrees southeast of the globular cluster Messier 3. Image credit: Joe Rao*

quantity of meteoroids (of a given size, which will correspond to the meteor brightness) at the given $\Delta\alpha0$.

It should be stressed, however, that comet 3D/Biela was brighter (an absolute brightness, pre-splitting, of *H*10 =+7.5 mag. versus +13.2 mag. for SW 3) and its nucleus considerably larger in diameter (~4 to 6 km)[5] than SW 3. These two factors unfortunately work against us, probably meaning fewer meteoroids are generated overall by SW 3. And furthermore, the material shed from 3D/Biela congregated *behind* the comet, as opposed to SW 3, where the material shed in the wake of the 1995 fracture of its nucleus, is assumed to be *in front* of the comet.

So, in spite of the similarity of all three dust trail parameters, such a difference in the orbital geometry for the SW 3 trail is, unfortunately, not exactly comparable with the two trails cited for 3D/Biela. Historically, however, there are certainly many other streams, including the Bielids, where *r*E-*r*D values of a few earth diameters have yielded outbursts or storms. This and the moderately good *f* M provide us with a bit of encouragement.

Sluggish Streaks…Short Duration

Once again, there is also the vexing problem of the very slow entry velocity of these meteors through Earth's atmosphere. A large proportion may end up appearing faint (magnitude +4 or +5) or even perceptible only by using radio or radar techniques (>+6). On the other hand, if many of the associated meteoroids end up much larger than normal, that could offset their slow speeds and make for a somewhat bright display. As a comparison, the Bielid/Andromedid meteors of 1872 were described as primarily "slow, faint and evanescent [23]," but some exceeded 1st magnitude, often appearing "red, with trains of orange sparks [24]."

So far as the duration of any potential outburst, like many other similar cases, it is likely to be short-lived, probably lasting on the order of several hours or less, with a sudden

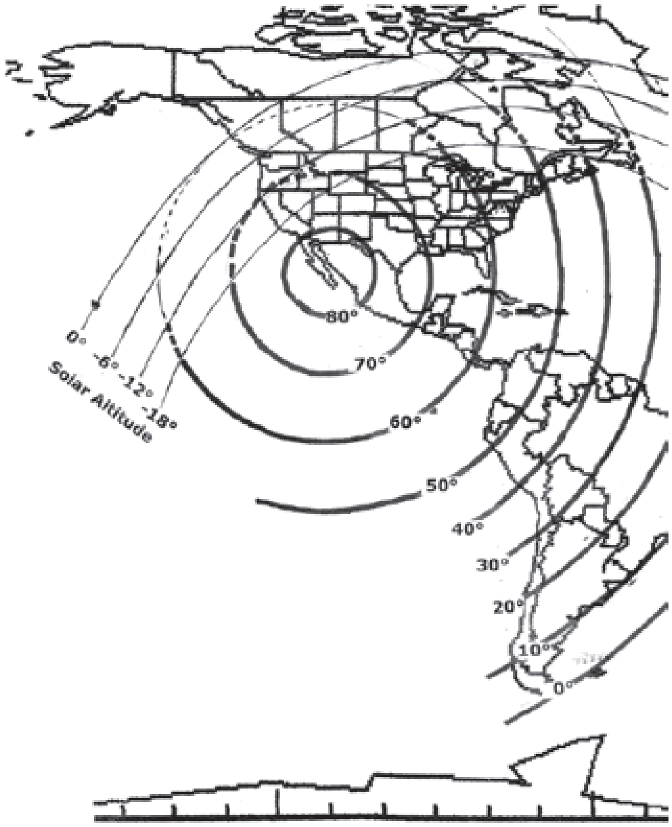

Figure 9 — The map presented here shows the geographic visibility of the potential meteor outburst and is based on the assumption that peak activity will occur close to 5h UTC on 2022 May 31. Zenithally attracted (apparent) radiant elevations are presented as concentric circles at 10° intervals. Also plotted are zones for civil twilight (Sun 0 to 6° below the horizon), nautical twilight (Sun 6 to 12° below the horizon), and astronomical twilight (Sun 12 to 18° below the horizon). Skies should be dark enough in the astronomical twilight zone to see a fair number of stars as well as any bright meteors. From near the Mexican resort town of Loreto, Baja California Sur, the presumed radiant will be at, or very close to the zenith. In contrast, from southernmost Chile and Argentina, as well as a slice of westernmost Africa (not pictured here), the radiant will be less than 10° above the horizon, likely resulting in true Earth grazers—very long-pathed meteors moving parallel to the Earth's surface. Radio and radar observations are possible from any location on the map (save for Antarctica) at the predicted peak time. Image credit: ***Joe Rao***

commencement and an abrupt end. Observers are urged, however, to watch for any forerunners that might be noted a day or two in advance of the main display; and maybe a straggler or two a day or so afterward.

5. Radiant, Area of Visibility, Moonlight

Until now, meteors associated with SW 3 have been referred to as "Tau (τ) Herculids." These are most likely directly related to Shibata's 1930 prediction of a possible meteor shower when the Earth passed close to the comet's node. That forecast was based on possible meteoroids *trailing behind* the parent comet.

However, our forecast for 2022 is based on meteoroids that are travelling *forward or ahead of* SW 3. The end result is a possible radiant positioned not in Hercules, but within the boundaries of the constellation Boötes, about 6° north-northwest of Arcturus and very close to the +4.8-magnitude star 12 Boötis (Figure 8). And, rather than a small patch of sky, it appears that the potential radiant may measure several degrees or more in width. This may be due in part to the "special circumstances" of this interaction, as well as the low geocentric velocity of this meteor shower, as other similar studies have shown [25].

If so, then any prospective display of SW 3 meteors in 2022 will appear to materialize from a relatively large region of the sky.

Table 5 compares our results to those of Lüthen et al. 2001 and Horii et al. 2008.

	α	δ
Lüthen	205.40°	+29.20°
Horii	209.48°	+28.13°
Rao	210.17°	+25.03°

Table 5 – Expected position of radiant (J2000.00)

As for the region of visibility (Figure 9), a large portion of the contiguous United States, south-central and eastern Canada (including the Maritime Provinces), Mexico, Central America, South America, as well as a small slice of West Africa are the regions of the world well positioned for this event. In the U.S., the altitude of the radiant ranges from around 50° in eastern New England to 80° or more in southern California and the Desert Southwest.

Across parts of the Pacific Northwest, northern Rockies, and Great Plains, as well as for a slice of the Canadian Prairies, northern Ontario, central Québec, most of Newfoundland and Labrador, the peak is expected to come during astronomical twilight (Sun 12 to 18° below the horizon), but the sky should still be sufficiently dark for sighting the brighter stars as well as any bright meteors. Unfortunately, for far western and northern North America, as well as for the rest of the globe, the twilight sky will either be too bright, bathed in sunlight, or facing away from any incoming meteors, precluding a view of any possible display.

So far as the situation regarding the Moon, it will arrive at new phase on 30 May (11:30 UTC) and will provide absolutely no interference.

Conclusion

In the aftermath of the breakup of the nucleus of comet P/Schwassmann-Wachmann 3 in 1995, two possibilities exist: Either the resultant material expelled will completely miss the Earth, or we will have a direct interaction with a swarm of large meteoric particles at the end of May in 2022. Our simulations confirm that both prospects are possible. The former case would result in little or nothing being observed. The latter case, might possibly result in a prolific display of very slow, bright, and colourful meteors. However, because of their slow speed, the meteors could also end up appearing very faint or not visible at all to the unaided eye. Unfortunately, this is all something new and without knowledge of the exact orbital parameters and physical circumstances, a precise forecast is well nigh impossible to make.

Such are the difficulties in meteor-shower forecasting: At what mass-loss rate and precisely what velocities is a comet releasing debris? Some ejection directions/speeds will provide very efficient delivery of fragmented meteoritic material to Earth, while others will not.

Comets also are rather erratic in their dust production, jetting (and break-ups of course), that only complicate matters. Additionally, particles of different sizes, morphologies, and compositions also react differently to the effects from the pressure of sunlight. So, as to exactly what might be expected at around 5h UTC on 2022 May 31 is anyone's guess.

With no Moon, at least we are confident that skies will be dark. But will the meteors be bright?

Acknowledgements

Special thanks to Glenn Schneider, Steward Observatory and the Department of Astronomy, The University of Arizona, for his editing of the original manuscript and David J. Asher, Armagh Observatory in Northern Ireland, for providing clear and succinct guidance regarding statistical parameters and ejection velocities. In addition, thanks are also extended to Peter V. Bias, John E. Bortle, Peter G. Brown, Gary W. Kronk, Robert Lunsford, Jérémie Vaubaillon, Junichi Watanabe, and Paul A. Wiegert, all experts in the field of comets and meteors, for help and encouragement.

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The author dedicates this paper to the memories of Sune Engelbrektson, Kenneth L. Franklin, Fred C. Hess, and Thomas D. Nicholson, astronomers at New York's Hayden Planetarium.

Endnotes

1 Nakamura-san's credibility is further strained regarding another meteor shower, one in 1921, the June Boötids ("Pons-Winneckids"). During the interval from June 26 to July 9, and observing under skies that varied from clear to mostly cloudy, Nakamura reported notable meteor outbursts on July 3 (153 meteors in only 35 minutes; an hourly rate of 262) and July 5 (91 meteors in 41 minutes; an hourly rate of 133). Nakamura claimed to have "very sensitive eyes," as his daily estimates of the mean magnitudes of these meteors varied from 4.5 to 5.0. William F. Denning, a highly regarded British meteor observer in his own right, voiced some incredulity about Nakamura's observations, "Unless," he wrote, "Nakamura is able to discern meteors of 6th, 7th and 8th magnitudes." – Denning, W.F., *The Observatory, 45* (March 1922), pg. 83.

2 On 2011 June 1, Pierre Martin, observing from Bootland Farm, Ontario, Canada, reported that he, "…signed on at 11:20 p.m. EDT. I was able to stay on for 37 minutes before the next wave of clouds arrived. During this time, I saw a few sporadics and a single gorgeous Tau Herculid! It was a mag –1 golden-yellow meteor that descended below Lyra in the east, ending near the double star Albireo. It had a thick wake! Checking the plot on this one confirms a perfect alignment with the TAH radiant." Taken from the now-defunct Meteorobs Internet mailing list.

3 $\Delta\alpha 0$ is defined as the initial difference in semi-major axis after ejection from the comet that allows the nodal crossing to occur at exactly the relevant time in late May or early June of the year in question. The "0" refers to ejection time (i.e. "time zero"), the "α" refers to semi-major axis and the Δ refers to the difference from the parent comet. Thus, it's the difference between the meteoroid's semi-major axis and the comet's semi-major axis at the time of ejection. The units are the units of the semi-major axis of an orbit.

4 Defined as the "mean anomaly factor," it is dust density compared to that in the unperturbed one-revolution dust trail. Or put another way, the ratio of the perturbed to the unperturbed dust density of the dust trail measured {averaged} over one revolution.

5 An estimate that we made by comparing other comets with similar absolute brightness. See [22].

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The Biological Basis for the Canadian Guideline for Outdoor Lighting 5. Impact of the Scheduling of Light

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Abstract

Nightfall keeps the circadian rhythm of plants and animals in synchrony with their natural activity and the environment. For humans, the threshold for the blue light of twilight is roughly a few times the brightness of the full Moon and somewhat less for some other species. Altering the night's brightness and its spectrum changes the natural cues for the onset of night that will shift or delay the biological benefits of night by changing or disabling some aspects of the organism's biochemistry.

There have been many diverse studies into the impact of artificial (anthropogenic) light at night (ALAN) on various aspects of wildlife. These highlight the dependence on the extent and brightness of the light and its spectrum. Scheduling or timing the use of light is the fourth attribute that has a profound impact on the biology of the night (Navara and Nelson 2007), but the timing of ALAN need not be exact.

Animals have a natural plasticity in their behaviour and biochemistry that can tolerate some shifts in the natural time of night (Reebs 2002, Wong 2015). This can be used to determine a schedule for outdoor lighting that will reduce its impact on the ecology, yet will accommodate human activity.

Introduction

Predators need illumination to hunt and forage, so some species take advantage of twilight and moonlight to extend the photoperiod. The activity of the prey may also require light, though this varies with species and habitat. Some nocturnal animals (porcupines for example) rely on smell because of their poor vision, but raccoons use both. With these limited examples, light generally benefits the predator.

The leaves of some plants become a liability as winter approaches. The lengthening nights message the need to retract the flow of nutrients and let the leaves dry and fall. Also, an early snowfall shortens the time for foraging animals to prepare for winter. It covers vegetation making foraging difficult for herbivores and will put these species, and those that rely on them, at risk.

To avoid procrastination, we will not wait until the threshold luminances for all, or even most species have been determined. We can assign lighting limits by monitoring activity of species when subjected to, for example, the different phases of the Moon and the range in the severity of seasons. The limits may be revised as new information becomes available, however more than a dozen years of additional research has not significantly changed our qualitative and quantitative understanding of sensitivities to ALAN presented in our first published work on this subject in 2008 (Dick 2008).

Behavioural Plasticity

The first three key attributes to ALAN have been discussed in the three preceding papers (Dick 2020b, Dick 2020c, and Dick 2020d). The fourth attribute, timing of when ALAN may be used that will have minimal ecological impact, is not as precise as we may wish.

Organisms benefit from being able to adapt their behaviour to the state of the environment—daily temperature, rainfall, food availability, the seasons, and the first snowfall, for examples. It can reduce stress from the changes experienced during long migrations, and it can also promote long-term evolution (West-Eberhard 1989) by allowing survival to bridge across an evolving environment.

This biological and behavioural "plasticity" makes precise timing of animal sensitivity to ALAN almost impossible. However, we need not wait for complete knowledge before we start protecting wildlife and humans from the effects of artificial light at night. Not all animals may share the same tolerance, but it is a beginning.

This "plasticity" has its limits. It may only involve a few traits (Bhat 2015), ALAN may be used where plasticity is demonstrated, but not depended on as a panacea for purposefully changing the environment.

Length of Night as a Cue

What duration of ALAN in the evening (and morning) can be used that will not significantly affect the ecology? As complex as this may be, we suggest it can be reduced to relatively simple analyses, especially in the temperate and northern latitudes of Canada where seasonal contrasts make change more apparent.

Snowfall is important to the survival of foraging herbivores (Jones 2000). Even relatively shallow snow packs can significantly affect the food intake of animals, which can force a change of diet (Goodson 1991). The sooner animals begin to prepare for winter the greater their chance of survival, however preparing too early may not significantly improve their prospects, as it may reduce available food that might be gathered in winter and later in spring. Since animals do tend to survive seasonal change—with its range in natural severity—the natural cues to seasonal change seem to be sufficient.

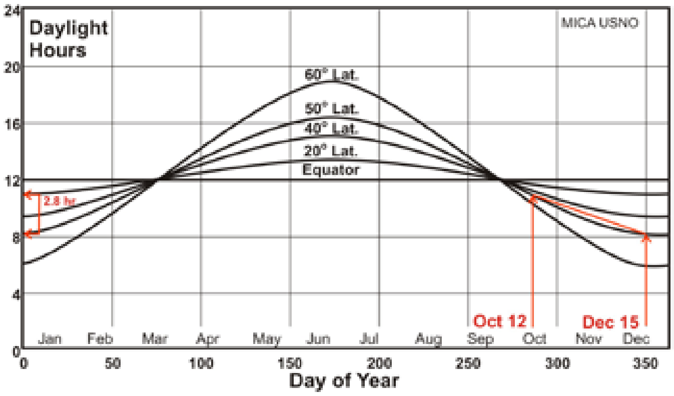

Figure 1 — Annual variation in length of daylight (sunrise to sunset) for latitudes typical of North America. In Ontario, significant snowfall may first occur as early as October or December—and even later. This corresponds to a range in the length of day of about 3 hours - 1.5hr (am) and +1.5hrs (pm). This might vary even more for other regions of the country. (Based on data from MICA-USNO)

Figure 1 shows the length of day throughout the year for temperate latitudes. Based on anecdotal reports from eastern Ontario (about +45 degrees latitude), a permanent snowpack may arrive as early as mid-October, or as late as the end of December. This has a significant impact on wildlifes' preparation for winter. These dates result in a difference in day length of 3-hours. Since the animals have apparently survived this natural variation, it demonstrates an acceptable range in behavioural plasticity to the length of day and corresponding length of night.

After the first snow falls, it suddenly becomes harder for active, foraging animals to dig for and find food. In this respect, survivability is affected by the snowfall, which is not well predicted by the preceding temperatures. In the temperate latitudes there is episodic cooling toward winter—warm periods are followed by cooler ones—and this cycle continues but with declining average temperatures (see Figure 2). Therefore, a more reliable indicator for animal survival, in the long term, is the length of daylight, or night.

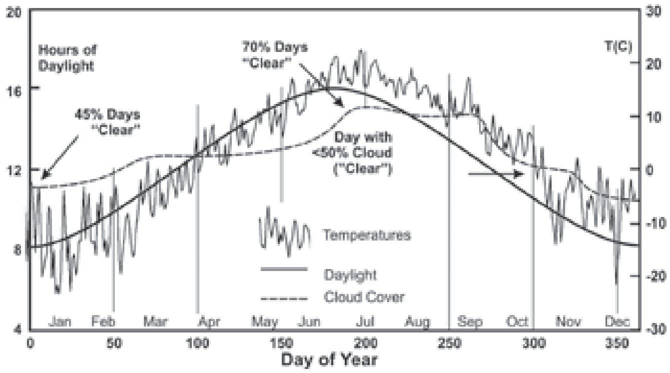

Figure 2 — Daylight, clouds, and average temperatures. The hours of daylight for Ottawa (2019) are from MICA-USNO. Cloud cover is from A. Danko, Ottawa Clear Sky Chart (SE direction between 2006 and 2020) based on average sky cloudiness with a sky <50% cloud). And, the temperatures are from www.wunderground.com/history/monthly/ca/ottawa/CYOW. Only long-term trends (monthly) are good indicators for seasonal change. Daily and weekly temperature trends are too variable from week-to-week and year-to-year to be used as reliable indicators.

Figure 2 focuses on the City of Ottawa and plots the length of daylight, average temperatures, and percentage of clear skies with the maximum range from 0 (cloudy) to 100% clear. These plots demonstrate there are several contributing factors to daytime heating and resulting challenges for animal survival.

This length of daylight has a direct effect on the accumulated solar heating, which is a function of the time the Sun is above the horizon, the angle the sunlight hits the ground,and the clarity of the atmosphere—all of which are not constant. Cloud cover and forest canopies will reduce the daytime solar heating and illumination level but will increase night temperatures in winter by reducing heat loss through radiation to the night sky.

After sunset the ambient illumination on a clear evening is halved about every 5 minutes—extending the apparent daylight by perhaps 30–35 minutes. However, the dimming effect of clouds reduces illumination from about 130,000 lux down to about 10,000 lux (about a 90% reduction). It is interesting to observe that the length of day (length of night) indicator shifts the autumn cue by about a month ahead of the typical temperature indicators, providing animals with extra time for preparation.

These variables complicate the light cues (brightness and spectra) that are used by wildlife. However, awareness of the shortening daylight is delayed by ALAN by extending daylight, and twilight ALAN —several hours might impact the animal's perception of seasonal change by up to an additional month.

These natural variations have been combined to define an approximate 2-hour dawn and 2-hour dusk tolerance or plasticity for ALAN.

Affect on Wildlife

The growth patterns of some plants, such as some cash crops, are not so closely tied to the actual length of day (Thomas and Vince-Prue 1997). Changes in the nocturnal lighting may help or hinder their growth depending on the species. Taking an urban landscape as an example, urban plants tend to be Long Day or Day Neutral plants, allowing them to tolerate the light-polluted urban environment. So the mix of urban species differs considerably from the mix of rural plants.

The departure times for migrating birds vary from year to year depending on not just the length of day but also the temperature and availability of food. Once on their journey, winds aloft will affect their progress and arrival times at their destina-

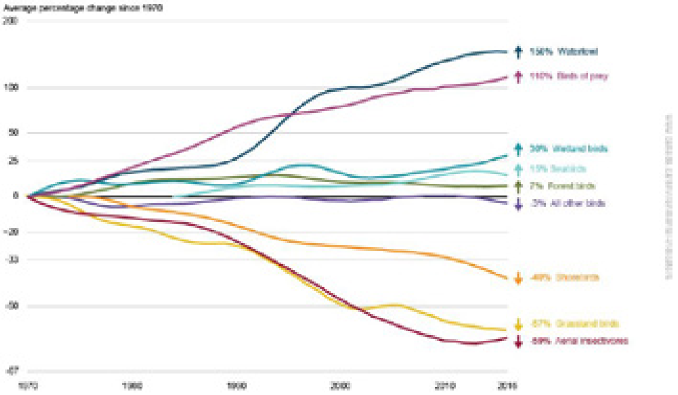

Figure 3 — Changes in bird populations over about 50 years. Not all these birds are migratory. Waterfowl and birds of prey are doing quite well at this time with the greatest declines in grassland birds and insectivores. (Canada A 2020)

tion. Given the long-term survival of the species, there appear to be some tolerance to their departure date and arrival time. Fortunately with these different cues, a cue that is at odds with the others will not rule the "fate of the fowl."

The ALAN in urban areas creates skyglow that extends over the countryside and combines with the increasing use of ALAN in rural areas. So the extended length of an urban day will have an additive effect on the local rural ALAN to delay migrations and other preparations for winter.

There is evidence for declines in some avian populations, and these patterns have been attributed to their sensitivity to urban development, and by extension ALAN. The success or failure seems due to the habitat of the species. In the migratory groups, the grassland and insectivores show the greatest decline (Figure 3 – Canada A and Figure 4 – Canada B). Factors other than the length of day or night probably affect the survival of birds but without a full understanding of this problem, for simplicity, we use a one-parameter calculation for animal plasticity (length of night) but this should be used as a "guide," not as a "rule."

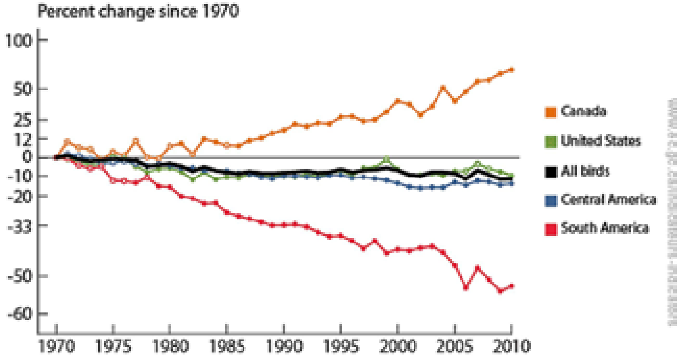

Figure 4 — Change in species by country over 40 years. The general increase in Canadian species may be due to the population concentration in relatively few urban areas. (Canada B 2020)

Human Schedule

When you go to bed and how long you sleep varies between individuals and their daily schedules, but there seem to be limits. These conclusions are based on chronobiology of many bodily functions and our circadian rhythm (Koukkari, Sothern 2006). As hunter-gatherers, our ancestors' activity was based on sunrise and sunset, and their "workday" was constrained by sunlight and did not differ very much from the animals they hunted.

In our modern society, the pattern of rural and urban activities is driven by two different priorities depending on whether the labour is outdoors (sunlight during the day and artificial light at night) or indoors (artificial light).

Urban activity is controlled only by "office hours" and is now virtually independent of the Sun. The workday is a cultural construct, which has become entrenched in our society. However, rural farm life bridges two worlds: urban and rural. It is still linked to the diurnal cycle of the Sun for planting, harvesting, and the tending of animals from before sunrise and after sunset due to their circadian rhythms.

There are relatively few people engaged in farming, but farms are expansive, and the flat, treeless fields allow light to shine for several kilometres—indeed it is limited only by the clarity of the air and the curvature of the Earth. Thus rural lighting can have wider impact on the ecology than urban lighting that is concentrated into smaller regions and is mostly shielded by tall buildings.

Urban lighting is also used by businesses to attract customers and advertise their services even after most offices are closed. This policy extends urban lighting well beyond the biological limits of the human species. It serves only motorists and pedestrians who are out to visit businesses well into the night. Regardless of the promoted popularity of late-night shopping, Figure 5 paints a different story. It is more reasonable to use the distribution of vehicle traffic density as a proxy for the need of ALAN.

The traffic records show a clear pattern of vehicle activity. Figure 5 shows the bimodal shape of the traffic density, reflecting the morning and evening rush hours. London, UK was selected for this figure because its latitude and sunset times are more similar to most of Canada than Toronto, Ontario, which shows similar patterns, as does New York, NY.

The after-hour traffic is about 1/4 that of the peak periods. Further analysis of this figure shows that for most of the year rush hour is in daylight. Anecdotal reports from residential areas indicate much less vehicle traffic and very few people walking about after 22:00. People consider this to be the end of their day and are more sedentary. Therefore even human activity abides by the 2-hour after–sunset guideline – but with an amendment.

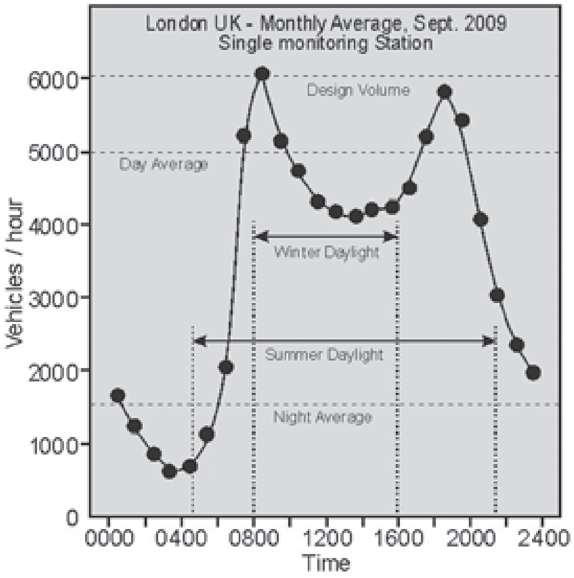

Figure 5 — Traffic pattern for a major city. Vehicle traffic shows a similar pattern in most cities. Two "rush hours" are separated by a relatively low congestion period. Before 06:00 and after 22:00, the traffic density wanes to below 1/4 peak levels. Rush hours in the northern temperate latitudes are in daylight. Therefore, ignoring car headlights, streetlights are only needed at full intensity from late autumn to early spring. (UK Gov. 2012)

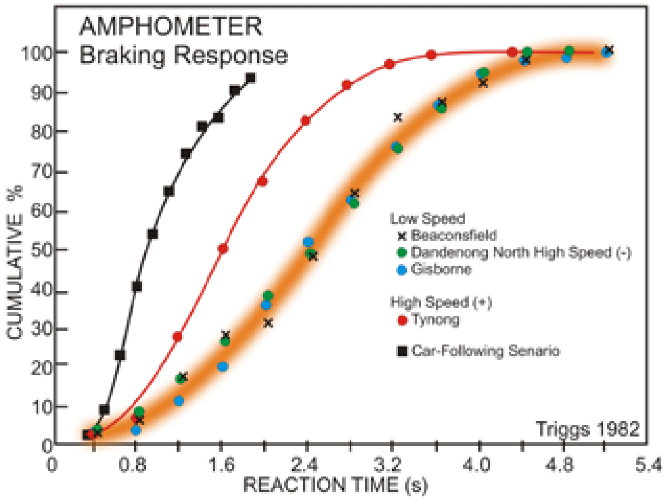

Figure 6 — Reaction times at low and high driving speeds. Arguments for increasing ALAN include the reduction of reaction times. However studies show that at low (urban) and highway speeds, reaction times are typically 2.5 seconds. It is interesting to observe that this study shows drivers travelling at much greater than the highway speed limit react faster than those going the legal speed. The study suggests this is because the drivers are being more alert. This seems supported by the "car-following scenario" that has much shorter reaction times. (Triggs 1982)

Instead of nature's sunrise and sunset, human activity is based on the workday, which is typically 8 a.m. to 6 p.m. So the 2-hour after-sunset guideline could be applied to these limits regardless of the Sun-time. The only time when there is a significant departure from the natural guideline will be in winter when nature's activity is low and the workday extends through twilight.

Light to Reduce Reaction Times

Road illumination levels are based on aesthetics through colour rendering and to improve safety by shortening the reaction time of motorists. Reaction times lengthen as illumination decreases, so busy areas require brighter levels of lighting. However, the connection between light and safety is not necessarily this clear cut (Triggs 1982).

It is generally understood that our blue- and green-sensitive scotopic vision results in slower reaction times—roughly 0.6 seconds. Our green-red-sensitive photopic vision provides shorter reaction times that extend to about 0.2 seconds. The difference is significant, so typical roadway lighting is designed for our photopic range (>5 lux).

However, Figure 6 indicates that driver attention, or distraction, has a greater impact on our reaction times than the difference between our scotopic and photopic vision. In most emergency situations when fast reactions are needed, drivers are generally distracted by the "art of driving" and roadside signage. Therefore traffic and roadway design should be based on addressing the "less-attentive situation," which delays reaction times to longer than 1 second. This renders as "academic" the need for lighting to be based on our photopic vision. It is more critical to reduce the illumination of distracting features (non-driving related signs and lighting) than to increase illumination levels that will increase the visibility of distractions.

Other Constraints on Duration of ALAN

The foregoing evidence covers the direct effects of ALAN through the night. However there are other, more indirect effects that stem from data not strictly related to light pollution. Because of the unusual nature of these studies, there has been little follow-up work. The following example is presented to show that we need to think "outside-the-box" when faced with new, and old, problems.

The Sun illuminates and heats the ground and oceans. Beyond this most obvious effect it was not clearly demonstrated until 1859 that the Sun affected the Earth's magnetosphere ("Carrington Event," Wikipedia). In the 20th century, light pollution was considered to be too tenuous to create more than a visual display at night. Yet in the 21st century, light pollution was found to profoundly affect the environment and undermine its ecological integrity.

Continues on page 78

Pen & Pixel

Figure 1 — Cygnus is a rich region home to the North America Nebula and the Pelican Nebula. Godfrey Booth took a wide-field image of the region using a ZWO 1600 mono cooled camera (Ha, OIII and SII), on a CGEM mount using a Rokinon 135mm ƒ/2 digital camera for a total of three hours. He processed it in the Hubble Palette with PixInsight and Photoshop.

Figure 2 — Accomplished astrophotographer Ron Brecher recently revisited the data he collected of the impressive globular cluster M22 in 2016, putting to use the skills he honed in the four years since. The original data was acquired in August 2016 from his SkyShed in Guelph, Ontario. Ron used an SBIG STL-11000M camera, Baader R, G and B filters, 10" ƒ/6.8 ASA astrograph on a Paramount MX. Ron guided with a QHY5 camera and 80 mm ƒ/6 Stellar-Vue refractor. All preprocessing and post-processing was done in PixInsight. 8 × 5 minutes R; 10 × 5 minutes G; 10 × 5 minutes B for a total or 2 hours and 20 minutes.

Figure 3 — Orion is a treasure trove of targets and amazing nebulosity and Klaus Brasch managed to capture some of that in an amazing mosaic of the region. In it is NGC 2024 (the Flame Nebula) near the belt star Alnitak, and the the dark Horsehead Nebula and, of course, M42 (the Orion Nebula). This image is a mosaic of several exposures taken with a TMB-92 ƒ/5.5 apochromatic refractor, coupled with an IDAS LPS-V4 filter and a modified Canon 6D Mark II, shooting at ISO 3200-6400. Total exposure time was about 30 minutes with the final image processed in Photoshop CS6.

Figure 4 — It might be hard to believe, but this incredible image of the Orion Nebula was taken from the light-polluted skies of Toronto, Bortle 8 to 9. Adrian Aberdeen used a ZWO ASI071 one-shot colour camera with a ZWO L-enhance dual band filter, and a Skywatcher Esprit 80MM telescope on a Celestron CGEM mount from his balcony. He processed it using PixInsight and Photoshop.

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Into the second decade of this century, ALAN has now been implicated in exacerbating the long-standing problem of air pollution (Stark 2010). The loss of solar radiation after sunset allows molecules to form that help destroy air pollution during the night. However the spectra of ALAN carries sufficient energy to reduce the formation of these cleansing molecules, allowing air pollution to accumulate day-after-day. This suggests that dimming or turning off ALAN in the late evening when it is less important will help improve the urban environment in ways we did not expect until a decade ago.

Summary

We have the responsibility to take measures that minimize the impact of ALAN by "critically" assessing when it is used. We must not apply more weight to our "want" of light than to the evidence for its ecological impact.

Similar to the Hippocratic Oath, "primum non nocere" (Wikipedia) (first, do no harm), the onus should not be to prove there would be harm, but to ensure harm shall not be done—to the best of our current knowledge. City and lighting officials are not doctors but we believe the ethical message is applicable—especially in the profession of engineering. With the preceding and referenced research and the publishing of these papers, it cannot be said, "no one could have known." In addition, our society is increasingly respectful of the well-being of non-human species, so it is fitting that this ethic apply to our treatment of nature.

Wildlife does not require ALAN. Therefore only light used for human activity should be used. We can now estimate when peak illumination is necessary and minimize its use at all other times when there is low human activity.

Developing a schedule for lighting must include a number of factors: natural biology and behaviour, and the human need for ALAN. In this paper we have taken into account behavioural plasticity, records of several environmental factors and animal survival during extreme weather, and contemporary records of human activity at night.

The timing and flexibility of animal behaviour has been found to closely match critically assessed human activity. We have found that by limiting ALAN to 2 hours before sunrise and 2 hours after sunset, or before and after the workday, it will satisfy most human activity with reduced ecological impact. In winter and early spring, people will still require ALAN into the evening, but the activity of wildlife is also low during this time of year.

Scheduling of ALAN is important but it must be coupled with the other three attributes: brightness (luminance and illuminance), extent (shielding), and colour (spectrum).

The last paper in this series combines these four attributes of light for populated suburbs, semi-rural, and rural areas, which cover most inhabited and recreational areas. It balances them into a practical specification for outdoor lighting, which will have low-ecological impact, and that will provide sufficient light at night for most human activity.

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Skyward

A Great Conjunction, the Christmas Star and Orion

by David Levy, Kingston & Montréal Centres

> *Said the night wind to the little lamb:*
> *"Do you see what I see?*
> *Way up in the sky, little lamb*
> *Do you see what I see?*
> *A star, a star, dancing in the night*
> *With a tail as big as a kite*
> *With a tail as big as a kite."*

– Noel Regney and Gloria Shayne, 1962

In the words of this beautiful Christmas carol, written during the Cuban missile crisis of 1962, we are reminded of Christmas, the biblical Book of Matthew, and the Star of Bethlehem. Famous as it is, this story appears but once in the Gospel according to Matthew:

Now when Jesus was born in Bethlehem of Judea in the days of Herod the king, behold, wise men from the East came to Jerusalem, saying, "Where is he who has been born king of the Jews? For we have seen his star in the East and have come to worship him."

When they had heard the king, they went their way; and lo, the star which they had seen in the East went before them, till it came to rest over the place where the child was.

When they saw the star, they rejoiced exceedingly with great joy; and going into the house they saw the child with Mary his mother, and they fell down and worshiped him. Then, opening their treasures, they offered him gifts, gold and frankincense and myrrh.

For more than 2,000 years, people have tried to attach some astronomical meaning to the star. From books and planetarium shows, I have gathered several possible interpretations:

1. The star was Halley's comet. Unlikely, because Halley's comet returned in October of the year 11 BCE.
2. An exploding star; a nova or a supernova. Although we have no evidence of such an event in those years, there could have been one.
3. A planetary conjunction. The Moon did pass close to Venus in the eastern sky (the location in the east appears twice in the biblical account). My personal favourite is a conjunction between Jupiter and Venus, on 2 June 17 BCE. However, this conjunction happened after the death of King Herod in 4 BCE, and it would have led the Magi in the wrong direction.

However, there was a Great Conjunction in 6 BCE. (Great conjunctions involve only Jupiter and Saturn and take place roughly every 20 years.) A subset of this series involved the Moon passing close to Jupiter on 6 April 17 BCE. True to the biblical account, Jupiter was in the east over Israel at this time, and King Herod was still living.

Figure 1 — This photograph of the conjunction was taken by Dr. Tim Hunter on 2020 December 21.

One thing I like about the planetary conjunction theory is that astrologers in those ancient days, more than the general population, paid attention to these events. One possible translation of "wise men" is "astrologers," people versed in how the stars and planets influence humanity.

They would have paid attention to planetary conjunctions more than the general population.

4. It could have been a miracle. In my own life, I consider every night out under the stars as a miracle, so why not?

Whatever the Christmas star was, we got to see it again as a "Great Conjunction" on Monday, December 21. It is the closest that Jupiter and Saturn have been close to each other since 1623, that long-ago year that also saw the first publication of the first folio of Shakespeare's plays. On that day in 1623, the conjunction took place in daylight, so no one would have paid attention to it. But the one in 2020 was visible in the early evening! Therefore, millions of people were definitely paying attention to it, and it reminds us of the Star of Bethlehem. Whatever it was, we shall never know. But for those of us who were able to gaze in wonder at this fabulous event, it acted to increase the nightly miracle of the magnificent sky.

Even in our postmodern age, the chance close alignment of the Solar System's two biggest planets is not a big scientific event. However, it is a big astrological happening. While no true scientist follows astrology these days, 2,000 years ago the night sky was all about astrology. And were it not for ancient astrology, we would not enjoy today's comprehension of the night sky. Even in 1623, the last time Jupiter and Saturn were this close, most people were more interested in astrology. I quote from Shakespeare, who did not follow judicial principles in astrology. The two opening lines of Sonnet 14 state clearly that:

Not from the stars do I my judgment pluck,

And yet methinks I have astronomy…

I believe that Shakespeare used astrology a lot in his plays because he knew his audience followed it. Now, after December's Great Conjunction, we have that rare opportunity to reflect on an astrological event, the joining together of two planets, a simple event that helps us to go outside, look toward the southwest, and revel in the beauty of the night sky.

Figure 2 — Orion and vicinity as shown from Castor House, one of the smaller buildings at Jarnac Observatory. A bright Geminid meteor is in the picture.

Orion in Winter

As twilight deepens these evenings, Orion is just clearing the eastern horizon. Robert Frost wrote eloquently in his famous poem "The Star Splitter":

You know Orion always comes up sideways,

Throwing a leg up over our fence of mountains.

Whenever I see Orion rising—which is almost every night from fall to midwinter—I am reminded of how poets like Robert Frost saw the mighty hunter as it entered the sky to take command of winter. Even if you have difficulty finding some constellations, the three stars in a row that form Orion's belt are a giveaway. And if you have a telescope, as Frost did, the view is even better. Just below the belt lies a fainter set of three stars. Surrounding the middle one is a gigantic cloud of hydrogen gas, which is the Great Nebula in Orion. It is one of the richest star-forming regions in our whole galaxy.

During that first winter I enjoyed watching lots of the fainter stars within the nebula change their brightness over time scales of days, hours, or in one case, minutes. According to Janet Mattei, the late director of the American Association of Variable Star Observers (AAVSO), these variable stars can "flicker" as they go through their carefree cycles of stellar youth.

Near the top of Orion, marking his left shoulder, is a much older, grandfather star. Named Betelgeuse, this star is at the other end of the stellar life cycle. An old, very large and massive star, Betelgeuse varies lazily from being almost as bright as Rigel, the star marking Orion's lower right knee, to not much brighter than Bellatrix, the star marking Orion's right shoulder.

Last winter Betelgeuse faded more than usual, and throughout 2020 some people believed that it was about to explode as a supernova. Probably not now, though it will likely happen within the next hundred thousand years or so. In the spring, Betelgeuse began to brighten again, but when I saw it rising above the eastern horizon in late August, it had faded once more. Around that same time, the *Hubble Space Telescope*, observing in ultraviolet light, provided data that suggested that the unusual dimming was caused by an ejection of some very high-temperature gas from within the star into space.

When Betelgeuse is finally done being the star we love, its core will collapse almost instantaneously, within a few seconds. Betelgeuse will increase exponentially in brightness. It will shine as brightly as the first-quarter Moon and will be easily visible in daylight for three months or more. It will be brighter than Tycho's great exploding star of 1572, and brighter even than the brilliant supernova of 1006. As large as it is, Betelgeuse is probably not massive enough that its core will shrink to a black hole. Instead, it will probably form a new neutron star, small, dark, very dense, and cold.

Stars are like people. They age just as we do. They enjoy the carefree times of youth, go through a long middle age like our Sun is doing, and then get strange again as they grow old. Please go out and enjoy Orion rising over the eastern horizon these evenings. It is time to settle back and enjoy this magnificent king of the winter sky. As you look, imagine how young stars like those in the nebula, and old ones like Betelgeuse, tell their beautiful story of the life cycle of distant suns. ✶

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.*

Binary Universe

The New Double Stars Program

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

In the fall of 2020, the RASC national Observing Committee launched the *Double Stars Program* for RASC members. This "beyond the basics" observing program follows nicely after *Explore the Universe*.

At a minimum, one needs a small telescope on a steady tripod, with ideally a couple of different eyepieces yielding different magnifications. A zoom eyepiece can reduce swapping oculars. Observers with large instruments will see additional companion stars. We assume the observer is comfortable finding celestial targets. The program permits star hopping or using a go-to telescope mount.

Filling a Gap

The new program will nurture interest in and encourage double-star observing, plus present an array of interesting targets. When the member's detailed log notes are approved, the effort will be recognized with a certificate of completion.

The *Double Stars Program* joins our family of interesting and unique observing programs, filling a gap. Now members can discover, explore, and learn about double stars.

As with our other programs, it will reinforce good observing practices and techniques, and provide another opportunity for active observing.

The *Observer's Handbook* reminds us that 85% of stars under magnification appear as doubles and multi-star systems, so there are many to enjoy.

Perhaps they represent something new and interesting to try. An awareness in doubles can enhance visual observing, offering more targets in nightly campaigns—viable targets in less-than-ideal conditions.

An ongoing interest in doubles may encourage astronomers to photograph them. Serious observers may wish to measure doubles and contribute to our body of knowledge, not unlike how citizen scientists contribute to variable-star research.

Double-star discoveries went through a "golden age" in the 1800s with significant work done by the Struve family, William Herschel, and Sherburne W. Burnham. A database called the Washington Double Star (WDS) Catalog, which was constructed by the U.S. Naval Observatory, currently stores over 153,000 pairs and is growing steadily.

Figure 1 — Perhaps the most famous of all double stars, Albireo, showing differences in colour and brightness.

What's the Big Deal?

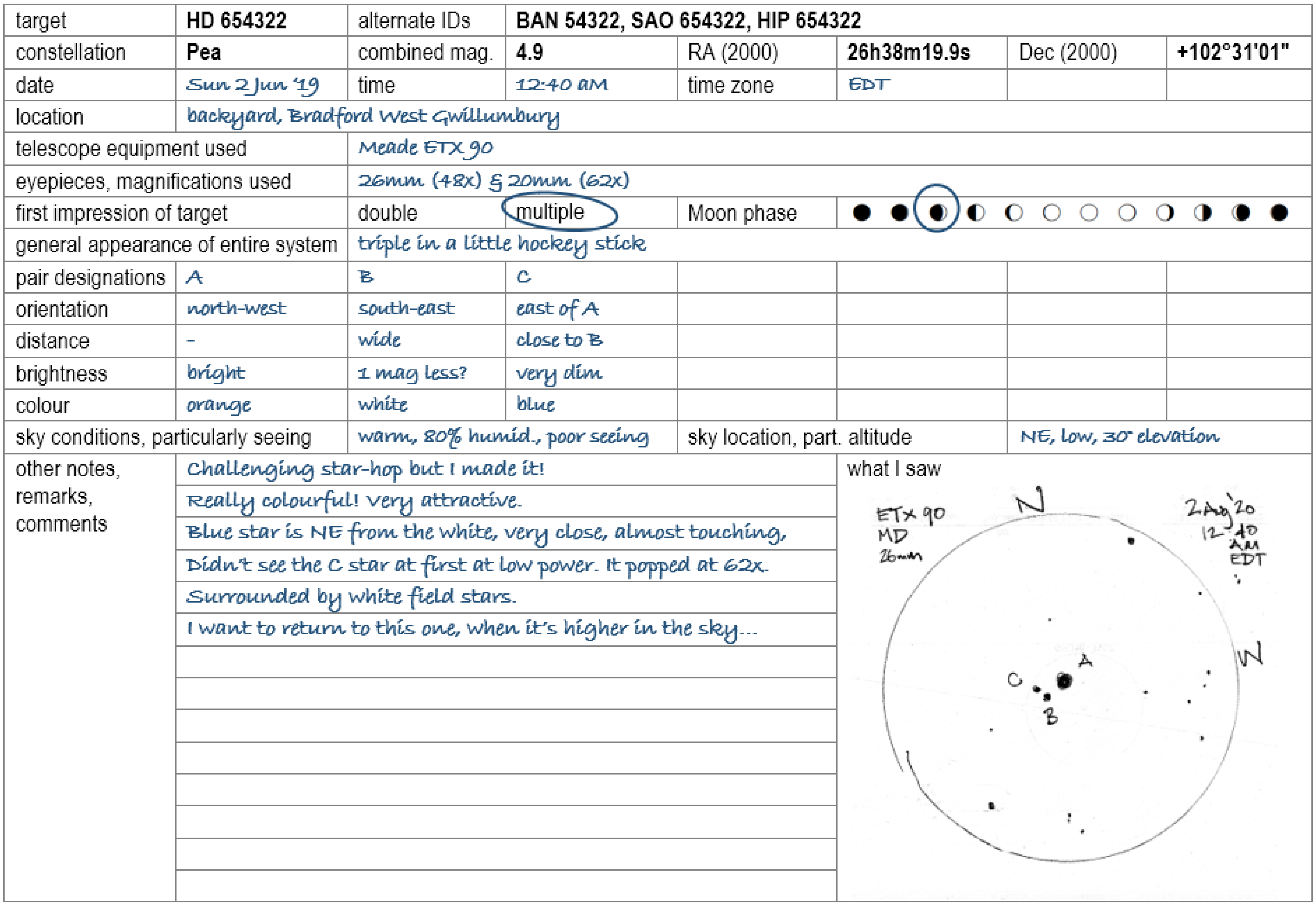
Double stars are like gemstones. Many people have seen Albireo (see Figure 1) or beta Cygni, startling yellow and blue stars at the head of the celestial Swan. The colourful components allude to spectral class and surface temperature. Double stars show true colour. The observer might immediately see blue, white, yellow, orange, and red stars.

Splitting pairs is easy and fun, yet it can sometimes be challenging. Some targets demand repeat viewing, perhaps months or years later to coax out a faint neighbour, a moving element, or, during excellent seeing, a close-in dance partner.

Doubles can be widely separated or tight, equal or unequal in brightness. Two, three, four, or more stars huddled together! They come in infinite patterns and arrangements, like hockey sticks, triangles, rhombuses, and flying Vs. Good examples include epsilon Lyrae (the Double Double) and Sulafat.

They can also be dynamic! A binary system, with one star orbiting another, may change over a few years. The two points of light may appear at different distances (angular separation) and position angles from each other. The companion in 70 Ophiuchi has a period of 88 years.

Everyone finds doubles impressive. To the public, they are eye candy with colourful pairs exhibiting the "wow" factor. They consistently prove excellent subjects at star parties evoking endless questions.



target	HD 654322	alternate IDs	BAN 54322, SAO 654322, HIP 654322				
constellation	Pea	combined mag.	4.9	RA (2000)	26h38m19.9s	Dec (2000)	+102°31'01"
date	Sun 2 Jun '19	time	12:40 AM	time zone	EDT		
location	backyard, Bradford West Gwillumbury						
telescope equipment used		Meade ETX 90					
eyepieces, magnifications used		26mm (48x) & 20mm (62x)					
first impression of target		double	[✓ multiple]	Moon phase	● ● [✓ ◐] ◐ ◌ ○ ○ ○ ◑ ◑ ◑ ●		
general appearance of entire system		triple in a little hockey stick					
pair designations	A	B	C				
orientation	north-west	south-east	east of A				
distance	-	wide	close to B				
brightness	bright	1 mag less?	very dim				
colour	orange	white	blue				
sky conditions, particularly seeing		warm, 80% humid., poor seeing		sky location, part. altitude		NE, low, 30° elevation	
other notes, remarks, comments	Challenging star-hop but I made it! Really colourful! Very attractive. Blue star is NE from the white, very close, almost touching, Didn't see the C star at first at low power. It popped at 62x. Surrounded by white field stars. I want to return to this one, when it's higher in the sky...				what I saw		

Figure 2 — Sample log sheet completed for a "double star," actually a colourful three-star system. The sketch clearly shows the view in a small telescope at 48× magnification.

As astronomical targets, double stars are interesting visually and important scientifically.

Achievable Targets

Double stars can punch through bright skies so one can observe them anytime! If the Moon is out, the observer can still star hop, and see many doubles. Poor transparency will not immediately affect doubles, although faint companions may disappear. Tight twins demand good seeing conditions.

Because many doubles can be observed in bright or light-polluted skies, one does not need to drive for hours to pristine dark conditions. We can observe anywhere! The backyard, driveway, inside city limits, the local park.

We can include doubles in "what's up" presentations for relatively easy and satisfying targets.

Program Particulars

The program targets span many constellations, which requires observing through a couple of seasons to a full year. They are visible in the Northern Hemisphere near a latitude of 45 degrees.

There are 110 targets in the *Double Stars Program*, and all must be observed and logged for certification.

Some of the target "doubles" are in fact triples or multi-star systems. An observation of the main or primary and second star is all that is required. Optionally, one can log additional elements.

An observation (Figure 2) is considered complete on viewing the target's two stars. The observation should note the overall system and the two main stars, their colour and brightness. One can use a simple notation for separation (e.g. "close" or "wide") and angle ("northwest" or "at 3 o'clock position").

We encourage sketching double stars, but complementary drawings are optional. Sketching a double is easy: make a large dot for the primary star and a small dot for the second star and provide annotations. Add some nearby field stars and note directions.

Occasionally, a target may not be obvious so double-check the location first. In some parts of the Milky Way, one might see several intriguing pairs of stars. "Which one is which?" Note them all and try sketching to review later. Also, poor conditions may limit what we can see. Like in other observing programs, factors may conspire against completing an observation. Simply return later.

Typical double-star lists show separation, position angle, colours, and magnitudes. The RASC program departs from this convention! To help observers view targets without preconceptions, we offer a target list with only coordinates and combined brightness. This allows the member to "discover" the nature of the double on their own without any bias.

The doubles do not require formal measurement, but an astrometric eyepiece may be used.

Interested?

Visit the *Double Stars* page on the RASC website and review the general information and file list.

https://rasc.ca/double-stars

Download the *Program Guide*. This 12-page document includes examples of observing notes with sketches, examples of what one might see, and how to best make log notes of doubles.

In a hurry? We offer a 4-page *Quick Start Guide*.

The "main" observing list shows all double-star targets with combined magnitude and location information only.

The detailed "supplemental" list includes magnitude for each star, the separation from the primary, the position angle, the WDS discoverer code, and verbose observational notes. Additional companion stars are noted. This is for the observer needing assistance or wanting to know the particulars of each target in advance.

We encourage the use of the main list (Figure 3), with minimal information, to experience doubles as the early discoverers did.

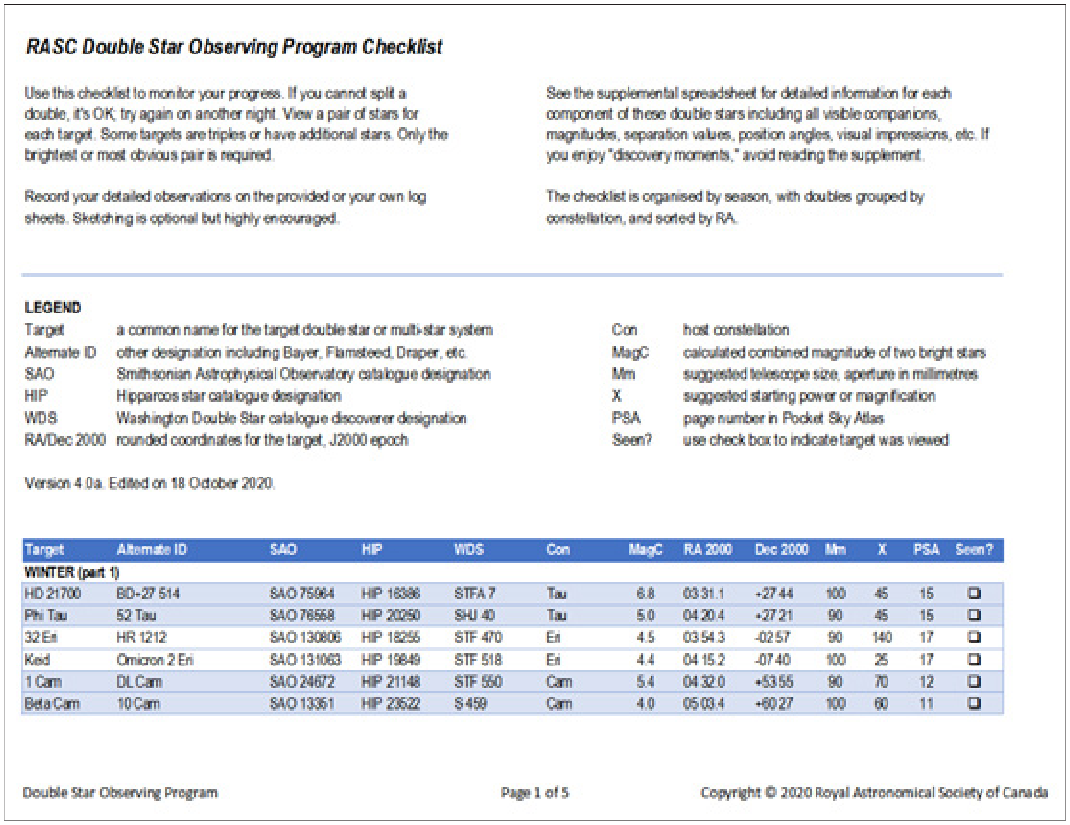
The target lists are available in electronic software formats for *SkyTools*, *SkySafari*, and *Excel*.

Members may wish to use paper charts and atlases such as the *Pocket Sky Atlas* or *SkyAtlas 2000.0*. If pursuing the go-to telescope version of the certificate, software can aid in the identification of double-star companions.

We provide a 112-page logbook with pre-filled target names and location details. Alternatively, one can also download a blank log page and duplicate it. The observer may use their own logbooks but should review the form to understand what data is to be collected.

Bruce MacAvoy, author of the *Cambridge Double Star Atlas*, says "Observing double stars is one of the great pleasures of visual astronomy."

From its first program created in 1981, the *Messier Catalogue*, to the *Explore the Moon* launched in 2016, the national Observing Committee is excited to present a new program to help RASC members enjoy viewing doubles. ✶



RASC Double Star Observing Program Checklist

Use this checklist to monitor your progress. If you cannot split a double, it's OK; try again on another night. View a pair of stars for each target. Some targets are triples or have additional stars. Only the brightest or most obvious pair is required.

Record your detailed observations on the provided or your own log sheets. Sketching is optional but highly encouraged.

See the supplemental spreadsheet for detailed information for each component of these double stars including all visible companions, magnitudes, separation values, position angles, visual impressions, etc. If you enjoy "discovery moments," avoid reading the supplement.

The checklist is organised by season, with doubles grouped by constellation, and sorted by RA.

LEGEND

Target	a common name for the target double star or multi-star system	Con	host constellation
Alternate ID	other designation including Bayer, Flamsteed, Draper, etc.	MagC	calculated combined magnitude of two bright stars
SAO	Smithsonian Astrophysical Observatory catalogue designation	Mm	suggested telescope size, aperture in millimetres
HIP	Hipparcos star catalogue designation	X	suggested starting power or magnification
WDS	Washington Double Star catalogue discoverer designation	PSA	page number in Pocket Sky Atlas
RA/Dec 2000	rounded coordinates for the target, J2000 epoch	Seen?	use check box to indicate target was viewed

Version 4.0a. Edited on 18 October 2020.

Target	Alternate ID	SAO	HIP	WDS	Con	MagC	RA 2000	Dec 2000	Mm	X	PSA	Seen?
WINTER (part 1)												
HD 21700	BD+27 514	SAO 75964	HIP 16386	STFA 7	Tau	6.8	03 31.1	+27 44	100	45	15	☐
Phi Tau	52 Tau	SAO 76558	HIP 20250	SHJ 40	Tau	5.0	04 20.4	+27 21	90	45	15	☐
32 Eri	HR 1212	SAO 130806	HIP 18255	STF 470	Eri	4.5	03 54.3	-02 57	90	140	17	☐
Keid	Omicron 2 Eri	SAO 131063	HIP 19849	STF 518	Eri	4.4	04 15.2	-07 40	100	25	17	☐
1 Cam	DL Cam	SAO 24672	HIP 21148	STF 550	Cam	5.4	04 32.0	+53 55	90	70	12	☐
Beta Cam	10 Cam	SAO 13361	HIP 23522	S 459	Cam	4.0	05 03.4	+60 27	100	60	11	☐

Double Star Observing Program Page 1 of 5 Copyright © 2020 Royal Astronomical Society of Canada

Figure 3 — The main double-star target list with names, constellation, location, combined magnitude of the two stars, and suggested telescope aperture and power.

Blake's interest in astronomy waxed and waned for a number of years but joining the RASC in 2007 changed all that. He helps with volunteer coordination in the RASC Toronto Centre and is a member of the national Observing Committee. Blake loves double stars.

Original Discoveries from The Celestial Objects for Common Telescopes, Vol. 2: The Stars

by Chris Beckett, National Member
(cabeckett@gmail.com)

T.W. Webb (1807-1885) has been called the "father of amateur astronomy." His day job was ministering to the Anglican Parish of Hardwicke in Herefordshire near the border of Wales while his nights were spent using a 3.7˝ ƒ16 Tulley refractor, a "common telescope" his father purchased for him, then later a 9 1/3˝ With-Berthon reflector. Such apertures remain among the most popular with amateur astronomers today and combine with Webb's clear writing style to make his *Celestial Objects for Common Telescopes* first published in 1959 still relevant today. Add to this the revelation that Webb made a handful of his own discoveries makes him an inspirational figure for all of us who use small telescopes to probe the depths.

I have been fortunate to have a small section dedicated to small instrument objects, Wide-Field Wonders, included in the RASC *Observers Handbook* since 2013. Having finished the list in the summer of 2012, I shared it with the observers at the Mt. Kobau Star Party during a brief presentation before observing with Alan Whitman. This past October, Alan emailed a suggestion; he mentioned that "*IC 4756 is called Graff's Cluster in some guidebooks because of his belated independent discovery in 1922.*" and that Webb was now considered the original discoverer of IC 4756, adding "if the cluster is to be named for its discoverer, it should be called Webb's Cluster. *An amateur of Webb's stature has earned a permanent place in the sky!*" I was surprised and found a detailed description in Wolfgang Steinicke's excellent book *Observing and Cataloguing Nebulae and Star Clusters: From Herschel to Dreyer's New General Catalogue* as well as reference to a 2007 article by Michael Fritz detailing each object.

Webb's book went through many editions, most recently in 1962. Margaret Mayall edited a two volume set, *Volume One: The Solar System* and *Volume Two: The Stars*. The second gives brief descriptions of each constellation followed by long lists of Struve Double Stars and short sections on Nebulae and Clusters. In the latest edition Mayall does us the favour of associating Webb's observations with Messier and NGC catalogue numbers, however, as Michael Fritz mentions, Webb frequently notes "Bright Group" and "Beautiful Field" where five have been determined as original open cluster discoveries by Webb but were not edited into the last edition. These objects we know were eventually catalogued as IC 4756, Stock 2, Stock 23, Trumpler 2, Stephenson 1, and NGC 7027, the last a planetary nebula he independently discovered. Webb didn't call out his open cluster discoveries, nor did he create his own catalogue nomenclature, perhaps assuming they were already known objects.

IC 4756 in Serpens – "Group. Very large, subdivided, chiefly 9 and 10 mag"–Webb

The open cluster IC 4756 already had a confusing history, with Bailey's 1896 photographic discovery overshadowed by Graph who independently found it in 1922, however, it was Webb who clearly located this object first. I sketched the cluster naked eye on a cold May evening in 2016 when I noted it appeared as a small knot protruding from the western edge of the Milky Way into the large dark lane that bisects much of the southern Milky Way. Webb lists IC 4756 under clusters in Serpens and Alan pointed me to Steve Gottlieb's website where I found the following description:

"Solon Bailey found IC 4756 in 1896 on a plate taken with a 1˝ Cooke lens at the Arequipa station in Peru (Annals of Harvard College Observatory, Vol LX, No VIII, 1908) and is credited with the discovery in the IC2. But it was discovered visually by Reverend Thomas Webb by 1859 with his 3.7˝ Tully refractor. In the listing for NGC 6633 in his "Celestial Objects for Common Telescopes" (1859) Webb wrote, "Between it [NGC 6633] and Theta, nearer the former, is a beautiful large cloud of stars, chiefly 8 or 9 mag., a nearer part, apparently, of the Galaxy: visible to the naked-eye, and requiring a large field." The nickname "Graff's

Figure 1 — Sketch by the author 2016 February 23

Cluster" comes from German astronomer Kasimir Graff, who independently discovered it in 1922."–Steve Gottlieb

Cassiopea – Stock 2 – "Follow the curve of stars *n*, which leads into a glorious region" – Webb

Webb placed this object we now know as Stock 2 in the constellation Perseus. This makes sense since the exacting IAU constellation boundaries were still decades away and this cluster's proximity to the Double Cluster in Perseus would have logically meant lumping it in with this group. However, Webb did note it as an entirely separate entity after his Double Cluster description as "Follow the curve of stars *n*, which leads into a glorious region". Indeed, I see this as one of the most beautiful regions both naked eye and and through binoculars where from the darkest locations the chain of stars Webb refers to forms a nebulous band while an additional band pairs with it even in a modest 7×35 binocular. The sheer number of stars in the region remains unresolved yet the "Muscle Man" outline of Stock 2 is clear.

Camelopardalis – Stock 23 – "…quintuple. In a beautiful wide group." – Webb

Stock 23, widely known as Pazimo's Cluster and made famous in observing circles by Walter Scott Houston as one of his favourite clusters. While Webb is certainly the first to note it, it was rediscovered by Jurgen Stock in the 1950s and again by New York amatuer astronomer Pazimo in the '70s. The cluster resides on the border of Camelopardalis and Cassiopeia with Webb's description not under Nebulae but the Double Stars of Camelopardalis and his description of Struve 362 as:

"…quintuple. In a beautiful wide group."

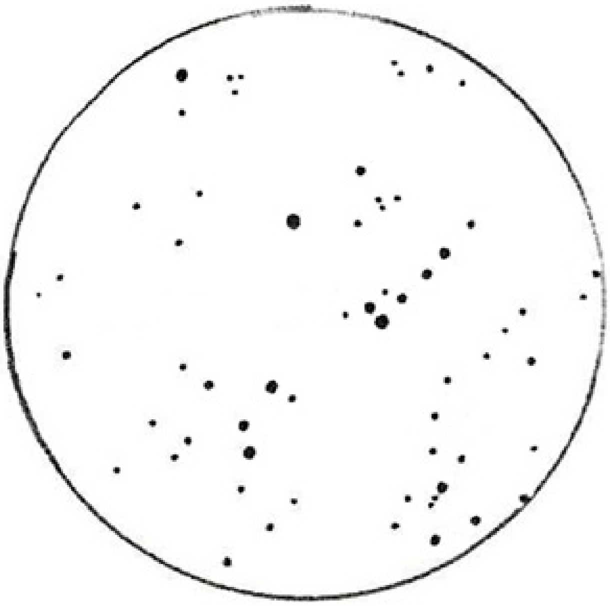


Figure 2 — Stock 23 Sketch by Randall Rosenfeld August 2018

Perseus – Trumpler 2 – "Group …with reddish star" – Webb

Sandwiched between his descriptions of NGC 957 and M34 we land on a distinct description in Perseus as "Group….with reddish star" on the eastern side. Plate 1 of Baranrd's *Atlas of Selected Regions of the MilkyWay* shows Trumper 2 outlined by Barnard while Trumpler's later discovery noted the same red star as Webb. I find this cluster is a small puff of Milky Way and placing Eta Persei in the bottom left of my 7×35 binocular puts Trumpler 2 over halfway to the Double Cluster with Stock 2 near the top of the same field!

Lyra – Stephenson 1 – "Bright broad group." – Webb

In 1959, 100 years after Webb published his first edition, Stephenson catalogued the Delta Lyrae Cluster asa physical group and the first in his catalogue.Located between Webb's descriptions of M56 and M57 is a separate description for an uncatalogued group he described as a "Bright broad group."

Cygnus – NGC 7027 – "Planetary, like an 8.5 mag. Star, about 4″ – Webb

Co-discoverer with Edouard Stephan of Stephan's Quintet fame, who discovered it a year earlier, but it was Webb who widely popularized this planetary nebula with his observation using the 9 1/3″-inch reflector. In addition to his description in Volume 2: The Stars, where he notes it as "7027 (Stephan.). Planetary, like an 8.5 mag. Star, about 4″, found by me independently, Nov. 14, '79." Steinicke mentions Webb also logged the following "object like a bluish 9 mag star, not quite of stellar character—a small pair, too close to be separated?" At higher magnifications it was seen as "bright, very ill-defined, nebulous disk of about 4″ diameter, surrounded probably by a little glow, and much resembling the planet Uranus." Commonly now known as the "Jewel Bug" nebula, this is one of those planetary nebulas that responds well to blinking the nebula filter in and out out the field.

If you find yourself looking for an easy to accomplish observing list for a relaxing summer evening, think about tackling Webb's Objects, there's no certificate but you may find enjoyment connecting with an amateur from so long ago. For those looking to decrypt Webb's work even further another 100 or so unnamed asterisms are sprinkled throughout his work.

The author thanks Alan Whitman, contributing editor for Sky & Telescope, and credits him with the original idea for

The June 2021 *Journal* deadline for submissions is 2020 April 1.

See the published schedule at

rasc.ca/sites/default/files/jrascschedule2021.pdf this article and also Mark Bratton of the Webb Society for supplying the Michael Fritz article on the *Webb Clusters*. ✶

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Chris Beckett is a long-time binocular and small telescope observer and author of the RASC Observer's Handbook WIDE-FIELD WONDERS. Since 2012 he has been the Continuing Education Astronomy Instructor at the University of Regina and enjoys observing under the dark skies of Grasslands National Park in southwestern Saskatchewan.

CFHT Chronicles

A Big Day for SPIRou

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

February brought a profusion of science news for CFHT, including one of the first planets characterized by SPIRou. I have copied the news release from our website and added more information where appropriate. Credit is shared with the SPIRou team and Peter Plavchan (George Mason University).

Our SPIRou story starts in June 2020 when Dr. Peter Plavchan along with his co-authors (including friend of CFHT and iREX member—Dr. Jonathan Gagné) announced the discovery of a planet orbiting the star AU Microscopii (AU Mic). The team used the NASA *TESS Telescope* and *Spitzer* to discover AU Mic b, which transits its host star once every 8.46 days. The observations constrained the radius to four times the radius of the Earth and determined an upper limit on the mass at < 0.18 Jupiter masses.

At 22 million years old, AU Mic b is a young red dwarf that is a member of the Beta Pictoris Moving Group. This group of stars shares a common motion through space, a common origin, and are the closest, youngest group of stars to the Earth. These characteristics make the Beta Pic Moving Group the perfect laboratory for astronomers to study planetary formation. The group is named for the star Beta Pictoris, which is home to two planets.

TESS detects planets via the transit method. As a planet passes in front of the disk of its host star, the brightness of the star decreases, usually by a small amount. TESS is the follow-up mission to the *Kepler Space Telescope*. Over the course of TESS's mission, it will focus on nearby G, K, and M type stars, studying an estimated 200,000 stars—an area 400× larger than the *Kepler Space Mission*.

As is common in very young stars, the low-mass red dwarf AU Mic is extremely active. Rotating 5× faster than the Sun, this active star exhibits giant starspots on its surface, frequent stellar flares, and strong magnetic fields, several orders of magnitude larger than the Sun. AU Mic's stellar activity complicated the detection of the planet.

To better understand AU Mic b and the entire system, it is critical to determine not only the radius of the planet measured by Plavchan and his team, but the mass and the density as well. AU Mic is an exciting system for astronomers, the star is surrounded by a huge debris disk, where prior to the discovery of AU Mic b, astronomers detected moving clumps of dust.

Enter SPIRou… A team of astronomers used SPIRou to measure the mass and density of AU Mic b. Additionally, they discovered the planet orbits in the equatorial plane of its host. These observations mark the very first time the mass, density, and orbital inclination of a planet so young are reliably characterized. The result was part of an international effort to unveil the properties of this newly discovered baby planetary system, spearheaded by astronomers at IRAP/CNRS[1], IAP/CNRS[2], IPAG/CNRS[3] and CFHT.

The team used SPIRou to follow up the TESS/NASA discovery of AU Mic b by measuring mass, density, and orbital tilt of the planet, enhancing astronomers' understanding of the object. Unlike TESS, which utilizes the transit method, SPIRou detected the minute gravitational pull induced by the close-in planet on its host star, AU Mic. Astronomers use SPIRou to detect the periodic wobble induced by planets orbiting their host star—known as the radial velocity. These tiny wobbles in the star's spectra are used to measure the mass of the planet due to its gravitational influence on its star. Simultaneously, SPIRou performs polarimetric analysis of the star's light, enabling the detection and characterization of the host star's magnetic field. The characterization of magnetic activity, like that detected in AU Mic b, removes wobbles in the star's velocimetric data that potentially shields planets from detection.

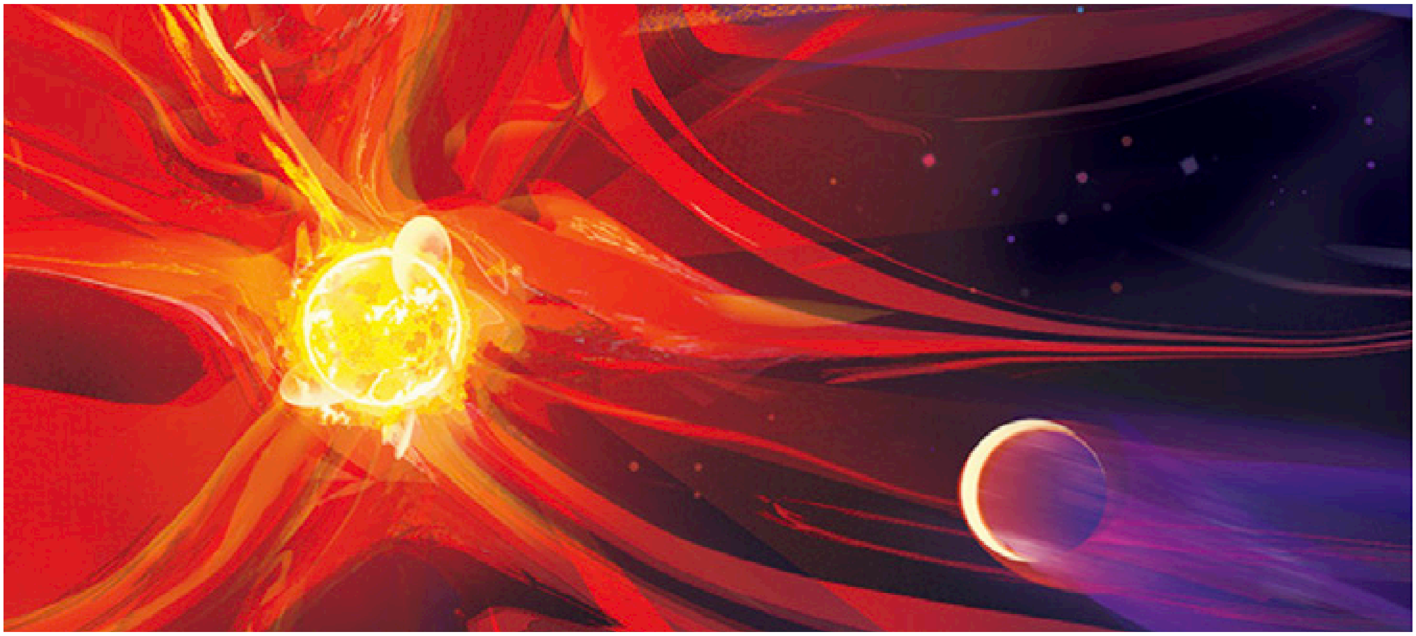

Figure 1 — Artist view of the very young eruptive red dwarf AU Mic (left) and its newly discovered close-in planet (right) with the debris disk from which the planet was born in the background. Image credits: NASA-JPL/Caltech

Using SPIRou spectra, the team measured the mass of AU Mic b to be approximately 17× the mass of Earth. Combining the TESS and SPIRou data, the team estimated the density of the planet and found it to be only slightly more dense than water, ~4× lower than the Earth's density, and surprisingly similar to Neptune and warm at ~300 °C.

"Constraining these critical characteristics of AU Mic b is a testament to the capabilities of SPIRou," said Dr. Claire Moutou, co-author on the paper and former SPIRou instrument scientist at CFHT. "The observations of AU Mic b are incredibly exciting for those of us involved in SPIRou since its beginning."

The same overactive stellar activity that made the detection of AU Mic b in the TESS transit data reared its head and complicated the radial-velocity measurements for SPIRou. Detecting the small planet in such a chaotic environment is extremely challenging: its signal is tiny compared to the ~10× larger noise caused by the star's activity. However, SPIRou's unique velocimetric and polarimetric capabilities enabled the team to detect the signal. The task also required a detailed analysis of the SPIRou data using complex numerical techniques combined with accurate modelling of the star's magnetic fields and stellar activity to tease out the planetary signal from the raw data.

Astronomers believe large planets form deeper in the debris disk surrounding their planet. These more distant areas are richer in gases and materials, allowing the planet to grow larger in size. At some point during their evolution, planets like AU Mic b migrate inward due to gravitational interactions with the gas disk or other planets in their system.

AU Mic and its planet stand in direct contrast to its moving group mate Beta Pic and its planets. As mentioned previously, both stars are similar in age. However, their planets are very different. Beta Pic c, 9× the mass of Jupiter, orbits at 2.7

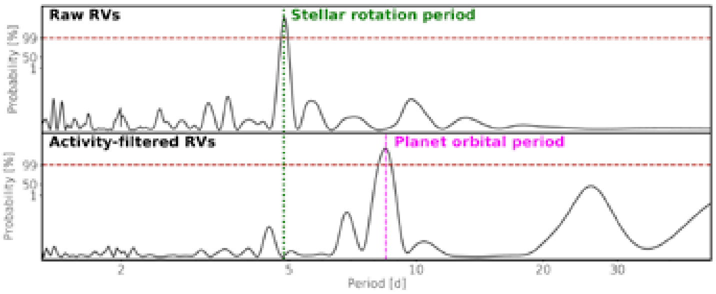

Figure 2 — These curves depict the probability of a periodic oscillation to be present in the SPIRou radial velocity (RV) data, for wobble periods ranging from 1 to 50 days. Once the periodic RV signal induced by the activity of the rotating star (at a period of 4.86 days) is corrected for in the raw RV data (upper panel), the periodic signal induced by the newly detected orbiting planet (at a period of 8.46 days) clearly shows up in the filtered RV data (lower panel) at a confidence level higher than 99.9%. Image credits: B. Klein

astronomical units (AU) from the star and the larger Beta Pic b, 13× the mass of Jupiter, orbits 9 AU (think Saturn's distance).

"To put in human terms at 22 million years old, AU Mic b is a couple of months old." says Dr. Baptiste Klein, lead author on the SPIRou AU Mic b paper focusing on the planet's characteristics. "Finding a Neptune-like planet orbiting so close to its star in a planetary system this young puts challenging constraints on our current models of how planets form and migrate."

Through observations of AU Mic as the planet transited, the team constrained the tilt of the planet's orbital plane and found it aligned with the equatorial plane of its host star, a result confirmed with ESPRESSO at the European Southern Observatory. AU Mic b's position close to the star and aligned orbit perfectly illustrate the predictions of current theory; giant planets form far away from the star and migrate closer due to gravitational interactions between the newly formed planet and the surrounding protoplanetary disk.

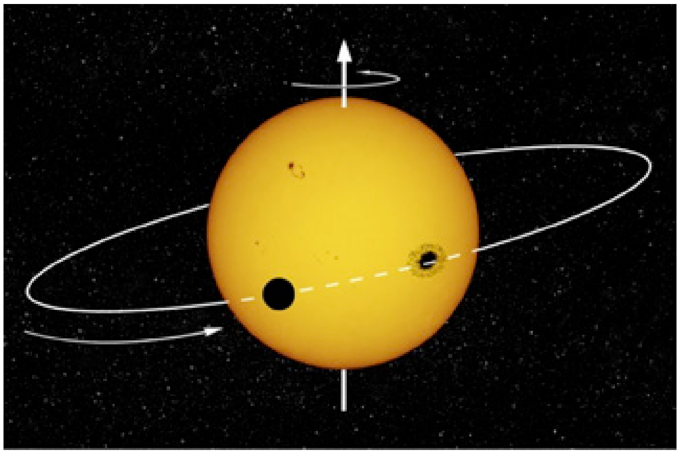

Figure 3 — To better understand the formation of stars and their planets, it is key to find out whether the planet's orbit is tilted to the equatorial plane of its host star. Our new results show that this tilt is small in the case of the giant planet of AU Mic, in agreement with recent models of planetary formation within protoplanetary disks. Image credits: R Cardoso Reis (IA/UPorto)

"The SPIRou observations revealed that the orbit of AU Mic b is prograde and aligned with the stellar rotation axis," says Dr. Eder Martioli, lead author on the SPIRou AU Mic b paper focusing on the planet's orbital plane. "These observations are strong evidence that this planet was formed in the protoplanetary disk that evolved into the current debris disk around AU Mic."

The AU Mic b observations are the first of many similar observations expected from SPIRou.

"This discovery is a perfect illustration and demonstration of SPIRou's unique velocimetric and spectropolarimetric capabilities, making it the best instrument worldwide for hunting planets around young active dwarfs like AU Mic." says Dr. Jean-Francois Donati, co-author on the paper and principal investigator of the international collaboration that designed and built SPIRou. "This first result comes as a great reward for the whole SPIRou team and partners who invested so much effort and resources over the last decade to deliver an innovative state-of-the-art instrument for the CFHT community."

I want to acknowledge the discovery team, which includes scientists from IRAP/CNRS (B. Klein, JF. Donati, C. Moutou[NM10]), most of whom also handled the construction, validation, and commissioning of SPIRou at IRAP and CFHT; from IAP/CNRS (E Martioli, G Hébrard, S Dalal); from IPAG/CNRS (X Delfosse, X Bonfils); and several other countries / partners involved in the SPIRou project (in particular Canada and CFHT) and George Mason University (P. Plavchan). These studies benefitted from additional funding from the ERC (European Research Council, grant #740651 NewWorlds) and the ANR (Agence Nationale de la Recherche, grant ANR- 18-CE31-0019 SPlaSH). SPIRou was funded by a worldwide consortium of partners from France, Canada, CFHT, Switzerland, Brazil, Taiwan, and Portugal.

As a fun note—AU Mic and AU Mic b mark the second time a planet characterized by CFHT was featured on one of the NASA Exoplanet posters. "Flares of Fury" highlights the extreme activity of AU Mic b. Our first poster appearance featured another member of the Beta Pic Moving Group, PSO J318.5-22, discovered by Mike Liu from the University of Hawaii. ✶

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.*

Astronomical Art & Artifact

Exploring the History of Colonialism and Astronomy in Canada

by R.A. Rosenfeld, FRASC (National Member)
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Abstract

Many societies have recently experienced increasing calls for racial and social justice, spurred by lethal abuses of authority and power originating in systemic imbalances. Land acknowledgements of varying degrees of sincerity have been confected, statues of slave traders have been toppled, and buildings, streets, and communities have been renamed. Research and educational institutions have not been untouched by this; the statements and records of benefactors have come under increased scrutiny. Many bodies, including astronomical ones, have started processes of self examination, and established committees to address issues of reform. The problems are generally considered to arise from colonialism continuing to shape post-colonial societies—an unwelcome haunting of the present by the past. The better we know that past, the better equipped we are to change what has to be changed. This paper looks at the history of colonialism and astronomy in Canada.

Rude Awakening

Many Canadians with an interest in the advancement of astronomy felt elation when on 2015 April 6 the Harper Government finally approved the funds to ensure full Canadian participation in the Thirty Metre Telescope (TMT). Elation turned to confused surprise when the vigorous and persistent opposition to the project by a significant portion of the Kānaka maoli made headline news.

Clearly many of us hadn't bothered to consider the colonial history of Hawai'i, else we would not have been surprised to learn that for some the TMT brought not the promise of a new competitive era in observational astrophysics, but rather the promise of continued colonialism through a sacral desecration in the making, transforming a big-science project into a symbolic summation of 130 years of injustice. In light of this, some of us may have nervously reviewed in our minds the astronomical installations on Canadian soil, wondering if any of them were on sacred sites, and whether their creation involved acts of desecration and dispossession of First Nations people, and if evolving perspectives could cause anything of those pasts to come uncomfortably alive in the present. Some of us may even have sighed with relief at the apparent absence of an obvious legacy of colonialism dogging astronomical installations on Canadian soil. With a bit of effort we could almost convince ourselves that the true north in its home and native land didn't place telescope enclosures on sites sacred to First Nations. Yet we were about to participate in that very thing elsewhere. And that is an uncomfortable knowledge.

From what I know of the ethos of the Canadian astrophysical community, no one working on the TMT set out to trample on native rights. What they did set out to do was ensure access to what promised to be an extremely productive engine of discovery at an unequalled observing site. The situations brought about by different cultural perspectives encountering each other on the same land can be complex. How easy will it be for the astrophysical community to abandon a prime observing site and forego a dream installation with great potential to advance knowledge of the Universe? How can one expect the Kānaka maoli, whose identity is inseparable from their landscape, to passively watch their sovereignty degraded, as the monuments of their cosmology are altered by others? Colonialism has much to answer for.

If we are to establish right relations with other communities, we will need to know our origins. Critically, we have to ask what is the history of colonialism and astronomy in Canada?

Before Beginning…

There are a few points it would pay to clarify before looking into that history. The first hardly needs saying, but I will say it anyway: the views expressed here are mine alone, and not those of the Society, or the *Journal*.

The second is to define "colonialism," and here I opt for the definition of Kohn and Reddy with which they open their article in *The Stanford Encyclopedia of Philosophy*: "Colonialism is a practice of domination, which involves the subjugation of one people to another" (Kohn & Reddy 1997). It is flexible enough to cover much of what one encounters. And I subsume "imperialism" under colonialism, which they responsibly refrain from doing.

The third is that colonialism is not a solely European invention and practice of the early-modern period. Examples? The Qin (221–206 BCE) & Han dynasties (206 BCE–220 CE) reigned over what is now known as China (Bodde 1986; Ying-Shih 1986), the Maurya Empire (ca. 322–ca. 184 BCE) ruled over India and adjacent areas (Thapar 2012; Lahiri 2015), the Aksumite Empire (ca. 100–ca. 940 CE) controlled Ethiopia (Phillipson 2012, 151–170), the Timurid Empire (ca. 1370–ca. 1507 CE) dominated much of the Near & Middle East, Central Asia, & western South Asia (Roemer 1986a; 1986b), the Aztec Empire (1428–1521 CE) controlled much of Mexico and Guatemala (Berdan 2017), the Songhai Empire (ca. 1464–1591 CE) mastered much of the Sahel (Hunwick 1999), and First Nations' colonialism thrived on the west coast of North America prior to contact (Leland 1997). Virtually every culture has found itself in the roles of oppressor and victim at one time or another. If you are unaware of evidence your culture ever dominated another you haven't looked hard enough.

Airing other cultures' dirty laundry can't whitewash our own. Whatever a culture may have done to others in the further past does not justify its subjection to a colonial regime closer to our time, at our collective hands. If we are concerned with present inequalities in our society borne of colonial regimes of which we are the heirs, our responsibility cannot be erased by citing convenient facts. The problems remain until the present inequalities caused by the active legacy of colonialism are righted.

In some cases, considerable effort is required to preserve historical detachment when attempting to understand the actions of our predecessors of a century or more ago in their contemporary context(s). That perspective has to be sought. The history of colonialism and astronomy in Canada is more than an informed glance over our shoulders; it is a glance back toward our present. Having sought historical perspective, we then have to judge the contemporary consequences of past actors and their actions by present values, because we are living through those consequences. Balancing historical perspectives and the present imperatives for justice is challenging. There are bound to be missteps in the process.

Finally, a full history of colonialism and astronomy in Canada could hardly be presented within the confines of a lone article. What I offer here are incidents and episodes that I hope give some indication of the contours of that relationship. While the theme of science in the service of colonialism has been of increasing interest to historians of science since the 1980s, and some of the classic works, such as the trilogy by Lewis Pyenson exploring German, Dutch, and French science in colonies overseas in the 19th and early 20th century (1985; 1989; 1993), or James McClellan and François Regourd's study of *Ancien Régime* science devote considerable time to astronomy in its colonial guise, the history of colonialism and astronomy in Canada has not received comparable attention. That ought to change, and this is a small contribution toward that change.

Early Modern Images of the Explorers

The story starts with the very beginning of "modern" contact, in the later 15th century with the voyages of exploration from Europe in search of more economical trade routes to the East (the earlier Norse contacts with North America appear unconnected to the European presence that eventually took hold on these shores). The relationship between astronomy and the colonial enterprise at this stage is easily stated. In order to arrive from Europe, practical astronomy, i.e. navigational skills, was needed. It could be argued that astronomy in the service of navigation was one of the commonest professional applications of astronomy in the early modern period.[1] Without those astronomical skills the explorers would not have stumbled onto North, Central, and South American shores to "discover" lands already known to their inhabitants, or been able to return.

The relationship between explorers, navigation, and astronomy was at times given strong visual expression when celestial bodies and astronomical instruments became the iconographic attributes of European explorers. One striking retrospective example is the portrait of Christopher Columbus in Isaac Bullart's multi-volume "great men" collection from the era of the Cassinis (Bullart 1682, IV 265–272). His sole attributes are a nocturnal (an observational device for determining the time at night), and some stars to which he gestures. The nocturnal isn't even a major navigational instrument!

Figure 1 — Johannes Stradanus (1523–1605), "Astrolabe. Amerigo Vespucci, [who] discovered the cross with four stars [i.e. the Southern Cross] in the dead of night," from Nova reperta (1580s). Taken from Hans Kraemer's Weltall und Menchheit, 3 (Berlin–Leipzig–Vienna–Stuttgart: Deutsches Verlagshaus Bong & Co., 1902–1904). One of the iconic names in accounts of heroic exploration Europeans and European descendants relate to themselves, in an elusively allegorical setting, dominated by the tools of practical astronomy. One of the visual lessons of this image is that the technologies of astronomy aided colonial exploration, and conquest. Reproduced courtesy of the Specula astronomica minima.

The explorers' reliance on astronomy is signposted even more unmistakably in the plate showing Amerigo Vespucci discovering the Southern Cross in Johannes Stradanus's (1523–1605) *Nova reperta* of the late 1580s (Figure 1; Baroni & Sellink et al. 2012, 300–306; Markey 2016, 119–138). The *Nova reperta*, or *New Discoveries*, depicts novel finds or inventions of the time replete with allegorical colouring, all viewed through a Florentine filter.

The engraving bears the inscription and title: "Astrolabe. Amerigo Vespucci, [who] discovered the cross with four stars [i.e. the Southern Cross] in the dead of night" (*Astrolabium. Americus Vespuccius, cum quattuor Stellis crucem silente nocte repperit*). Three astronomical instruments are shown, an astrolabe, an armillary sphere, and a quadrant, along with associated mathematical tools, a straight edge, proportional dividers, and another set of dividers. Additionally, a source of artificial light, an inkwell, a pen and penknife, a logbook, and an open chest of books, presumably with texts relevant to his celestial work.

The astronomical instruments are far from competently drawn; the quadrant spans less than 90 degrees, the armillary sphere is a prolate spheroid with poorly placed circles, and the astrolabe doesn't appear to have successfully made the transition from a three-dimensional sphere to a projection onto a two-dimensional surface. It's just conceivable that Stradanus was attempting to portray one of the universal astrolabe designs, such as the Azarquiel, or De Rojas projections. As botched as the details of the instruments are, they still suffice as representations of astronomical instruments. They signal that these men are explorers. And they remind us that the techniques of astronomically aided navigation were essential to the exploring they did in the first steps to European colonization of these shores.

Closer to home, what of images of John Cabot, the "Canadian" Columbus? Are there any portraits of him with the attributes of early-modern astronomical technology? No, because there were hardly any early-modern portraits of Cabot; he was too insignificant a figure to attract the attention of artists, poets, and their patrons. In a very real sense, the images of Columbus, Vespucci, and Magellan were also images of any explorer, such as Cabot. Their iconography symbolizing the astronomical technology enabling exploration in the service of colonialism was a common one.

A Brazen Astronomical Icon, and Its Memorialization

In 1867, the year of Confederation, and a year before the first founding of the RASC, a teenage boy working with his father to clear land near Cobden, Ontario, came across an unusual stray find, an early 17th-century mariner's astrolabe (Figure 2; Mcnamara 1919, 107–108). Within a dozen years this artifact was associated in print with Samuel de Champlain (ca. 1570–1635), the "founder of New France" (Russell 1879). It has since been elevated to a national icon, featuring prominently as an attribute of Champlain's in the statue (1915) by MacCarthy at Nepean Point near the National Gallery of Canada (Figure 3), and on gold (2014) and silver coins (2015) issued by the Royal Canadian Mint. National—and some expert—sentiments about the instrument had reached such a point that it was acquired for $250,000 for the recently opened Canadian Museum of Civilization, as a signature piece for the museum (Anon. 1989; now rechristened the Canadian Museum of History).

Figure 2 — Facsimile of "Champlain's Astrolabe," by Réal Manseau, 2004, Dorner Telescope Museum 14.2019111. The original in the Canadian Museum of History in Ottawa (CMH 989.56.1) is now the ultimate early-modern astronomical artifact turned icon of the advent of European settlers to Canada. Reproduced courtesy of the Dorner Telescope Museum.

In the present state of knowledge, while the material, manufacturing techniques, and form of the astrolabe are not dissonant with Champlain's era, there isn't enough evidence to decide if the astrolabe was to Champlain what the surviving telescopes and digits are to Galileo; authentic relics of their respective cults (Brooks 1999; Chrestien 2004). What isn't subject to doubt is the powerful symbolic charge of this instrument of practical astronomy. It is virtually synonymous with the explorer himself.

Which brings us from the instrument, to the man. In one of the dedications to his royal patron, Champlain has left us his views on the great utility of the professional applications of astronomy within the colonial enterprise:

> "Among all the most useful and admirable arts that of navigation has always seemed to me to hold the first place; for the more hazardous it is and the more attended by innumerable dangers and shipwrecks, so much the more is it esteemed and exalted above all others, being in no way suited to those who lack courage and resolution. Through this art we gain knowledge of different countries, regions, and kingdoms; through it we attract and bring into our countries all kinds of riches; through it the idolatry of paganism is overthrown and Christianity proclaimed in all parts of the earth. This art it is which from my tender youth won my love, has stimulated me to venture nearly all my life upon the turbulent waves of the ocean, and has made me explore and coast a part of the shores of America and especially of New France, where it is my constant desire to make the Lily flourish along with the unrivalled Catholic, Apostolic, and Roman religion" (Champlain 1922, 209–210).[2]

Champlain tells us that the practical astronomy that enabled him to sail where he wished, and know where he was on land, had wider implications. Practical astronomy served the economic goals of advancing trade and transferring resources to Europe, it furthered the introduction and establishment of a militant (Counter-Reformation) Christianity, and it enabled a French presence to take root in the "new" land. It was astronomy in the service of empire.

Venture Capitalism and Advances in Astronomical Telescopes

HBC, or Hudson's Bay in the present apparition of its consumer retailing guise, likes to remind visitors to its website that "Founded in 1670, HBC is the oldest company in North America" (HBC 2017). In 1670 it was "the Governor and Company of Adventurers of England tradeing into Hudsons Bay." It is certainly entitled to boast of the oldest colonial past among businesses affecting to vestiges of Canadian affiliation. And, for our present purposes, the HBC enjoyed some intriguing astronomical connections in its first years.

News of those connections is nothing new. When the first scientific edition of the earliest records of the HBC were published in 1942, Sir John Clapham took the opportunity to note that:

> "It is odd to note how many of the early adventurers were Fellows of that Society [The Royal Society of London for Improving Natural Knowledge], that is to say—as things then were—men known, or wishing to be known, for their enlightened curiosity" (Rich & Clapham 1942, xxvii).

Among the adventurers were Sir Christopher Wren (1632–1723), Savilian Professor of Astronomy at Oxford (1661–1673), and formerly Professor of Astronomy at Gresham College (1657–1660), and the courtier, Sir Paul Neile (1613–1682), an active and apparently intelligent patron developing long-focal-length telescopes for astronomy in the 1650s and 1660s working with the noted optician, Richard Reeve (van Helden 1968). Neile was a charter member of the HBC (Rich & Clapham 1942, 131; Simpson 2009), and Wren joined in 1679 (Rich & Clark 1945, xxv), and both were charter members of the Royal Society. Ted Binnema points out that, at first glance, the relationship between the HBC and the Royal Society seemed to hold much promise for the production (or perhaps one might say extraction) of natural philosophy from Rupert's Land, but for a variety of reasons, that promise was not realized in the early years (Binnema 2014, 56). It has been said that Wren's growing commitment to architecture diminished the attention he could devote to the HBC and the Royal Society during the 1680s (Binnema 2014, 57), and that Neile became inactive in the latter by 1680 (Binnema 2014, 56), yet, during the time both were active in the Company and the Society, there is evidence that their interests and involvement in astronomical questions and instrumentation were still alive (Bennett 1982, 42–43, 50–53; Birch 1756, 398; 1757, 1).

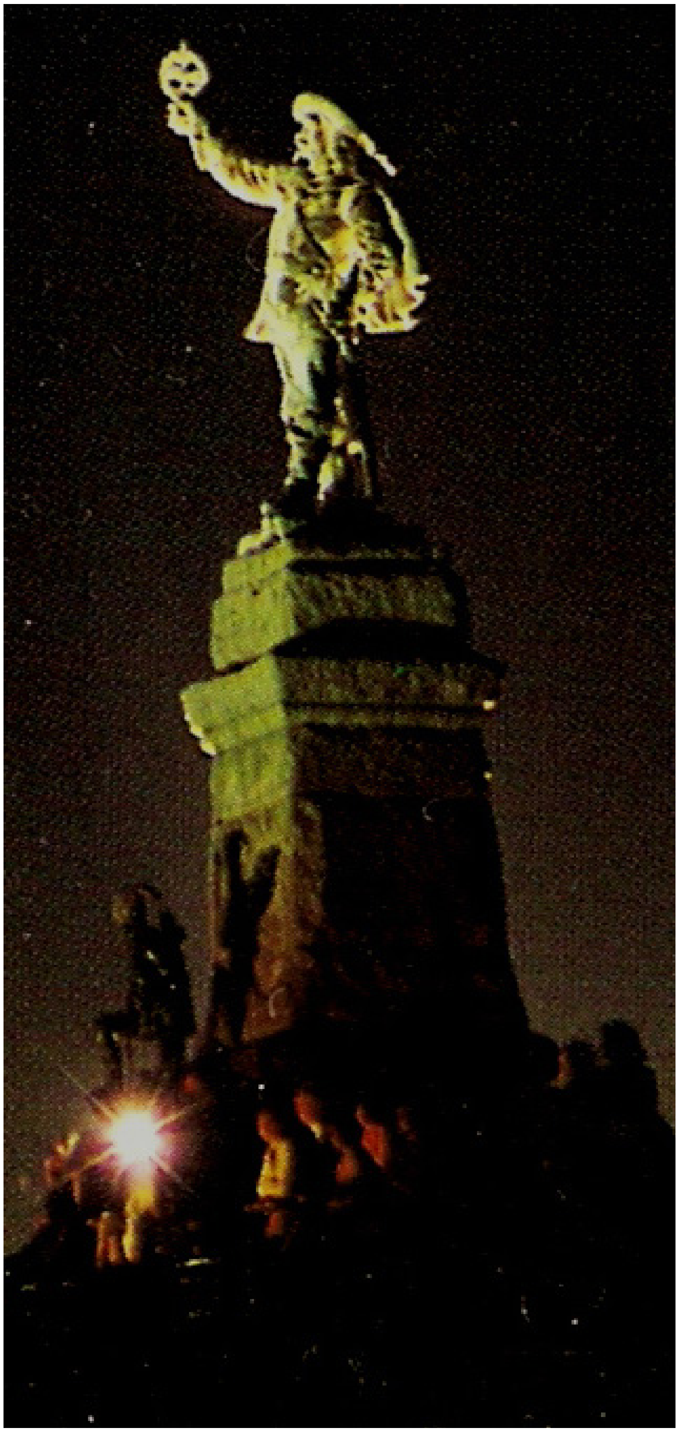

Figure 3 — H.T.C.P. MacCarthy's bronze statue (1915) of Samuel de Champlain at Nepean Point, Ottawa, dramatically lit at night, in a detail from a postcard from the 1960s. In its realized form, this ended up as a sculpture of two bronze figures, Champlain the great European explorer using his astrolabe (which is shown upside down!), and an unnamed "Anishinabe Scout" (replacing a less acceptable anonymous name in the 1990s) crouched at the bottom of the monument. It is very much a work of its time, now seen to present a colonial view of a very unequal power relationship. An attempt was made to adjust that message, by altering the relationship of the figures in the National Capital landscape through moving the statue of the First Nations person to a more dignified position in Major's Hill Park. Is that enough of a gesture? Reproduced courtesy of the Specula astronomica minima.

Figure 4 — The Dominion Observatory (1905) in Ottawa, in a postcard taken not long after it became operational. This observatory, Canada's answer to Greenwich, combined work in astronomically based land surveying, time determination, astrophysics, and geophysics. Its origin was in Canada's tradition of colonial surveying. Reproduced courtesy of the Specula astronomica minima.

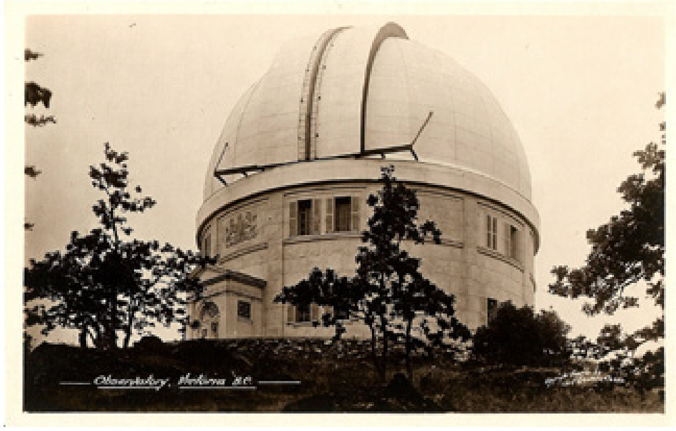

Figure 5 — The Dominion Astrophysical Observatory (1918, now part of the Herzberg Astronomy and Astrophysics Research Centre) on Little Saanich Mountain, in a postcard probably from the early 1920s. The DAO, the offspring of the Dominion Observatory, is Canada's first major astrophysical facility, and has been—and is—wonderfully successful. Reproduced courtesy of the Specula astronomica minima.

Did either Wren or Neile fund their involvement in astronomy and their other philosophical interests in England through profits gained adventuring from their HBC shares? It would be both exciting, *and* troubling if the funding for particular astronomical projects by members of the Royal Society during the *Principia* era could be tied directly to colonial profits. Exciting, because one could hold the metaphorical supporting ropes connecting a long-focus refractor of London's Scientific Revolution to the new-world ("Canadian") resources that funded it. Troubling, because the funds were colonial. I am unaware of anyone establishing such an instance from the 1660s–1680s. But what is established is that some astronomers and natural philosophers were also merchant venturers, which could arguably be a case of colonialism supporting the practice of astronomy.

I am unaware of any evidence that either Wren or Neile derived income from slavery. Were there any Canadians involved with astronomy in the 17th or 18th century who did? We should be prepared to face the fact of a "Canadian" Thomas Jefferson when the time arrives, as it inevitably will.[3]

A Rebellion, and the Latest Accurate Star Positions

> "On top of all the unfortunate occurrences, in comes Col. Dennis, with his party of surveyors, to divide and subdivide the land into sections as they saw fit. This, at all events, was premature on the part of the rulers at Ottawa, before any arrangements had been made with the people here, regarding the incoming government. And, although Col. Dennis acted in a gentlemanly and proper manner in the discharge of his troublesome duties, still the people looked on the act of his party going to work before the establishment of the new order of rule as arbitrary and presumptions"— Alexander Begg's letter to the editor of the *Globe*, 1869 November 10 (Bumsted 2003, 83).

John Stoughton Dennis (1820–1885), trained as a surveyor, rose to be the first Surveyor General of the Dominion Lands Branch—in effect the top practical astronomer of the Government of Canada (Read 1982a; 1982b). The eventual post of Chief Astronomer, and then Dominion Astronomer of Canada, would grow out of that of Surveyor General, well past Dennis's lifetime.

He seems to have been respected by the profession, and he produced the first of the long series of surveying manuals for the Canadian Government (Dennis 1871). In the table of contents, one of the section headings near the beginning stands out as an injunction, "Surveys to be astronomical," that is, they are to be based on techniques of astronomical observation (vii, 10).

Before he became Surveyor General, Dennis enjoyed the dubious distinction of adding to the immediate tensions igniting the Red River Rebellion, during the process of the transfer of Rupert's Land by the HBC through the Deed of Surrender to the Canadian Government. As described in the contemporary letter that starts this section, the survey he was directing ventured very quickly onto Métis lands, a people who were not a direct party to the transfer. They were less than pleased by this division of their land through foreign survey techniques, however astronomically based, for in their context, this was widely perceived to be the first step leading to their dispossession. This example of astronomy serving a colonial end led to real and dramatic political consequences, which are still not entirely resolved.

Figure 6 — The Dominion Radio Astrophysical Observatory (1960, now part of the Herzberg Astronomy and Astrophysics Research Centre), in Penticton, as it appeared in a postcard from the 1960s. The DRAO is in its turn an offspring of the DAO. Reproduced courtesy of the Specula astronomica minima.

Four decades after the appearance of Dennis's survey manual, near the end of the run of such things, the Dominion Land Surveys of the Canadian Department of the Interior published G. Blanchard Dodge's *A Catalogue of Stars for Latitude Observations on Dominion Land Surveys* (1914). Dodge remarks that the:

> "Catalogue was originally prepared from the Berliner Jahrbuch, Nautical Almanac, Star List of the American Ephemeris, Connaissance des Temps, Greenwich Second Nine-Year Catalogue, 1900, Greenwich Second Ten-Year Catalogue, 1890, and Ambronn's Sternverzeichnis, 1900…. When the Boss Catalogue arrived and was compared with our catalogue, it was found that a great many of these Ambronn stars were given in Boss, but that there were very many differences in declination. Tabulated below is a list of all the Ambronn stars in our catalogue superseded by Boss…." (9).

These tables of stellar positions for practical astronomy are based on the most accurate, and up-to-date catalogues of the time, culminating with Lewis Boss's *Preliminary Catalogue* (1910). The data of precise research astrometry is put to use for a very colonial purpose—surveying. It is impressive, and, encountered now, surprising that such a level of precision would be needed for field purposes. Nearly as surprising as if someone had said that Canada's national observatory that pioneered our foray into professional astrophysics (Figure 4), and led to the creation of the Dominion Astrophysical Observatory (Figure 5), and then in turn to the Dominion Radio Astrophysical Observatory (Figure 6), came from these roots. But the surprising thing is what indeed happened.

Canada owes the creation of its national observatory in 1905 in large measure to the needs of practical astronomy, checking and certifying surveying instruments, rating chronometers, providing the true time, conducting meridian work, longitude determination, and so on. The new building was to replace an inadequate facility engaging in many of the same tasks. The Dominion Observatory was no different in its emphasis on practical astronomy than the Observatoire de Paris (1667–1670), and the Royal Observatory, Greenwich (1675), both founded in the first instance to find the longitude to aid navigation, the most practical of astronomies in a colonial context.

And the two government scientists responsible for the design and creation of the Dominion Observatory, William Frederick King and Otto Julius Klotz, had long careers as government surveyors (Hodgson 1989, 1–23). The Dominion Observatory differs from its two foreign counterparts in that it could benefit from its foundation at the turn of the 20th century to include astrophysics from the start, due to King's foresight. And he was the one to hire J.S. Plaskett, who founded the DAO (Broughton 2018, 45–46). Yet the origins of the Dominion Observatory, which eventually gave rise to our pure astrophysical research facilities, were in serving the needs of practical astronomy in a colonial system. It's an origin we cannot change, or ignore. What we do with that knowledge is up to us. ✶

Acknowledgements

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Endnotes

1 A very good account of some of the navigational instruments and techniques used can be found in De Hilster 2018, and the astrolabes are listed and discussed in Castro et al. 2020.

2 "Entre tous les arts les plus vtiles & excellens, celuy de nauiger m'a tousiours semblé tenir le premier lieu: Car d'autant plus qu'il est hazardeux & accōpagné de mille perils & naufrages, d'autant plus aussi est-il estimé & releué par dessus tous, n'estāt aucunement conuenable à ceux qui māquent de courage & asseurance. Par cet art nous auōs la cognoissance de diuerses terres, regions, & Royaumes. Par iceluy nous attirons & apportons en nos terres toutes sortes de richesses, par iceluy l'idolatrie du Paganisme est renuersé, & le Christianisme annoncé par tous les endroits de la terre. C'est cet art qui m'a des mō bas aage attiré à l'aimer & qui m'a prouoqué à m'exposer presque toute ma vie aux ondes impetueuses de l'Oceā, & qui m'a fait nauiger & costoyer vne partie des terres de 1' Amerique & principalement de la Nouuelle France, où i'ay tousiours en desir d'y faire fleurir le Lys auec l'vnique Religion Catholique, Apostolique & Romaine;" Champlain 1922, 209-210.

3 Jefferson owned some good astronomical equipment, patronized the makers of apparatus, designed observatories, and had an interest in developments of his day, such as the publication of Messier's Catalogue—and was a slave owner; Bedini 1990, 136, 246–247, 413–415, 453–458.

John Percy's Universe

The Death of the Sun

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My first research project, in 1962–63, was to use a primitive electronic computer to calculate evolutionary models of the Sun's life, up until now, to see whether they predicted the present size and luminosity of the Sun. They did. Now, almost 60 years later, I find myself (and my students) studying variable stars that are Sun-like stars literally in their death throes.

At 4.5 billion years old, the Sun is middle-aged, but it is already on the way to its eventual fate. It is very slowly expanding, cooling, and brightening as it fuses hydrogen into helium in its core. In the next few billion years, it will gradually swell into a *red giant*, a million times its present volume, engulfing the innermost planets in the Solar System. Aldebaran and Arcturus are bright examples of red giants.

How can we predict the future of the Sun? Two powerful methods. First: because we understand the laws of physics that apply to the stars, we can use computer simulations to model their structure and evolution, as I did in 1962–63. With powerful modern computers, these simulations can now incorporate complex microphysics and macrophysics, such as convection, rotation, pulsation, and mass loss. Second: Sun-like stars have been forming and evolving and dying in our galaxy for over ten billion years, so we can now observe such stars in every phase of their life, from birth to death, and put the jigsaw puzzle together. Star clusters are especially helpful; they show us samples of stars with the same age, but different masses. Massive stars evolve much more quickly.

When the centre of the future Sun's helium core becomes hot enough (100,000,000 K!), and dense enough (a tonne per cm^3!), the helium will ignite in an explosive event called the *helium flash*. The explosion will be muffled by the dense core, so it will not be obvious to an outside observer. Over the following few thousand years, the Sun will settle into a new and smaller equilibrium, as it fuses helium into carbon in its core. Then again, it will slowly expand, cool, and brighten, and become an *asymptotic giant branch* (AGB) star, even larger than a red giant (1). By this time, it will extend almost to Earth—which by this time will, of course, be hot and lifeless.

Observational and theoretical study of AGB stars is a growth industry, especially in Europe. There is a very useful monthly *AGB Newsletter*, freely available on-line at www.astro.keele.ac.uk/AGBnews/, which contains summaries of AGB-star research papers.

Figure 1 — The Cat's Eye Nebula in Draco - a sphere of ionized gas around a 125,000K white dwarf, 200 times more luminous than the Sun. The concentric shells, bubbles, and filaments of gas within the nebula suggest multiple episodes of heavy mass loss, at intervals of thousands of years, in the stages leading up to this one. This is much like what the Sun may appear in about five billion years. Comment: if my cat's eye looked like this, I would take him to the vet. Source: HST/ESA/NASA.

If the Sun had a companion star, as many stars do, then its future evolution and death would be even more complicated. If the companion was more massive than the Sun, then it would go through its life and death before the Sun, which would undoubtedly affect our star's evolution—and our planet's. If the companion was less massive, then the opposite would be true. We see many red giants interacting with binary companions in many different ways, causing eclipses, eruptions, explosions, and other forms of variability.

As an AGB star, our Sun will undergo two forms of instability. One begins when the Sun first enters the red-giant or AGB phase: it will become unstable to radial pulsation. Initially, the pulsation period is a few days, and the amplitude is only a few percent but, as the Sun swells, the period will increase to a year or more, and the changes in brightness will increase to several magnitudes—easily visible. The Sun will become a Mira star (2). Amateur astronomers make significant contributions to astronomy by observing these pulsating red giants—mostly visually in the case of the large-amplitude Mira stars, and photoelectrically in the case of the smaller-amplitude pulsating red giants.

As the Sun fuses helium into carbon in a shell around its carbon core, and hydrogen into helium in a shell around the helium zone, the shells will slowly interact, and the Sun will undergo the second instability—a handful of *thermal pulses*, about 100,000 years apart. For a few hundred or thousand years, the Sun will become warmer and smaller, and then return to its initial state.

Building on the results of Fadeyev (2018), Molnar *et al.* (2019) have presented strong evidence that the variable star T UMi is undergoing such a rare pulse. They base this conclusion on new evolutionary models, and a century of visual observations from the American Association of Variable Star Observers (AAVSO), which show that the period of T UMi has decreased from about 313 to 198 days in the last four decades as its size shrinks. This is one specific example of how observations made by skilled amateur astronomers are contributing to astronomical research.

Large-amplitude Mira-star pulsation has serious repercussions. According to the pioneering work of Bowen (1988) and Bowen and Willson (1991), the pulsation in the outer layers of an AGB star produces shock waves, which move upward and outward, and compress the gas in the upper atmosphere of the star. As the gas cools, dust particles condense. They absorb visible and infrared radiation from the star, and are pushed outward, carrying the gas along with them. Within a million years, the outer half of the star is stripped away by *mass loss* and will eventually be visible as a *planetary nebula* (3) around a *white dwarf* (4) core. Mira itself is a bright example of an AGB star in this final stage of life. Its pulsational variability is easily visible to the unaided eye.

The final transition from AGB star to white dwarf plus planetary nebula occurs when the hydrogen-rich layer on the outside of the star is reduced, by mass loss, to about one percent of the star's mass. Miller Bertolami (2016) has recently modelled this transition in great detail. The transition is rapid—typically 10,000 years—so only a few *post-AGB stars* (or *proto-planetary nebulae*) are expected to be seen at any one time. According to these new models, the transition is 3 to 10 times faster than predicted by previous models. Furthermore, the details of the transition process, including the time scale, are very sensitive to the precise mass, structure, and composition of the dying star. It would be helpful to have some way of directly testing the models and sorting out the details.

Fortunately, there is one! Many of these stars are unstable to pulsation, with periods of a few tens of days—they are *RV Tauri stars* or *yellow semi-regular variable stars* (5); see Bono *et al.* (2020) and Fadeyev (2020) for excellent new models of these stars. It should be possible to observe their evolution directly by looking for a decrease in their pulsation period as they shrink toward the white dwarf stage (6). Note: Some RV Tauri and SRd stars are probably undergoing thermal pulses and may leave and return to the AGB phase; their periods may be decreasing or increasing. I have an undergraduate research student working on that project right now, using the century-long database of observations by the AAVSO. So, stay tuned.

This final transition results in a white-dwarf star with a surface temperature of 100,000 K or more, and a luminosity of several hundred Suns. It emits copious ultraviolet radiation, which excites the surrounding gases, causing them to glow as a planetary nebula. The delicate structure of the nebula hints at both the continuous and discrete mass-loss processes that produced it. See Figure 1 for an example: The Cat's Eye Nebula. The gases are flowing outward at 10 to 20 km/s. In 10–20,000 years, the nebula will disperse.

The Sun Lives On!

Some might define this as the death of the Sun. But consider first that, over billions of years, the approximately 10^{58} atoms ejected from the Sun, by its mass loss, will mix with the Milky Way's interstellar gas and dust. Some will become part of future stars, and planets, and perhaps even living things. Cosmic recycling at its best.

The exposed core of the Sun will live on as a white dwarf. Initially, its temperature will be 100,000 K or more. It will emit mostly ultraviolet and X-ray radiation, but it will quickly cool. It has no source of energy other than the heat that is stored within it. Its mass—about half its initial mass and radius, which is about the same as the Earth's—will remain constant. Its luminosity will decrease as the fourth power of its temperature.

Three times, as it cools, it will become unstable to complex pulsation—at temperatures of about 125,000, 25,000, and 12,000 K. These are referred to as DO, DB, and DA stars, analogous to the OBAFGKM temperature sequence of normal stars. The instabilities are caused by the thermodynamic effects of the oxygen/carbon, helium, and hydrogen in the star's outer layers. Continuous observations of such stars' variability, from the ground or from space, provide a sort of CT scan of the stars' interior structure.

For instance: GW Vir is the prototype DO variable star. From 264 hours of nearly continuous ground-based photometry by Winget *et al.* (1991), Kawaler and Bradley (1994) were able to identify 125 individual periods or modes of pulsation, from which they derived the star's temperature (136,000 K), mass (0.59 Suns), luminosity (220 Suns), rotation period (1.38 days), composition, and many other parameters.

White dwarfs are common. Sirius, the brightest star in the night sky, has a white dwarf companion—Sirius B. It was once a normal star, but now it has a density of one tonne per cm^3—equivalent to cramming a small car into a sugar cube. Sirius B was the first white dwarf discovered and, over history, it and other white dwarfs have told us much about the lives of stars, and the physical processes going on within them.

It's said that white dwarfs eventually cool and become black dwarfs. That's true—but only after infinite time. For trillions of years, our ex-Sun will continue to shine, like any other white dwarf, and qualify as one of the hundreds of billions of interesting stars in the Milky Way.✶

Endnotes

1 An asymptotic giant branch (AGB) star is a helium-fusing red giant. It is so-called because, in the famous Hertzsprung-Russell Diagram of luminosity plotted versus surface temperature, the locus of AGB stars is asymptotic to the locus of hydrogen-fusing red giants.

2 A Mira star is a pulsating red-giant star with a peak-to-peak visual amplitude of 2.5 magnitudes or more.

3 A planetary nebula is a small expanding nebula around a newly formed white dwarf. In a small telescope, it may look like a planet; otherwise it has nothing to do with planets.

4 White dwarfs are stars, with masses less than 1.44 Suns, that have exhausted their thermonuclear energy sources, and contracted to a density of order tonnes per cm^3. They are stable because the inward pull of gravity is resisted by the quantum forces between the densely packed electrons.

5 RV Tauri (RV) and yellow semi-regular (SRd) variable stars are pulsating yellow supergiant stars. RV variables tend to show alternating deep and shallow minima in brightness. SRd variables have less regular pulsation.

6 The pulsation period is approximately proportional to the radius to the power 1.5, so it increases as the star expands.

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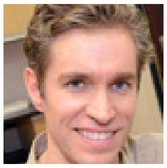
Dish on the Cosmos

In Memoriam Arecibo



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

On 2020 December 1, the Arecibo radio telescope was fatally damaged when the cables supporting the secondary feed structure broke, dropping the 820-ton structure onto the dish. The telescope had already suffered severe structural damage from Hurricane Maria in 2017 and a series of earthquakes, leading to signs of structural failure in November that forced the end of operations. After support cables broke in November, the structures were deemed unsafe and were being monitored remotely, which is why the drones were in flight and no one was injured in the monitoring of the facility. The catastrophic failure was the final chapter in the operations of this facility, which had produced excellent science since 1963. In this column, I wanted to reflect on the almost unique design of the Arecibo telescope and how it enabled a rich legacy of science.

With a diameter of 305 m, the Arecibo telescope was the world's largest telescope as measured by collecting area and was easily recognized because of its unique construction (Figure 1). The telescope was featured in movies like *Contact* (1997) and *Goldeneye* (1995), a James Bond installment. While apparently impressive, Arecibo is a fairly simple construction. The telescope is built directly into a naturally occurring bowl-shaped sinkhole. The sinkhole shape meant that the main "dish" of the telescope was constructed by simply building up relatively small supports from the floor of the valley and constructing a spherical surface of a wire mesh. The wire mesh acted as a mirror for radio waves.

While a metal mesh may not seem like much of a mirror, the only thing that such a mirror needs is to be a conductor of electricity and be smooth on a level that is smaller than the wavelength of the light. The rule of thumb in optics is that the bumps and holes on the surface should be smaller than 1/20th of the wavelength of light. Arecibo typically observed light with wavelengths longer than 10 cm, so the holes in the mesh could be 0.5 cm wide and still be a good mirror for the telescope. You can see this principle at work in a microwave oven, where the door is covered by a metal mesh. Microwave ovens typically operate by giving off radio light in the "microwave" subband, which is the same band that Arecibo observed in. Hence, the holes in the mesh on the door just need to be 0.5 cm or smaller to keep the microwave radio light inside the oven. In the case of Arecibo, these big holes meant that the reflecting surface was inexpensive, which is good because there was a lot of surface to cover. Once the big radio mirror had been constructed, it focused radio radiation at a set of points above the dish. The secondary structure was suspended by a set of cables over the dish and different instruments could be rotated into the focus position to make different observations.

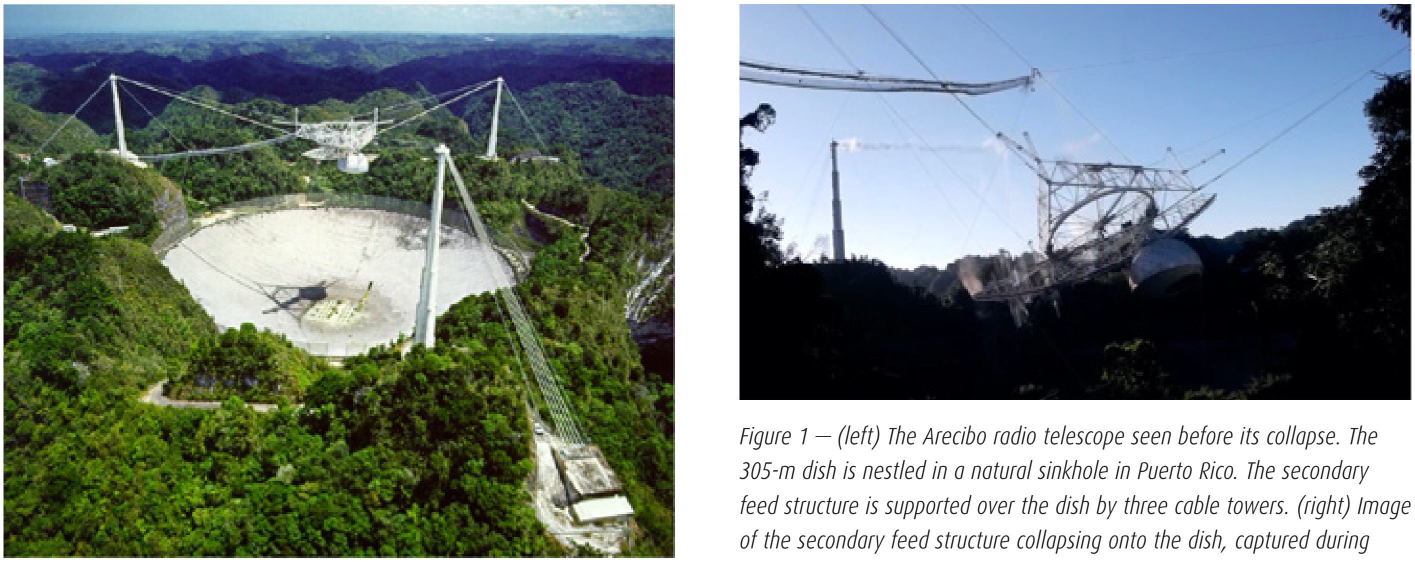


Figure 1 — (left) The Arecibo radio telescope seen before its collapse. The 305-m dish is nestled in a natural sinkhole in Puerto Rico. The secondary feed structure is supported over the dish by three cable towers. (right) Image of the secondary feed structure collapsing onto the dish, captured during the collapse of the telescope on 2020 December 1. Image Credits: Arecibo Observatory, a facility of the US National Science Foundation.

While the huge collecting area was a major strength of the facility, the big drawback of this design is that the telescope was not "steerable" so it could only see a limited part of the sky. The telescope worked best when looking directly overhead, seeing all the objects at a declination equal to the telescope's latitude at 18° N. By moving the secondary instruments around, astronomers could look at objects a small distance away from the zenith. While Arecibo couldn't observe the whole sky, it could readily observe between the celestial equator and +40° N declination, making several observations and discoveries inside that area.

In particular, roughly half the ecliptic lies inside this observable region, meaning that Arecibo could readily observe Solar System objects. But, unlike a lot of telescopes, Arecibo was more than just an observer; it was the largest radar facility on Earth. From a physics perspective, using a radio telescope to transmit a signal is essentially just running the telescope in reverse: instead of radio light coming in from space and being detected by a receiver, the radar transmitter takes a signal and broadcasts the radio waves out into space. The engineering of the systems is vastly different, but with Arecibo, you could operate the telescope as a transmitter, sending a megawatt of radio transmission hurtling across the Solar System to reflect off an object. A parallel receiver on the telescope can then detect those reflected signals as they arrive back on Earth. By measuring the timing and the structure of the reflection, the planetary radar users could make careful measurements of the distance to remote planets and asteroids as well as mapping out their shapes. Before interplanetary probes became common, radar measurements to other planets were essential for establishing the size of the Earth's orbit around the Sun. This measurement ultimately sets the distance scale for our measurements of the entire Universe.

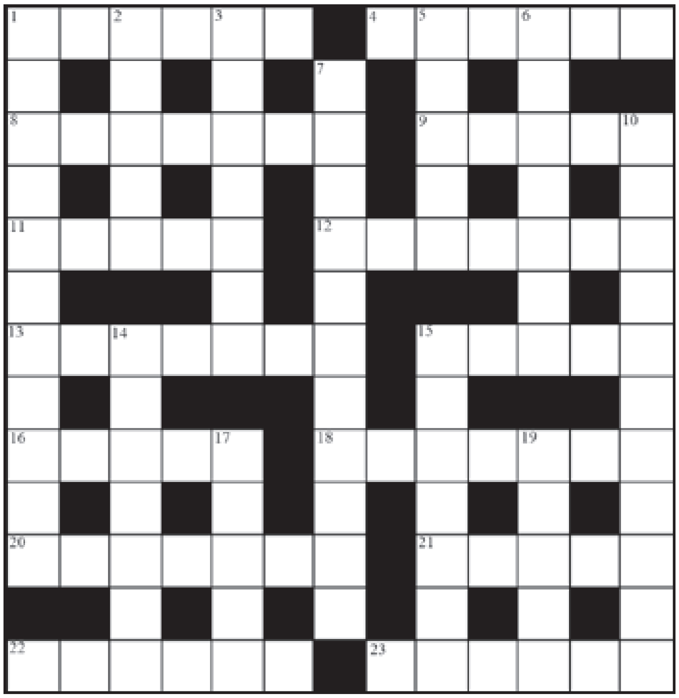
Arecibo's vast collecting area made it our most sensitive radio telescope over the region of the sky that could be observed by the facility. This sensitivity made it an essential tool for detecting the faint signals from radio pulsars in the inner part of the Milky Way Galaxy. Careful timing of pulsar signals from Arecibo have provided some of the best available constraints on our understanding of gravity through the general theory of relativity. Arecibo's sensitivity also made it an ideal tool for measuring the faint signals from hydrogen gas in our galaxy and others, revealing small, faint clouds of gas as material condenses out of the hot plasma between galaxies and is absorbed onto the outskirts of galaxies. This process is thought to slowly build up the galaxy masses over the course of time. In addition to the astronomical uses, Arecibo was also heavily used to study Earth's ionosphere, capturing radio waves from the ionosphere and directly probing this region of the atmosphere with radar.

Astronomers and the public will miss this iconic facility. The US National Science Foundation, which provided most of the support for the Arecibo telescope, has elected to prioritize other facilities with their limited funding. The next big questions that astronomers hope to answer require new and different facilities. Fortunately, this sort of science will continue at the newly commissioned 500-metre FAST telescope in China. By taking advantage of a similar geographical quirk, the FAST telescope shares a lot of the same design principles as Arecibo. The optical design can observe over a wider area of the sky than Arecibo could, but the effective collecting area of the two telescopes is similar. Astronomy requires several different tools in the broader toolkit. Interferometers like the Very Large Array provide the best resolution, but large, fixed telescopes like Arecibo and FAST are what scientists need when their discoveries rely on sensitivity. ✶

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.

Astrocryptic

by Curt Nason



ACROSS

1. A big hole in the cup (6)
4. Prison terms heard taking notes on the Society Board (6)
8. Impetus to make Ma orbit Saturn (7)
9. Places for star parties and a radio telescope, I hear (5)
11. Part of Messenger found in Germany (5)
12. Physicist with a constant interest in atomic spectra (7)
13. Moncton has N-P exchange scattered in a gamma ray observatory (7)
15. Big hill on which to put a telescope (5)
16. Earl's broken pointer is more controlled (5)
18. Star in excellent condition also known as being in the loop (7)
20. Astrophysicist with prizes around initial telescope in space (7)
21. I roam around with those who saw the big Emu (5)
22. Millet's night for observing at Yale (6)
23. Entertains a pair like Clio and Urania (6)

DOWN

1. Crush chili about eastern variable of 2021 (3,8)
2. Leaps around a lunar range (5)
3. Gone like the Pup or Comet ISON (7)
5. Stellar process for making iridium by pair instability as dawn begins (5)
6. Our first astronaut to range out to an astronomical unit (7)
7. Young Moon starers somehow become them (11)
10. Bowman with Gauss trait I reform (11)
14. Bear's nose hides identity in the fly (7)
15. Little silence for low point of Mira (7)
17. Right azimuth or tool for a Foucault test (5)
19. A most confusing array of particles (5)

Answers to previous puzzle

Across: **1** ARECIBO (anag+bo); **5** TYCHO (hid); **8** TAURI (TA+homonym); **9** CORONAL (anag); **10** LATERAL (later+Al); **11** OASIS (2 def); **13** CORIOLIS FORCE (anag); **16** SOUTH (2 def); **18** GALATEA (gala+tea); **20** EQUULEI (an(L)ag+I); **21** NUNKI (nun+KI); **22** ELARA (anag); **23** CAROLYN (2 def)

Down: **1** AUTOLYCUS (AU+to+LY+C+us); **2** EQUATOR (anag); **3** ICIER (hom); **4** OCCULTING DISC (anag); **5** TURNOFF (2 def); **6** CANES (2 def); **7** OWL (2 def); **12** STERADIAN (S+anag+N); **14** OPHELIA (anag+ail(rev)); **15** RETINAL (anag); **17** UHURA (U(Hur)A); **19** LUNAR (anag-E); **20** EYE (hom)

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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.

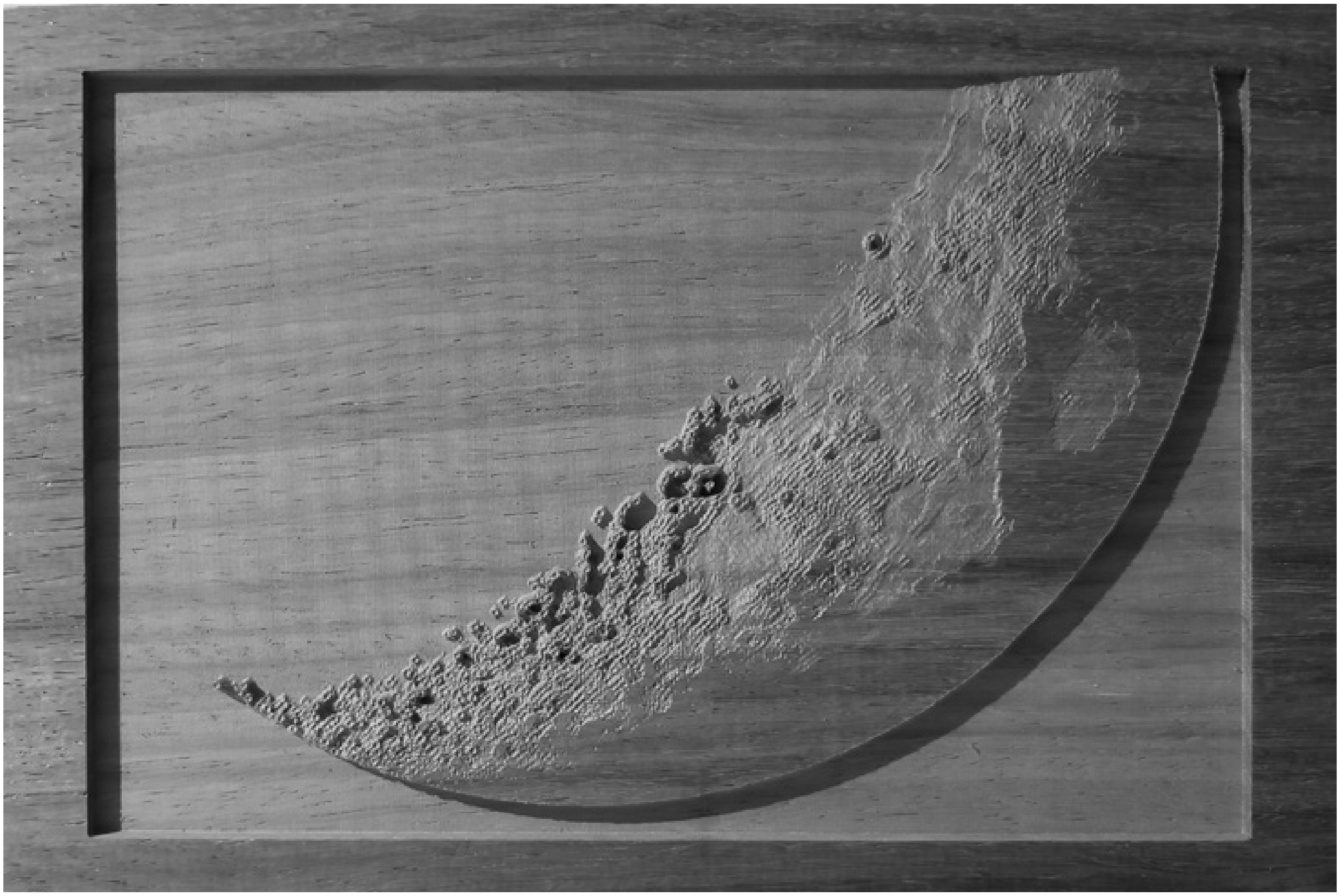
Values

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

Great Images

by James Edgar

The real caption for the inside front cover (April Fools!): James Edgar captured this Moon image at the 40-mm eyepiece of a Celestron Classic-8 telescope using a Canon 50D camera at ƒ/2, ISO 100 for 0.5 sec, through a 50-mm lens.



This carving by Journal *Production Manager, James Edgar, is made using the Moon image featured on the inside front cover. He used an Iconic CNC carving machine in his shop to reproduce the photo on a piece of African coralwood (padauk). The wood has a nice tight grain so holds a crisp edge—perfect for this type of carving. The carver interprets light as shallow and dark as deep, so some distortion occurs in the bright craters along the terminator.*

Journal

This lovely moonbow was taken on in November 2020 from Debra Ceravolo's backyard, using a Canon 6D with 14mm Sigma lens. ƒ/4, 6-second exposure at ISO 800.