

2019 CFHT Annual Report



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Front and back covers: On the front is an iconic image of Messier 92 recorded with MegaCam. This cluster includes roughly a quarter million stars that orbit our Milky Way Galaxy. On the back cover is the full moon rising over Kahinahina on Maunakea through volcanic haze during the Kilauea eruptions. Photo provided by Don Mitchell, lead author of the [EnVision Maunakea](#) report. Don is a lifelong resident of Hilo and has captured numerous spectacular images from the slopes of Maunakea.

Director's Message

CFHT celebrated its 40th anniversary in 2019 – a year that also marked some of the greatest challenges the Maunakea Observatories have faced in their collective histories. It was a year of contrasts at CFHT, with reasons for celebration and concern juxtaposed in an unfamiliar alignment.

While I was engaged throughout the year in complex challenges, perhaps the pinnacle of those contrasts for me occurred July 17, 2019 – the day TMT attempted to send construction equipment to the summit of Maunakea and arrests were made at the base of Maunakea Access Road. The day before, the Maunakea Observatories executed an unanticipated evacuation of the summit out of concern for staff safety, leaving a billion dollar research complex eerily idle and cut-off. As fate would have it, months before I was scheduled on that same day in July to support a program involving a couple dozen Hawaiian immersion schoolteachers as part of the [A Hua He Inoa](#) program at 'Imiloa Astronomy Center. The task for the teachers was to name two important astronomical objects that had been discovered recently from Maunakea – a quasar and dwarf planet in our solar system. Dr. Larry Kimura and I also provided our joint presentation about the Physics of Pō – an exploration of the prelude to the Kumulipo, the ~2000 line Hawaiian creation chant that describes the formation of the universe and includes an extensive



Figure 1 – A montage of images capturing some events during 2019 including (upper left) a flier for CFHT’s community birthday party, (upper right) the protest site at the base of Maunakea Access Road, (lower left) a 1979 newspaper article about CFHT’s dedication 40 years ago, and (bottom right) one of many interviews during extensive media coverage of the Maunakea Observatories’ efforts to regain access to the summit.

description of the evolution of life forms on earth, through the establishment of the first humans. The Kumulipo has been translated several times but Dr. Kimura’s unpublished translation of this chant’s prelude provides remarkable insights into ancient perspectives, some of which appear both counterintuitive and prescient. This surreal juxtaposition of working with and learning from a classroom filled with Hawaiian teachers in Hilo while protests were erupting on Maunakea was a poignant reminder of the many complex facets of what was becoming a social movement in Hawai’i, and how our community is sometimes highly fractured. The words that frequented my mind that day in July were simple – “this is where I belong – this is where I can do the most good”. It would take another ~6 months before Maunakea Access Road was opened to the public, law enforcement withdrew, and the natural serenity of Pu’u Huluhulu (the site of the encampment) slowly returned.

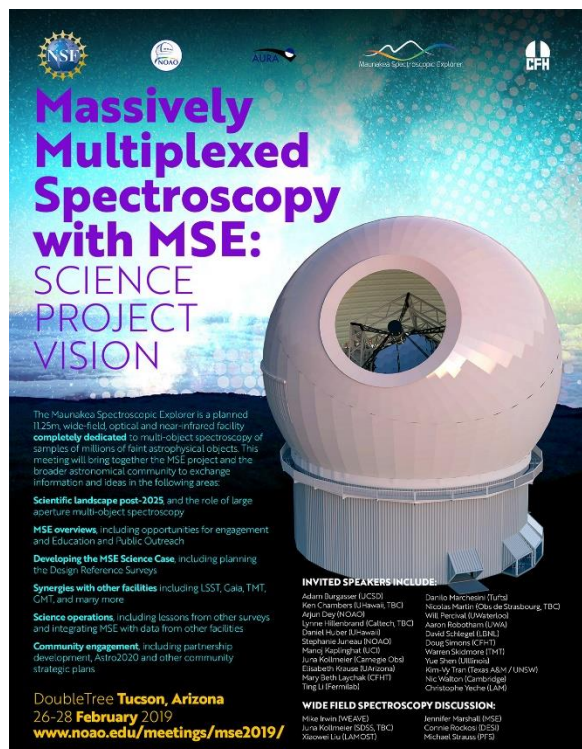


Figure 2 – MSE held an excellent conference in Tucson during early 2019. Above is the conference flier, below is a photo of conference participants.



Figure 3 – A group photo of the 100+ participants in CFHT’s 12th Triennial Users Meeting in Montreal.

The year 2019 featured many memorable events stemming from CFHT’s 40th anniversary since the dedication of the telescope in 1979. These included a wonderful CFHT Users Meeting in Montreal featuring well over a hundred participants and a special 80th birthday celebration for René Racine during the conference dinner. René made countless contributions to CFHT in its early days, when he served as Director and helped establish CFHT (and its site) as the premier 4 m telescope in the world soon after first light. We also had an exciting MSE conference in Tucson, hosted by NOAO, in which the science applications for this planned successor to CFHT were explored in depth. Smaller but still important events included numerous outreach events across Hawai’i Island commemorating CFHT’s 40th anniversary, culminating with a community party on the front lawn complete with live music, a dunk tank, face painting, and hundreds of hamburgers and hotdogs for our Waimea community to enjoy.

In this year of contrasts Maunakea astronomy forever changed. It will take time and patience to fully understand the nature of that change as we continue to focus on the future, cognizant of the past, trusting our compass as we bridge between both.

Science Report

Hawai'i Team Catches Asteroid As It Self-Destructs

Asteroid Gault, discovered in 1998, has begun to slowly disintegrate. The crumbling was first detected on Jan. 5, 2019 by the University of Hawai'i Institute for Astronomy (IfA) Asteroid Terrestrial-Impact Last Alert System (ATLAS) telescopes on Maunaloa and Haleakalā. "Each night, the ATLAS survey scans the sky looking for hazardous near-Earth asteroids, and we also observe tens of thousands of known asteroids in the main asteroid belt," said Larry Denneau, ATLAS Project Scientist. "Our collaborator Ken Smith in Belfast found an unusual looking moving object, and he alerted us that it might be a new comet. Instead, it turned out to be an asteroid in the main belt that just developed a comet-like tail. These events are rare and mysterious, and we were lucky to detect the event right after its turn-on."

Gault is a well-known asteroid, and the newly found tails are the first evidence of any misbehavior. These new observations suggest that asteroids are dynamic, active worlds that can ultimately disintegrate due to the long-term subtle effect of sunlight, which can slowly spin them up until they begin to shed material.

Astronomers estimate that this type of event is rare, occurring roughly once a year among the 800,000 known asteroids between Mars and Jupiter. That's why only the latest astronomical surveys — like ATLAS — that map vast swaths of the sky nightly, can catch asteroids as they fall apart.

"Asteroids such as Gault cannot escape detection anymore," noted Olivier Hainaut of the European Southern Observatory in Garching, Germany, a member of the observing team. "That means that all these asteroids that start misbehaving get caught."

Once the new tail was discovered, Denneau and IfA colleague Robert Weryk looked back into archival data from ATLAS and the University of Hawai'i (Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) telescopes. The tail also turned up in data taken as far back as December 2018. In mid January, a second shorter tail was spied by Jan Kleyna using the Canada-France-Hawaii Telescope as well as other observers. An analysis of both tails suggests the two dust releases occurred around Oct. 28 and Dec. 30, 2018.

Tantalized by this new discovery, IfA astronomers Jan Kleyna and Karen Meech, along with several colleagues, began to observe Gault with telescopes around the world and in space. Spectacular images of asteroid 6478 Gault from NASA's Hubble Space Telescope show two narrow, comet-like tails of debris



Figure 4 – Top: Hubble Space Telescope captured this striking image of asteroid (6478) Gault, showing two narrow, comet-like tails of dusty debris. Each tail represents an episode in which the asteroid gently shed its material — key evidence that Gault is beginning to come apart. Credit: NASA, ESA, K. Meech and J. Kleyna (University of Hawai'i), and O. Hainaut (European Southern Observatory). Bottom: Asteroid Gault as observed with the Canada-France-Hawaii Telescope on Jan. 15, 2019. Credit: Jan Kleyna (University of Hawai'i), CFHT.

streaming from the diminutive 2.5-mile-wide asteroid. The tails are telltale evidence that Gault is beginning to come apart by gently puffing off material in two separate episodes over the past several months.

Gault is only the second asteroid detected whose disintegration is decisively linked to a spin-up process, known as a YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) torque. When sunlight heats an asteroid, infrared radiation escaping from its warmed surface carries off momentum as well as heat. This creates a tiny force which can cause the asteroid to spin faster and faster. If this centrifugal force overcomes gravity, the surface becomes unstable, and landslides send dust and rubble drifting into space.

Watching an asteroid come unglued by this natural process gives astronomers the opportunity to study the makeup of these space rocks without sending a spacecraft to sample them. Analyzing an asteroid's ingredients as they are spread out into space offers a glimpse into planet formation in the early solar system.

"We didn't have to visit Gault," explained Hainaut. "We just had to look at the image of the streamers, and we can see all of the dust grains sorted neatly by size. All the large grains (about the size of sand particles) are close to the object and the smallest grains (about the size of flour) are the farthest away, because they are being pushed fastest by pressure from sunlight."

For astronomers, piecing together Gault's recent volatile activity is an astronomical forensics investigation, involving telescopes and astronomers from around the world. The first clue was the accidental detection of the first debris tail. Follow-up observations with the William Herschel Telescope and ESA Optical Ground Station in La Palma and Tenerife, and the Himalayan Chandra Telescope in India, measured a two-hour rotation period for the object, close to the critical speed at which a loose "rubble-pile" asteroid begins to break up. "Gault is the best 'smoking-gun' example of a fast rotator right at the two-hour limit," Kleyna said.

But the seeds to this self-destruction may have been sown 100 million years ago, a time when the dinosaurs roamed Earth. Pressure from sunlight slowly began spinning up the tiny asteroid at an estimated rate of 1 second every 10,000 years. "It could have been on the brink of instability for 10 million years," Kleyna said. "Even a tiny disturbance, like a small impact from a pebble, might have triggered the recent outbursts."

The researchers suggest that as the asteroid rotated ever faster, destabilized material began cascading toward the equator. When the rotation rate reached a critical point, landslides sent debris drifting off into space at a few miles per hour, or the speed of a strolling human. Gault's weak surface gravity couldn't hold it any longer. The gentle process was like scattering powdered sugar into the air, where wind — or, in the case of Gault, sunlight — stretches it into a long streamer. An analysis of the asteroid's immediate neighborhood by Hubble revealed no signs of excess dust, which rules out the possibility of a collision with another asteroid causing the outbursts.

Hubble's sharp imaging also reveals that the tails are narrow streamers, indicating that the dust was released in short bursts, lasting anywhere from a few hours to a few days. These sudden events puffed away enough debris to make a "dirt ball" approximately 500 feet across if compacted together. The tails will begin fading away in a few months as the dust disperses into interplanetary space. Based on CFHT observations the astronomers estimated that the longer tail stretches over half a million miles and is roughly 3000 miles wide. The shorter tail is about a quarter as long.

Added Kleyna: "If the dust cloud lasts a couple of months, and the surveys see things once a month, we will see them. But if traditional observers are looking every couple of years, they'll miss these events." The team said that this discovery shows the synergy between all-sky surveys such as ATLAS and Pan-STARRS, ground based telescopes, and space-based facilities like the Hubble Space Telescope. This discovery would have been impossible without contributions from all three. The researchers hope to monitor Gault for more dust events. Their results have been published in *Astrophysical Journal Letters*.

[Link](#) to paper.

VESTIGE Traces Ionized Gases of M87

The VESTIGE team, lead by Alessandro Boselli, from the Laboratoire d'Astrophysique de Marseille, using MegaCam at the Canada-France-Hawaii Telescope has recently released an extremely deep image in the narrow-band H α filter of the elliptical galaxy M87. Located at the heart of the Virgo Cluster, M87 is one of the most studied galaxies in the Universe. The image, used on the cover of the March 2019 issue of *Astronomy & Astrophysics* journal, reveals the presence of spectacular filaments of ionized gas extending several kilo parsecs from the galaxy. These filaments illustrate an ongoing interaction between M87 and the surrounding environment.

M87 is the dominant elliptical galaxy in the Virgo cluster, the closest and richest cluster of galaxies located 50 million light-years from Earth. The galaxy is located in the heart of the cluster potential well and is surrounded by hot gas emitting X-rays. M87 hosts the powerful radio source Virgo A, whose presence can be detected by an extended radio jet visible at multiple wavelengths across the electromagnetic spectrum. The radio jet interacts with the surrounding diffuse hot gas, producing giant bubbles that disturb the superheated plasma or intracluster medium lying between the galaxies of the Virgo Cluster.

"The very nature of these radio monsters, typical in the core of massive clusters, is still quite unclear", says Alessandro Boselli, the VESTIGE principal investigator and lead author on the A&A paper. "They play a crucial role in galaxy evolution within high-density regions."

VESTIGE or Virgo Environmental Survey Tracing Ionized Gas Emission, one of the large surveys currently being observed using CFHT, focuses on the Virgo Cluster in part to learn more about the role of radio monsters.

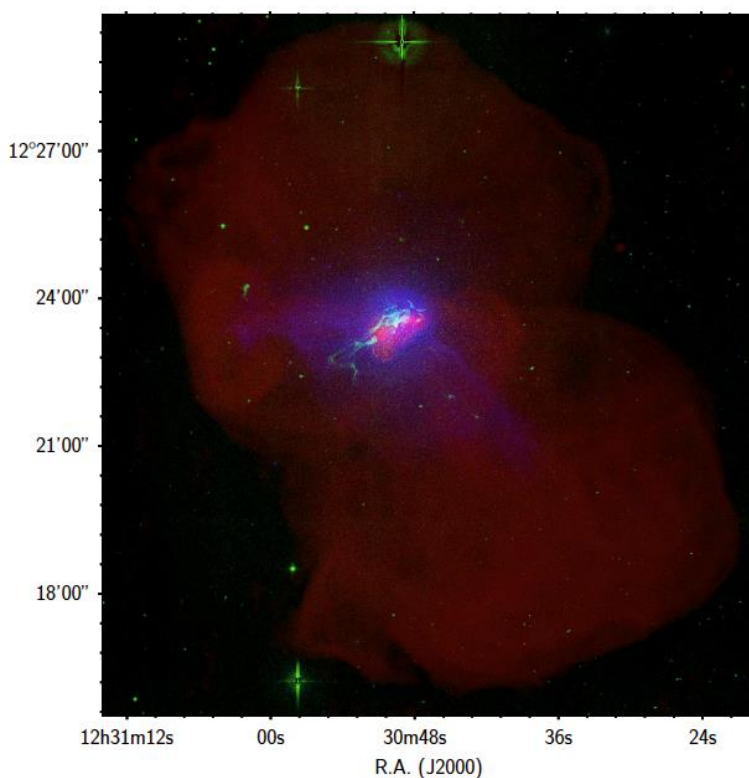


Figure 5 – The pseudo-colour image of M87 obtained by combining Chandra 1.0-3.5 keV (blue), VESTIGE H α + [NII] (green), and the VLA radio continuum at 90 cm (red) frames of the galaxy. Image credit: VESTIGE team.

With fifty nights of telescope time at CFHT over the course of two years, VESTIGE aims to understand the role of environment on galaxy evolution. As a follow-up of the Next Generation Virgo Survey (NGVS) which covered the area through broad filters (ugiz) with MegaCam, the VESTIGE team uses a narrow band H α filter with MegaCam to conduct a deep imaging survey of the same area. These extremely deep images revealed the presence of spectacular filaments and plumes of ionized gas crossing the galaxy from the south-east to the north-west. Follow up spectroscopy taken with MUSE at the VLT (ESO) suggests that the gas is shock ionized. The geometry of the gas filament and its position in relation to the radio jet and the hot gas previously observed in X-rays suggest that the gas is ionized by the expanding bubbles. Local instabilities in the intra-cluster medium cause the gas to cool along magnetically supported filaments into the central elliptical. These filaments may also be the remnant of the cold gas disc of a star-forming galaxy recently accreted by M87 through galactic cannibalism. As the gas falls into the galaxy, it may feed the black hole in the center of M87 and thus be at the origin of the strong radio activity of this intriguing object.

The exceptional sensitivity and angular resolution of MegaCam coupled with narrow-band filters allows the VESTIGE team to detect extended low-surface brightness ionized gas associated with the environments of galaxies. “The observing technique used by the VESTIGE team is crucial for the study of the role of the environment on galaxy evolution,” says Todd Burdullis, QSO operations specialist at CFHT. “The VESTIGE team’s research using MegaCam is really probing one of the main questions in extragalactic astronomy.”

[Link](#) to paper.

Omega Centauri’s Lost Stars

A team of researchers from the Strasbourg Astronomical Observatory, Bologna Observatory and the University of Stockholm has identified a stream of stars that was torn off the globular cluster Omega Centauri. Searching through the 1.7 billion stars observed by the ESA Gaia mission, they have identified 309 stars that suggest that this globular cluster may actually be the remnant of a dwarf galaxy that is being torn apart by the gravitational forces of our Galaxy.

In 1677, Edmond Halley gave the name “Omega Centauri” (ω Cen) to what he thought was a star in the Centaurus constellation. Later in 1830 John Herschel realized that it was in fact a globular cluster that could be resolved into individual stars. We now know that Omega Centauri is the most massive globular cluster in the Milky Way: it is about 18,000 light years from us and contains several million stars that are about 12 billion years old. The nature of this object has been the subject of much debate: is it really a globular cluster, or could it be the heart of a dwarf galaxy whose periphery has been dispersed by the Milky Way?

This latter hypothesis is based on the fact that ω Cen contains several stellar populations, with a large range of metallicities (i.e., heavy element content) that betray a formation over an extended period of time. An additional argument in favor of this hypothesis would be to find debris from the cluster scattered along its orbit in the Milky Way. Indeed, when a dwarf galaxy interacts with a massive galaxy like our own, stars are torn off by gravitational tidal forces, and these stars remain visible for a time as stellar streams, before becoming dispersed in the vast volumes of interstellar space surrounding the massive galaxy.

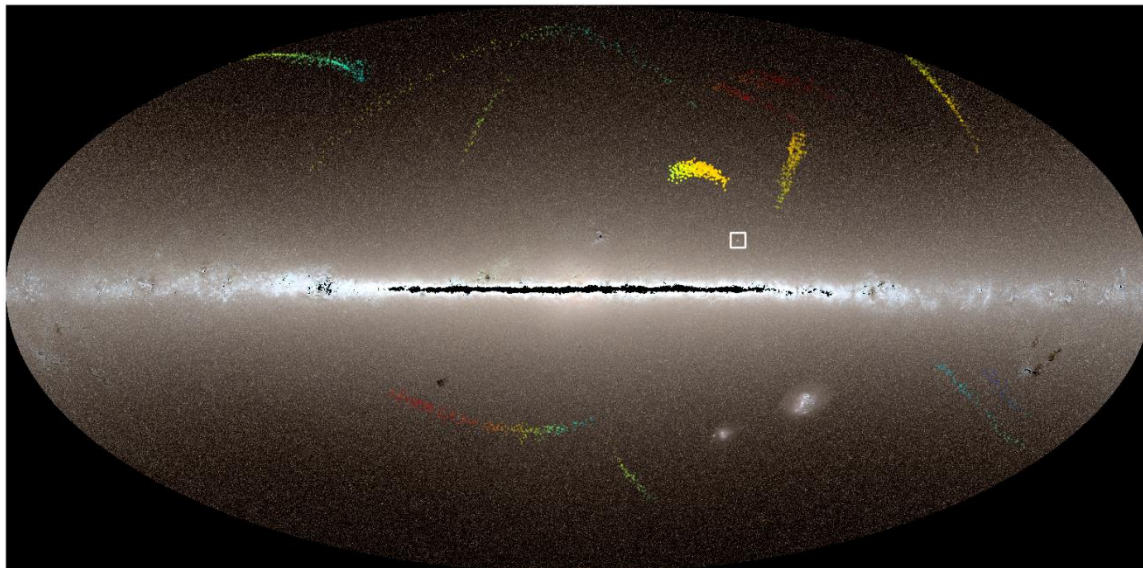


Figure 6 - The Milky Way, as seen by the Gaia satellite. Streams of co-moving stars are shown colored according to their motions as measured by Gaia. The “Fimbulthul” stream which is due to stars lost from the Omega Centauri globular cluster (white box) has been highlighted. Credit R. Ibata.

By analyzing the motions of stars measured by the Gaia satellite with an algorithm called STREAMFINDER developed by the team, the researchers identified several star streams. One of them, named “Fimbulthul” (after one of the rivers in Norse mythology that existed at the beginning of the world), contains 309 stars stretching over 18° in the sky.

By modeling the trajectories of the stars, the team showed that the Fimbulthul structure is a stellar tidal stream torn off ω Cen, extending up to 28° from the cluster. Spectroscopic observations of 5 stars of this stream with the Canada-France-Hawaii Telescope show that their velocities are very similar, and that they have metallicities comparable to the stars of ω Cen itself, which reinforces the idea that the tidal stream is linked to ω Cen.

“The stars that the team observed were quite faint for the instrument we were using,” says Dr. Nadine Manset, instrument scientist for ESPaDOnS and CFHT’s astronomy group manager. “It is great to see such challenging observations reinforce the Fimbulthul structure’s link to ω Cen.”

The researchers were then able to show that the stream is also present in the very crowded area of sky in the immediate vicinity of the cluster. Further modeling of the tidal stream will constrain the dynamical history of the dwarf galaxy that was the progenitor of ω Cen, and allow us to find even more stars lost by this system into the halo of the Milky Way. [Link](#) to paper.

A Search for Distant Collisional Remnants

The distant Solar System contains a large reservoir of objects beyond the orbit of Neptune, which are the icy remnants of planetary formation. These small icy bodies are challenging to discover, but their orbital properties and surface composition provide critical information about the formation and evolution of the Solar System. The Outer Solar System Origins Survey (OSSOS) and its companion surveys (CFEPS, HiLat, Alexandersen) covered 1,209 square degrees and discovered more than 1,000 trans-Neptunian objects (TNOs). The main surveys were conducted using the Canada-France-Hawaii Telescope on Maunakea.

Hidden among this large number of discoveries are three objects which may belong to the Haumea family. Named after the dwarf planet of the same name, the Haumea family of objects is thought to have formed as the result of a collision several billion years ago. Called a collisional family by astronomers, the family members are identified by their similar orbital elements and surfaces which display water-ice. The namesake object, Haumea, was named after the Hawaiian goddess of childbirth, paying homage to Maunakea where Haumea's moons were discovered.

While the asteroid belt contains more than 100 collisional families, only one family has been identified in the Kuiper belt. The Kuiper Belt is a region of our Solar System located 30-50 times more distant than the Earth from the sun. Understanding the collision which created the Haumea family provides critical information about the types of collisions which have occurred in the Kuiper belt, and potential insight into how to best search for additional families of objects past Neptune.

A recent paper in Nature Astronomy written by Rosemary Pike from ASIAA and the OSSOS team shows surprising results for the Haumea family. The OSSOS team discovered three potential Haumea family members significantly brighter than the survey limits.

"Based on our discovery of these three large objects, we expected to find 10-30 smaller Haumea family TNOs" said Rosemary Pike, lead author of the Nature Astronomy paper. "We didn't find the smaller objects which gives us important clues about the formation of the Haumea family".

Pike and the team carefully tested the survey sensitivity and models of the orbital distribution of the Haumea family, and determined conclusively that the Haumea family has significantly less small objects than the other TNO populations. They describe this result as a shallow size distribution in their model. The OSSOS survey has well understood discovery bias, so the team conducted the first statistically rigorous testing of the Haumea family size distribution, which provides the first robust constraints on how many small and large Haumea family members exist in the Kuiper belt.

Pike and the OSSOS team determined that the shallow size distribution of the Haumea family members is different from the size distribution of all other TNOs, important implications for the formation of this family. A shallow size distribution like the one seen with the Haumea

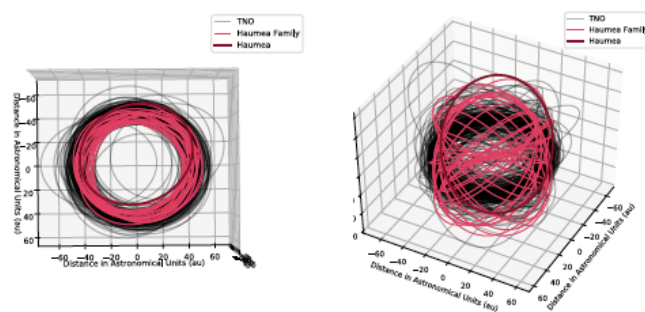


Figure 7 – Top: The summit of Maunakea includes many telescopes, including the Canada-France-Hawaii Telescope (CFHT, center, white) and Gemini Observatory (closest, silver). These distant icy objects were discovered in the Outer Solar System Origins Survey (OSSOS) on CFHT. Half of the OSSOS survey fields are visible in the photo, and they are marked with white rectangles. Bottom: Haumea and its family members (red/pink) have orbits that are different from the majority of classical TNOs (gray). The Haumea family members have higher inclinations, so their orbits extend further from the ecliptic plane where the classical TNOs cluster.

family is produced by graze and merge simulations, where the impacting object grazed the proto-Haumea, slowed, and returned to collide again and merge with Haumea. The newly merged objects rotate quickly and shed material forming the other family members. However, the orbital distribution expected by a graze and merge collision does not match the known orbital distribution of Haumea family members. Rather the Haumea family has an isotropic orbital distribution. An isotropic orbital distribution results from a catastrophic collision, where the impactor is immediately destroyed. Catastrophic collisions produce a steep size distribution conflicting with the team's results. This conflict inspires future work on the Haumea family, which will focus on understanding possible formation scenarios which reproduce both the observed orbital and size distributions.

"The OSSOS team's long history of observations with MegaCam here at CFHT and coordinated observations with Gemini Observatory means they really understand how their discovery of these three objects reflects the number of Haumea members in the Kuiper Belt," says Todd Burdullis, QSO operations specialist at CFHT. "Their discovery about the formation of the Haumea family adds to the long string of great discoveries about the outer Solar System from CFHT". [Link](#) to paper.

First Detailed Kinematic Model of 'Oumuamua Sheds Light on its Nature

'Oumuamua is the first interstellar minor body (out of only two; the second one is the recently discovered 2I/Borisov comet) to pass through the Solar System. It was detected by Pan-STARRS1 on 19 October 2017 as an extremely faint unresolved dot moving very fast across the plane of the sky. Soon many large telescopes, including CFHT, were tracking this object. From the very beginning researchers were puzzled by its strange and unique properties. To start with, the expectation (based on current theories of how planets form) was that the first interstellar visitor would be a classical comet - an icy body quickly developing a large and bright coma and tail due to outgassing (evaporation of the surface ices driven by solar radiation). Instead, the object remained point-like and unresolved, as if it were a rocky asteroid. The second puzzle was the extreme brightness variations (by more than a factor of ten - more than any known minor body in our Solar System) of 'Oumuamua. The popular explanation is that 'Oumuamua is a strongly elongated cigar-shaped object spinning about its smaller axis, though a thin disk (pancake) rotating about its larger axis would produce the same effect. The latest puzzle was the discovery of non-gravitational acceleration exhibited by this object - the effect which is normally associated with strong outgassing in comets - combined with the fact that 'Oumuamua never showed any signs of outgassing. This conundrum led some researchers to speculate that 'Oumuamua is a solar sail from an advanced civilization, experiencing non-gravitational acceleration due to solar radiation pressure.

A recent paper in Monthly Notices of the Royal Astronomical Society written by Sergey Mashchenko from McMaster University, Hamilton, Canada, shed some more light on the nature of 'Oumuamua. The researcher wrote a GPU-accelerated code which was used to generate hundreds of millions of physical models of the asteroid. By comparing the simulated light curves from the models with the observed light curve of 'Oumuamua two important conclusions were made.

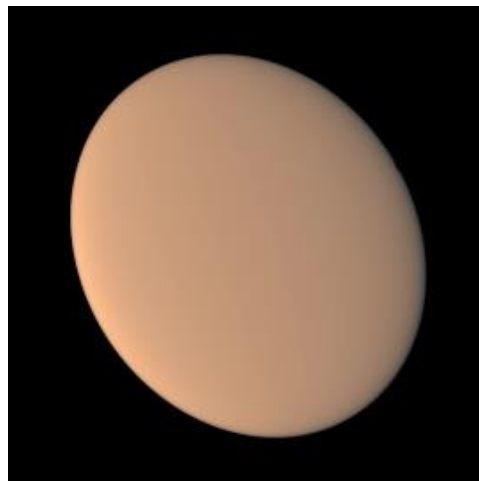


Figure 8 – Visualization of the disk model for 'Oumuamua. To view the 45 second video of the team's simulation, click [here](#). Image credit: Mashchenko.

First, it was discovered that to reproduce the specific timings of the most conspicuous features of the observed light curve - deep brightness minima - some torque (non-gravitational spin-up or spin-down) was required. This seems to have given more credibility to the idea that 'Oumuamua is a comet, as there are a few Solar System comets which exhibit both non-gravitational acceleration and non-gravitational torque (both driven by the same mechanism - strong outgassing from the surface). On the other hand, the lack of any outgassing detections from 'Oumuamua remains unexplained. One possible way out of this dilemma is to assume that the object is a solar sail with some parts brighter (more reflective) than others. Solar radiation would push the object as a whole, reproducing the observed non-gravitational acceleration, while the variable reflectivity would result in some spin-up or spin-down (torque) of the sail.

Second, it was shown that the proposed cigar shape is very unlikely, as it would require an extreme fine tuning of the object's orientation. Specifically, the observer would only see large brightness variations if the cigar was repeatedly pointing at the Earth with a high accuracy. The disk (pancake) shape has no such issue, and is hence much more likely. Mashchenko showed that the disk can be potentially as thin as the solar sail requirement (less than 1 mm), though the best quality fit was obtained for a disk with 6:1 aspect ratio. Assuming a 10% albedo, this would correspond to the physical size of 115x111x19 m.

"Our model implies that 'Oumuamua is a pancake shaped comet that experienced some outgassing as it passed through the inner Solar System" said Sergey Mashchenko, author of the paper. "Too bad the comet is no longer observable, so I am afraid the lack of any signs of outgassing will remain an unsolved puzzle." [Link](#) to paper.

Cannibalistic Andromeda – The Violent History of a Neighboring Galaxy

Astronomers have pieced together the cannibalistic past of the neighboring large galaxy Andromeda, which has set its sights on our Milky Way as the main course. The galactic detective work found that Andromeda has eaten several smaller galaxies, likely within the last few billion years, with left-overs found in large streams of stars. Australian National University (ANU) researcher Dr. Dougal Mackey, who co-led the study with Professor Geraint Lewis from the University of Sydney, said the international research team also found very faint traces of more small galaxies that Andromeda gobbled up even earlier, perhaps as far back as during its first phases of formation about 10 billion years ago.

"The Milky Way is on a collision course with Andromeda in about four billion years, so knowing what kind of a monster our galaxy is up against is useful in finding out its ultimate fate," said Dr. Mackey from the ANU Research School of Astronomy and Astrophysics. "Andromeda has a much bigger and more complex stellar halo than the Milky Way, which indicates that it has cannibalized many more galaxies, possibly larger ones." The signs of ancient feasting are written in the stars orbiting Andromeda, with the team studying dense groups of stars, known as globular clusters, to reveal the ancient mealtimes. "By tracing the faint remains of these smaller galaxies with embedded star clusters, we've been able to recreate the way Andromeda drew them in and ultimately enveloped them at the different times," Dr. Mackey said.

The discovery presents several new mysteries, with the two bouts of galactic feeding coming from completely different directions. "This is very weird and suggests that the extragalactic meals are fed from what's known as the 'cosmic web' of matter that threads the universe," said Professor Lewis from the Sydney Institute for Astronomy and University of Sydney School of Physics. "More surprising is the discovery that the direction of the ancient feeding is the same as the bizarre 'plane of satellites', an unexpected alignment of dwarf galaxies orbiting Andromeda." Dr. Mackey and Professor Lewis were part of a team that previously discovered such planes were fragile and rapidly destroyed by Andromeda's

gravity within a few billion years. “This deepens the mystery as the plane must be young, but it appears to be aligned with ancient feeding of dwarf galaxies. Maybe this is because of the cosmic web, but really, this is only speculation,” Professor Lewis said. “We’re going to have to think quite hard to unravel what this is telling us,” he said.

Dr. Mackey said studying Andromeda also informed understanding about the way our galaxy has grown and evolved over many billions of years. “One of our main motivations in studying astronomy is to understand our place in the Universe. A way of learning about our galaxy is to study others that are similar to it, and try to understand how these systems formed and evolved. Sometimes this can actually be easier than looking at the Milky Way, because we live inside it and that can make certain types of observations quite difficult.”

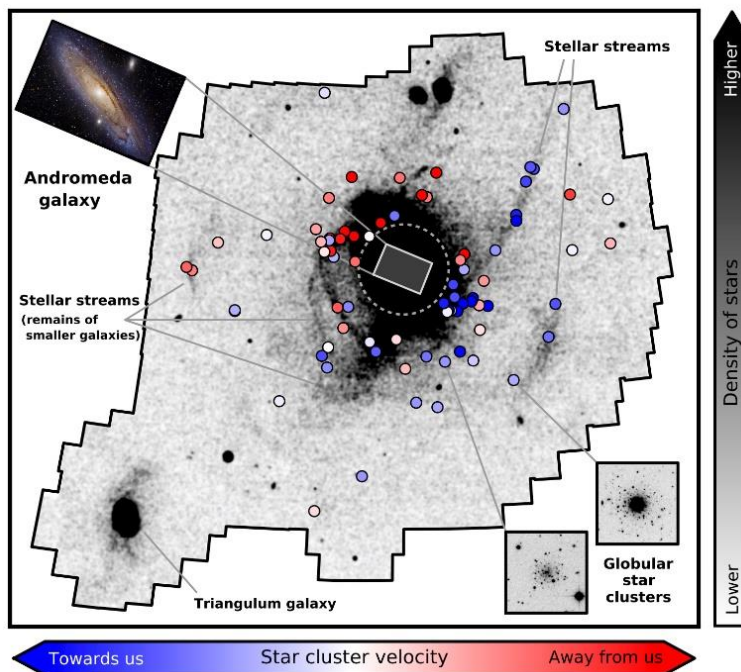


Figure 9 - PAndAS map showing the stellar halo of Andromeda, traced using red giant stars. A wide variety of stellar streams and over-densities are apparent, representing the shredded remains of cannibalized galaxies. Over plotted are the positions of 77 globular clusters, discovered in PAndAS, and observed spectroscopically for the present paper. Clusters with motions towards us are colored blue, and away from us are colored red. Credit: Mackey and PAndAS team.

The study, published in *Nature*, analyzed data from the Pan-Andromeda Archaeological Survey, known as PAndAS. Canada-France-Hawaii Telescope (CFHT) supported the PAndAS program from 2008-2010 as part of CFHT's large program observations. PAndAS used CFHT's wide field optical imager MegaCam for 226 hours spread over a two year period. The goal of the program was to provide the deepest and most complete panorama of galactic halos for the Milky Way's nearest neighbors, M33, the Triangulum galaxy, and M31, the Andromeda galaxy. The PAndAS team intended to create the primary reference dataset for all subsequent studies of the stellar populations of M31 and M33. "CFHT and the PAndAS team spent considerable time crafting the observing strategy for the program with the hope that the survey would lead to discoveries like those made by Dr. Mackey's team" said Todd Burdullis, QSO operations specialist at CFHT. "We are incredibly proud of the dataset and its continuing impact on astronomy's understanding of the histories of our nearest neighbors."

“We are cosmic archaeologists, except we are digging through the fossils of long-dead galaxies rather than human history,” said Professor Lewis, who is a leading member of the survey. The team involved institutions from Australia, New Zealand, the United Kingdom, Netherlands, Canada, France and Germany.

[Link to paper.](#)

Engineering Report

SITELLE Image Quality

In the 2018 Annual Report the results of re-aligning SITELLE with respect to the telescope were shown. The next step to improve image quality was to flatten the field with the help of two field-flattening lenses that replaced the flat cryostat windows on SITELLE's two cameras. Laurent Drissen at Université Laval funded this upgrade, which improved delivered image quality markedly. The image quality of SITELLE is now meeting specification over the entire field in both cameras.

In more detail, the SITELLE corrector lenses received in the spring were installed in the cryostats in June. The on-sky engineering test on September 12 showed that the corrector was operating as designed, though the poor transparency and variable seeing conditions during those first tests meant that the on-axis IQ was slightly degraded from our pre-repair comparison images. Regardless, it was observed that the IQ at the edge of the field was significantly improved. Furthermore, the IQ obtained during the engineering run was sufficiently good to allow the tilt of the CCDs to be removed. The piston between the CCD cameras was identified later and removed and then tested using an artificial star, off-sky.



Figure 10 - Field flattening lens being installed as a replacement for the cryostat window in the clean room.

A through-focus sequence in the C3 filter (511 – 556 nm band pass) was taken during the late September 2019 science campaign, in good seeing conditions for a crowded stellar field. The improvement to the IQ is clearly seen when comparing the encircled energy diameter (EED) maps in Figure 11. In what follows, any quantities quoted correspond to port 1 although the difference between the EED maps for the two ports is now much smaller.

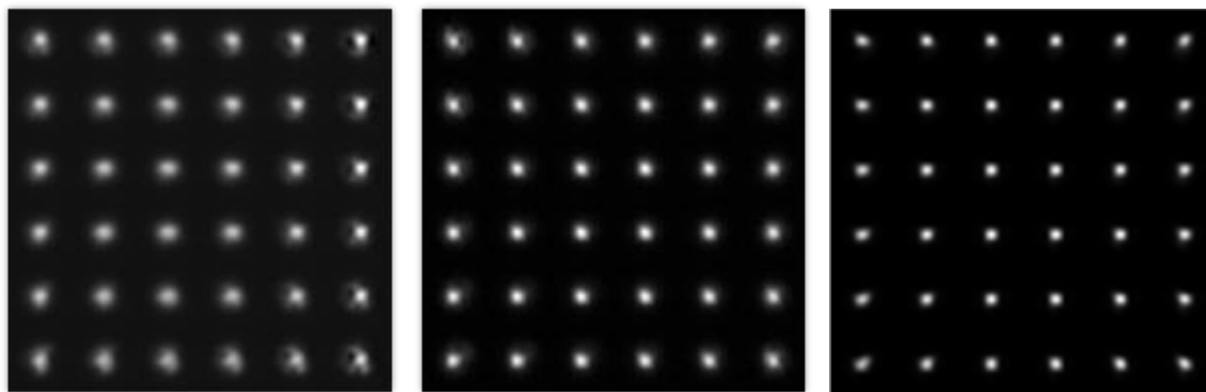


Figure 11 - Left: Average PSF before realignment and corrector installation in the SN3 (red - H α) filter. Middle: Average PSF after realignment and before corrector installation in the SN3 (red - H α) Right: Right Average PSF after realignment and corrector installation in the C3 (green) filter. Image scale units are pixels (i.e. not corrected for the before/after platescale difference). Images courtesy of Simon Prunet.

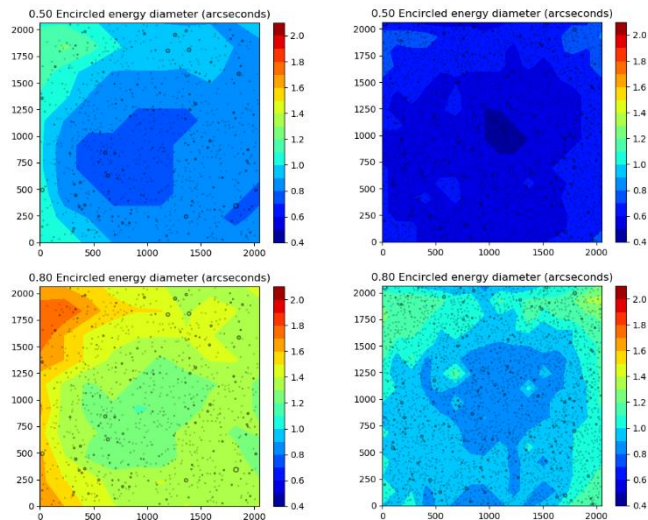


Figure 12 - Left: 50% (top) and 80% (bottom) encircled energy diameter (EED) maps before corrector lens installation, but after instrument tilt adjustment made in 2018. Right: Same data after corrector lens installation. The EED maps calculated from a crowded star field. Black circles indicate stars selected for the analysis, the diameter of the circles scales with the source intensity.

The top right corner of each port’s field of view still shows the worst IQ, with an 80% encircled energy diameter (EED) of 1.1”, however this is much improved over the 80% EED of 1.7” measured prior to corrector installation. Even more impressive are the 50% EED maps; the 50% EED of 0.8” – 1.1” seen in the corners before the corrector was installed has been reduced to 0.6” – 0.7” with the correctors in place. Note that the 50% EED metric is equivalent to FWHM if the PSF profile is Gaussian.

With the improvements made both in 2018 and this year, the optics now easily achieve design requirements over the entire field. More importantly, the more stringent 80% EED is now seen to be below 0.9”–1.0” over the central 5’ field, vs. 1.2”–1.6” previously, which means that we also meet the intent of the IQ requirement, which assumes a roughly Gaussian PSF profile without significant energy in the wings of the PSF. Specifically, the 80%-EED of a Gaussian PSF has a diameter of 1.53 times the FWHM, or 1.22” for the 0.8” FWHM criterion – at 1”, the 80% EED is now well below this requirement. In addition, the EED maps show a marked improvement of the near on-axis IQ, from 1.2” down to 0.8” for the 80% EED. This is likely a result of the field being flatter.

Note that SITELLE’s field of view has been reduced by 2.6% with the correctors installed. The diameters in arc-seconds of the EED plots take this plate-scale change into account. For reference SITELLE’s current plate scale is 0.3114”/pixel.

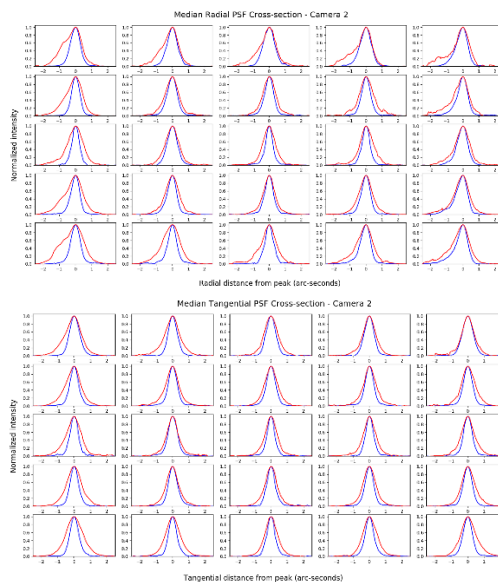


Figure 13 - Comparison of PSF cross-sections from before (red) and after (blue) installation of the corrector. Top set of graphs is the cross-section for the PSF collapsed along the axis perpendicular to that crossing through the center of the field (i.e., these are radial cuts through the PSF). The negative coordinate axis is toward the field center. The effect of the “comatic” radial flaring of the PSF in the image corners is evident in these cross-sections. The bottom graph is the cross-section of the PSF collapsed in the direction perpendicular to the radial cut, which is roughly bilaterally symmetric, as expected. The graphs represent the average PSF over blocks of size 1/9th x 1/9th of the image plane. Only a 5x5 sample of these blocks is shown. The graph positions follow the same orientation conventions as a SITELLE FITS image viewed in DS9.

SPIRou Technical Update

SPIRou worked well overall in 2019. A summary of technical issues at the end of the year includes –

1. Throughput sub-nominal in Y and J

The team is optimistic that the new Rhomboid prism manufacturer, Winlight, will produce prisms with better throughput in the blue due to sourcing different ZnSe material through a different material vendor. New prisms from Winlight will arrive by the end of this year or early next year. We note that much of the throughput loss in the blue is attributed to bulk absorption in the ZnSe material through the entire system. The rhomboid prisms only represent part of the ZnSe optic system. The cross dispersing prisms also appear to absorb in the blue and these will not be replaced.

2. K-band background 1 magnitude higher than specification at 2.33 μ m

Some progress has been made on cooling the fiber interface along with tests to cool the Cassegrain unit. The current background level has not changed significantly, but the tests are promising.

3. Calibration wheel variability - RV variability in calibration images (vs. reference channel) is observed

This is believed to be caused by some non-repeatability of the calibration wheel mechanism. The variability also extends to the flux levels in the science channels by as much as 30%, although infrequently. This problem has been corrected.

4. Variation of the alignment of the fibers with temperature

Testing suggests that the level of change is larger than would be estimated simply by part expansion with temperature. The hypothesis is that it involves motion of the powered optics to magnify the effect. More testing is needed. This task is still being worked on by IRAP and CFHT staff.

5. Neutral Density wheel variation on the reference channel

The ND wheel on the reference channel varies the RV of the reference channel depending on position. This problem has been corrected.

6. Rhomboid prism

Throughput is low on one of the two prisms. Replacement expected in 2019 or 2020. This is still an issue, see answer in item 1 above.

7. Helium leak in the 2nd cryo pump

Operational impact but no science impact. A spare cryo pump was installed to replace the leaking one, however the spare is now leaking. This leak does not represent a risk to science operations.

8. Slow loss of vacuum in cryostat

Likely due to outgassing in the system. Operational impact but no science impact. No progress on this issue.

9. Fiber agitator not robust - new design underway for a replacement

Progress has been made on the sensing of the agitator. Sensing hardware is planned to be in place in 2019 but related software will likely take longer to complete.

10. Detector controller "SAM" card reliability - currently no impact but may need to source a new design option in the future

We believe this issue has been retired. A creative solution was implemented by CFHT staff, which removed the Windows dependency from the detector controller/readout system. The solution was implemented in November 2019 and is currently performing well.

11. RV Oscillations

Oscillations of the relative RV signal as measured by Fabry-Perot (FP) images were observed with a period of 2-4 hours. The oscillation was ~ 2 m/s P-V and has subsequently come down to the current level of ~ 0.5 m/s P-V. It was also observed that the signal is mainly seen in just a few orders of the spectrum, with the primary order changing over time. The most recent sequences do not show the oscillation but it is noted that the oscillation has been observed to be intermittent in the past. The source of the oscillations is still perplexing and under investigation.

12. Optical Bench Temperature Oscillations

A temperature oscillation has been noted in the middle of the optical bench on the spectrograph with a period of ~ 20 hours and an amplitude of $\sim 1-2$ mK. The RMS of the temperature is still below 1 mK over 24 hours so the impact of the oscillation on RV precision should be small.

The source of the oscillation is under investigation, but it is clear that this has been ongoing at least since SPIrou arrived at CFHT, and likely while it was in Toulouse. As the effect is small, this is not a high priority investigation, but attempts will be made to fix this in the future as it would likely improve the overall stability of the instrument.

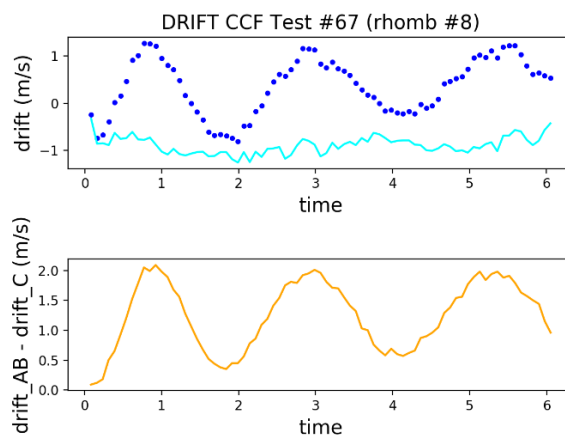


Figure 14 – Relative RV oscillation. This shows the worst oscillation seen in the worst order.

13. Thermal Background Mitigation

In addition to general heat extraction from the spectrograph environment, investigations are underway to further cool the two areas of the instrument mainly responsible for the excess K-band thermal background excess. The main culprits are the Cassegrain unit and the fiber interface into the spectrograph.

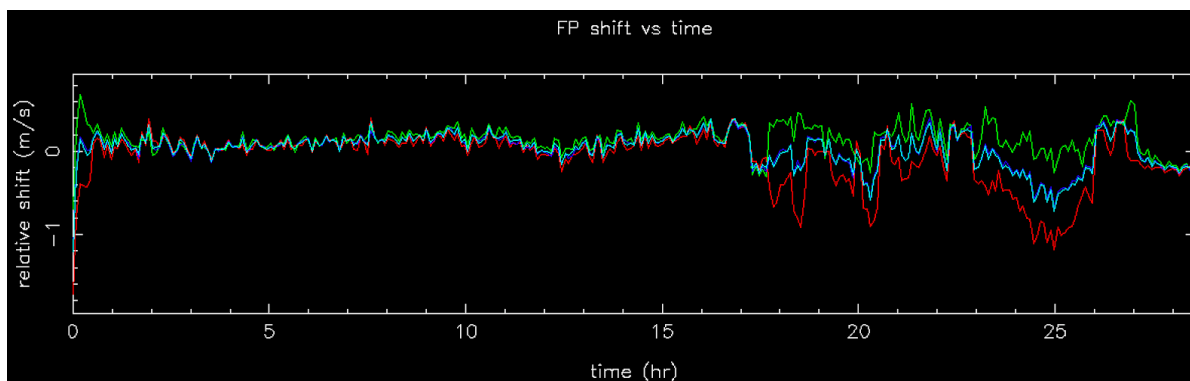


Figure 15 – The 3 colors correspond to RV in the two science channels and the reference channel. No periodic oscillations are currently seen. RV errors shown after 15 hours in the plot are due to telescope motion.

A contact cooling system for the spectrograph fiber interface, designed by IRAP, was implemented and shown to have a positive effect on the thermal background. The cooling source was recently changed to have a lower temperature giving further gains and improved insulation.

In addition, tests have been conducted to show the effects of cooling the dry air on both the Cassegrain and spectrograph units. Tests have also been done to measure the effectiveness of contact heat exchangers (cold plates) on cooling the body of the Cassegrain unit.

The results of these tests are still being analyzed, but it is hoped that they will allow us to determine the level and type of cooling needed in each place to achieve the desired reduction in thermal background on the instrument.

14. Rhomb/throughput analysis

At the end of the last semester, it was found that the throughput of SPIRou had dropped significantly and this drop was traced to the newest rhomb. It is likely that the molecular adhesion joining the two halves of the rhomb failed. Given the high index of refraction of ZnSe, this separation caused large reflection losses at the, now air-spaced, interface.

The previous rhomb1 was returned to service even though it has less than ideal retardance and anti-reflection coatings. This rhomb was one of the first produced by Fichou, who has been unable to produce another rhomb of similar quality for SPIRou. For this reason, IRAP has now contracted Winlight, who has

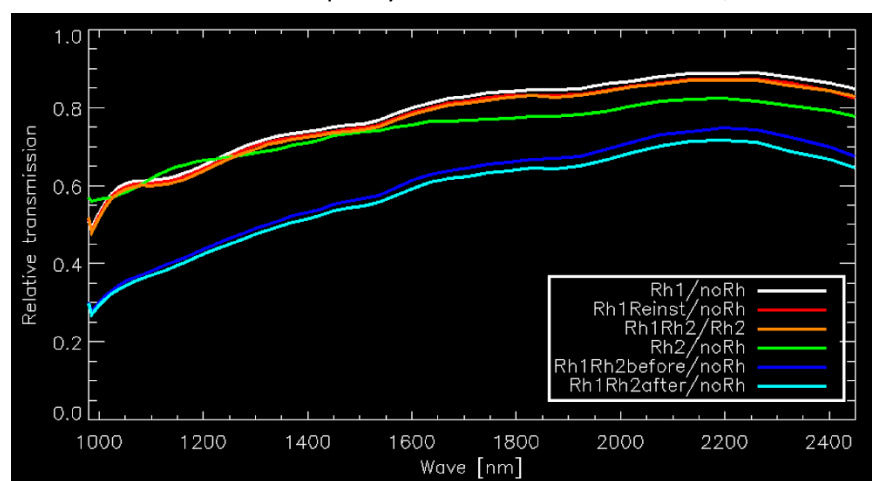


Figure 17 - Transmission curves for SPIRou with various rhomb configurations in the Cassegrain unit with the current rhombs installed.

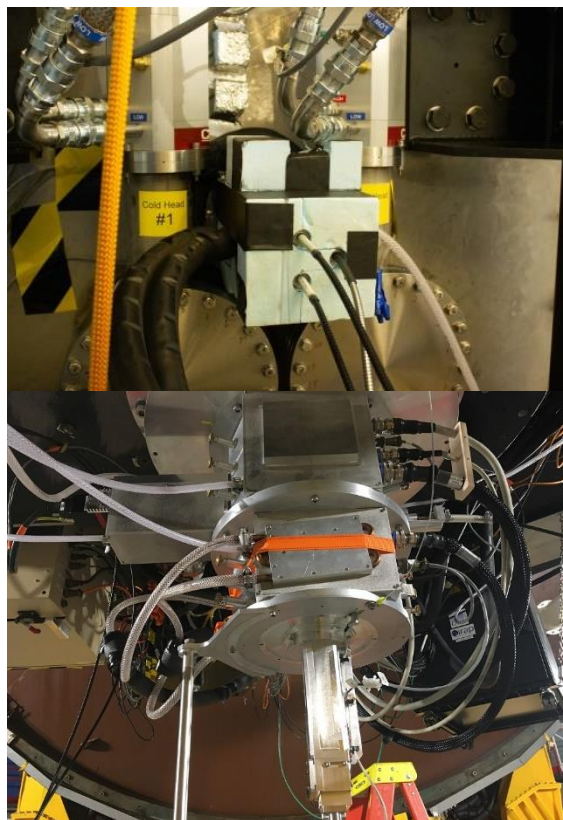


Figure 16 – Top: New insulation on the spectrograph fiber interface box. Bottom: Cold plate attached to the side of the SPIRou Cassegrain unit.

more experience in molecular adhesion of optics, to produce new rhombs for SPIRou. Winlight has refurbished one of the old rhomb sets from Fichou. The new rhombs will now be secured in titanium barrels (instead of aluminum) which has a better match to the thermal expansion characteristics of ZnSe. This should reduce the stress on the optic so that prism separations will no longer take place.

This refurbished rhomb has arrived at CFHT and is being tested in SPIrou. The parallelism and retardance appear excellent, while throughput appears unchanged. To improve the throughput, Winlight has procured additional ZnSe material from a new vendor. The new material is reported to have significantly less scattering in the blue than the material used in the current rhombs. If true, it is possible that the new rhombs will have significantly better throughput in the blue than the current ones. It is hoped that new rhombs will be available near the end of the year or early next year.

Feasibility Study for Co-mounting ESPaDOnS and SPIrou

A study of the feasibility of co-mounting SPIrou and ESPaDOnS for simultaneous observations is being pursued. The use-case for this configuration was investigated by an intern, Austin Jennings, at CFHT in 2018. The conceptual design is driven by the following considerations:

- Polarization effects at the dichroic beam-splitter and fold mirrors need to be compensated, so that each fold must be implemented as a pair of mirrors rotated about their optical axes by 90°
- Space constraints associated with the minimum two pairs of fold mirrors for the path feeding each instrument, and the desire to maintain the as-built gravity orientation experienced by both instruments
- Throughput losses associated with the fold optics favor having the infrared instrument, SPIrou, in reflection off the dichroic beam-splitter.

A diagram showing the current concept is shown in Figure 18. The concept is likely to require minor modifications to both SPIrou and ESPaDOnS, machining off small sections of the mounting flange on each instrument, as well as removing and repackaging the end-to-end unit. As a result, the SPIrou calibration feed would be relocated to the Cassegrain Bonnette fold. This would provide additional space and ensure that the calibration light enters the instrument before the fold mirrors and dichroic beamsplitter. In Figure 18, the mounting flanges of the two instruments are drawn as overlapping and the fold optics are partially buried in the Cassegrain Bonnette as far as possible (without major modifications to the Bonnette design). A full 3D model of the envelope of both instruments is necessary at this point to determine what modifications to the instruments are necessary.

CFHT has contacted vendors for the dichroic coatings. Once a coating design is selected, its polarization effects will be characterized using a model developed by Jenny Atwood at NRC Herzberg.

As two bright time instruments, it is very likely that SPIrou and ESPaDOnS are scheduled on the telescope one after the other. When this is the case, having them co-mounted will give us more flexibility to schedule windowed or monitored observations.

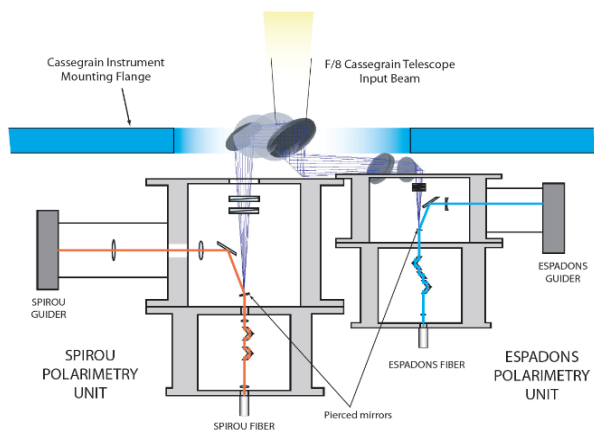


Figure 18 - Concept for mounting SPIrou (left) and ESPaDOnS (right) for simultaneous spectroscopic observation in the visible and near infrared. The chromatism of the dichroic fold, which is in transmission for the ESPaDOnS path, is compensated for by fabricating the dichroic from two optically contacted or cemented glass elements. A small tilt at the glass interface allows for correction of two colors over ESPaDOnS' bandpass. Further analysis is required to determine if this correction is at an acceptable level to avoid introducing systematic effects in the ESPaDOnS spectrum.

In the coming years, SPIrou and ESPaDOnS will probably share the majority of the bright time modulo WIRCam allocations. In the last 5 years, WIRCam was allocated 15% +/- 4.5% of the bright time on average so if the trend continues, SPIrou and ESPaDOnS will share 85% of the bright time. If both instruments share this time evenly without a co-mount, SPIrou PIs will have access to 42.5% of the time while a co-mount will potentially give access to all the 85% of the bright time for time constrained observations. This corresponds to about 39 more nights available each semester. However, this number could be considered a lower limit since it is expected that WIRCam usage will drop in the upcoming semesters due, among other things, to the end of a WIRCam Large Program at the end of 19B. If WIRCam is eventually retired, then SPIrou PIs will have access to 100% of the bright time for time constrained observations, and in practical terms this would amount to something like an additional 10 full nights each semester for both SPIrou and ESPaDOnS.

The 2019A allocations for ESPaDOnS were lower than usual at 11.5% of the total time. Even with this low allocation, we could have reached around 15% more SPIrou targets had we had the two instruments co-mounted. This number can easily double if the time allocated to ESPaDOnS is closer to the mean of the last 5 years of 30%.

Dome Crane Status

Maintaining availability of the bridge crane and 12-ton hoist is perhaps the most important maintenance operation required inside the observatory. Regularly scheduled instrument exchanges require that a fully-functioning bridge crane be operational to meet science demands.

History: The 12-ton bridge crane, we believe, is original and was delivered after the beginning of the construction of the telescope. Furthermore, we believe that it was overhauled with a major upgrade in 1992, and at that time was brought up from 9-ton capacity to a 12-ton capacity. The crane has experienced routine maintenance since then by several outside companies, the latest of which is Pacific Overhead Crane (POC), which has been maintaining the crane for about five years.

Earlier this year CFHT experienced several failures of the 12-ton hoist. The first occurred April 26 during a routine instrument exchange, when the hoist was observed to slip slightly. The repair by POC consisted of a complete clutch-rebuild and returned the crane to operations on May 14.

The next failure was encountered June 21 during which the hoist fell approximately 6-inches impacting the storage stand. Fortunately, no damage was noted to the storage stand or the F8 upper end. POC inspected the drive-train and found a sheared keyway in a mechanical coupling. Repairs included replacing the coupling as well as the shaft connecting the motors to the gearbox. On August 23 a ½ second “Timer-



Figure 19 – DeMag motor, Gearbox, and Stearns Brake (Left). New motor/gearbox coupler (right).



Figure 20 – Damaged drive shaft and bearings shown removed.

Off” delay contactor to remove potential interference between the motor and secondary brake was added. The bridge crane has been operating fine in this configuration since the repair.

Another failure irrelevant to the work conducted previously involved a brake on the main crane trolley (gearbox-side) when a broken-wire caused this brake to engage. Unfortunately, in an effort to return the crane to its stowed position the brake discs were damaged by over-riding the brake.

These crane system failures expose the vulnerability of our aging crane system. As a result, CFHT has evaluated replacement vs complete overhaul of the crane system. In response to this discussion, POC has submitted a proposal to integrate Variable Frequency Drive (VFD) controllers along with a series of additional upgrades to bring the crane up to modern standards. This includes increasing the capacity of the crane from 12-tons to 15-tons. According to POC, this proposal is far less than the cost of replacing the crane. It is expected that once this upgrade is in place, the crane will perform well for many years.

Dome Vents

After several years of successfully operating the dome vents, the exterior shutter doors experienced failures during closing at freezing temperatures. Operations assembled a team late last year to investigate, understand, and develop a solution to return all the vents to normal operation. During investigation the team identified a channel running the entire length of each door slat on the exterior as a possible problem. This area traps and collects water that ultimately freezes during cold temperature conditions; causing the doors to unfurl improperly. A technique to remove this trapped water was tested and incorporated into the normal operation of the dome vents. This “water shedding” technique is essentially exercising the doors between open and closed position several times during the day in order to remove any trapped water. If the weather forecast is favorable the vents will then be placed into operation for the night. The vents have been operated under these guidelines for almost a year and have not encountered



Figure 21 - Scaled down dome vent test fixture.

any failures. The current situation is that all dome vents are released to open up to 2/3 capacity, with the exception of 2 vents that are under repair.

While this is a temporary solution, a long term solution incorporating a design change is being explored. Possible design changes to solve this include -

1. Add a heat source to vent door housing to assist with melting ice after observing but before door closing
2. Integrate a leading edge sensor to track the position of the bottom vent slat
3. Add dedicated temperature sensors to provide accurate surface temperatures

A test platform was developed this past summer in order to enable the testing of different design solutions of the observatory dome. This test platform is a scaled down vent door prototype. A summer intern from the Akamai internship program designed and built this scaled-down unit with assistance from the Operations team. One plan is to approach “Tropical Dreams” ice cream factory in Waimea and inquire about the possibility of using the prototype to test design techniques in one of their commercial freezers as CFHT has done in the past.

MegaCam

MegaCam GigE replacement for the SLINK

Starting in 2017, a small fraction of the science, flat, and bias images were lost due to corrupted data originating from the dethost computer. The cause was traced to the PCI-bus fiber communication boards, SLINK (CERN standard fiber communication protocol). The SLINK boards are proprietary and obsolete technology. While CFHT does have a number of spare SLINK boards, they are not replaceable and represent an operational liability. Therefore, to support MegaCam for the next 10-15 years, a decision was made to replace the SLINK with a GigE interface, an industry communications standard used by many applications including commercial cameras.

A new board using the GigE interface was designed and built by CFHT staff and is in the final phase of software testing. The hardware is fully operational and identically mimics that of the SLINK interface. Software development is complete, but only the version running a single controller has been extensively tested. Test results of the single controller version have shown the software to be reliable and stable.

The Ethernet connection between the GigE interface and dethost is a private LAN, designed to limit traffic and allow for a single dethost as in the original SLINK configuration. Synchronization between the controllers and image reconstruction software would be significantly more complex if separate dethosts are required. Testing of the dual controllers and upgraded dethost is currently on-going. The setup along with the dethost are shown in Figure 22. Results of noise tests on the test detector with the GigE interface

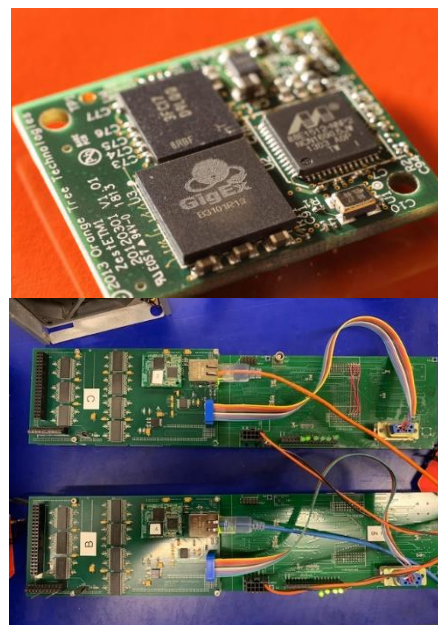


Figure 22 – Top: Dethost has two Ethernet ports - a private connection to controller Gigabit Ethernet switch and a public connection to interface with the external network. Bottom: Master and slave SHARC/GigE under test.

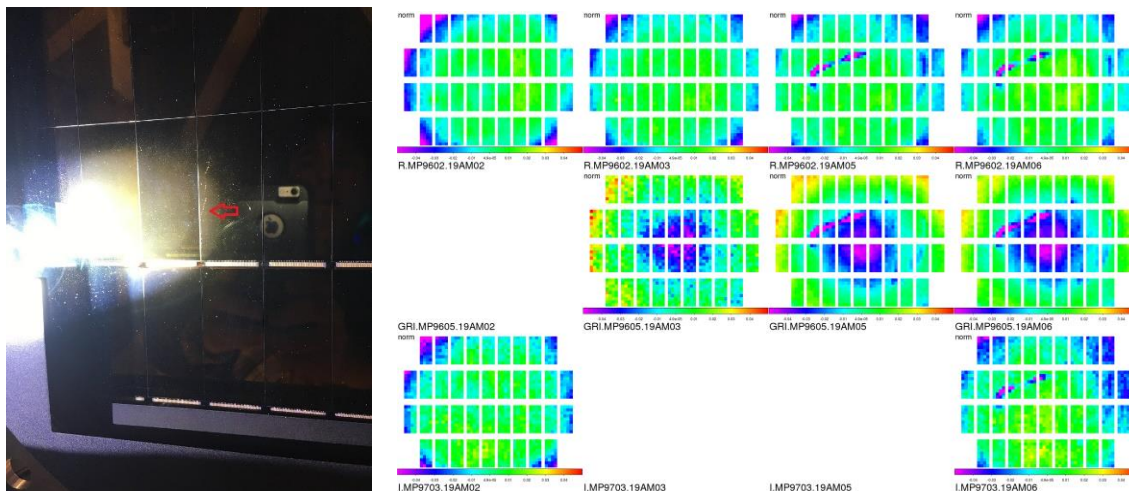


Figure 23 – (Left) Image of the problematic area. The streak is not obvious in the image due to the lighting and angle at which the photo was taken. (Right) Showing color coded zero point measurements across the full MegaCam field. Vertical tiles represent different filters and horizontal tiles represent different points in time. False-color images show the blob as a diagonal streak near the center of the field. The blob shows up for the last two runs prior to the MegaCam maintenance (two right hand columns) and is present in all filters. It's not present before the 19AM05 run, which started in June 2019. The scale in each image runs from -0.05 to $+0.05$ magnitudes. Image courtesy of Stephen Gwyn.

are promising. *There was no appreciable difference between the noise levels measured in the GigE and SLINK configurations in Waimea*, although the absolute noise levels, ~ 9 ADUs, were about twice that measured on MegaCam. The difference may be attributable to the test hardware and test environment in Waimea. The GigE interface should not affect MegaCam noise performance.

The current plan is to complete the dual controller testing in Waimea and begin testing on MegaCam at the beginning of November and deploying the new system in the early part of 2020.

Optics cleaning and removal of “the blob”

As part of MegaPipe, Stephen Gwyn (Herzberg Astronomy and Astrophysics) built a map of the zero-point variation across the MegaCam mosaic. Normally, these maps are fairly flat across a lot of the field, with a drop in zero-point near the edges and are pretty stable from run to run.

However in the last few runs prior to MegaCam servicing, there was an extra elongated blob near the center of the field (visible in Figure 23) and is present in all filters. It was not observed before the 19AM05 run, which started in June 2019.

In order to address this issue and as part of the normal bi-annual maintenance of MegaCam, all the accessible optics were cleaned. These include the cryostat window, guide probe mirrors, and ISU. During the cleaning process it was observed that the cryostat had a streak of what appeared to be cinder dust that collected at the edge of a condensation patch. The streak is visible in the image in Figure 23. The location and shape of the streak matched those of “the blob” seen in images from the prior observing run. The “blob” disappeared in subsequent images after the cleaning.

Mirror Cleaning and Throughput Impact

In 2018, we proposed the idea of cleaning the telescope mirrors with Red First Contact from Photonic Cleaning Technologies. We started by testing smaller optics, small patches on the primary mirror, and

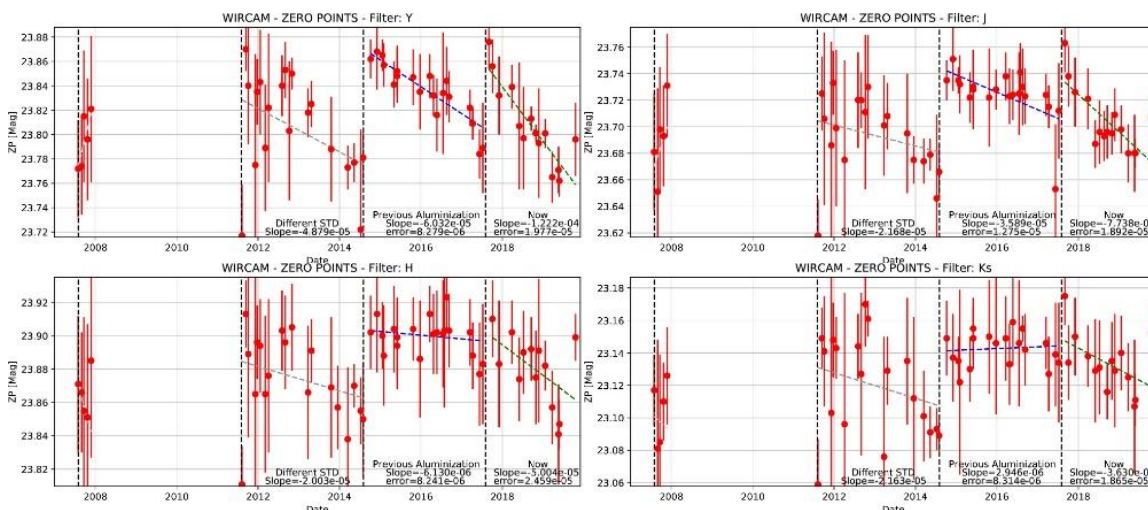


Figure 24 – WIRCam zero points for the previous two post-recoating periods and the current period. Note the rightmost data point is after the mirror cleaning.

finally a complete cleaning of the primary mirror in October, 2019 (Figure 26). The procedure took a single day and did not result in any time lost on sky.

First Contact is applied using a sprayer. Once dried, dust particles are encapsulated in the First Contact and are removed by peeling it from the mirror’s surface. After peeling, the mirror appeared to be cleaner, but not pristine. This is not surprising, considering the coating on the mirror had been subject to ongoing volcanic eruptions from Halema’uma’u and Fissure 8 from August, 2017, until September, 2018.

A single set of zero point measurements for MegaCam and WIRCam have been taken and analyzed after mirror cleaning (see details below). Both instruments show an improvement in reflectivity. The fact that the gains were higher in the infrared than in the visible suggest that the cleaning removed particulates from the surface of the mirror, but that finer scale damage to the coating, or smaller particles not removed by the First Contact, are still contributing to scatter. We won’t have a complete picture of the effect of the cleaning until additional zero point measurements have been made during future observing.

A WIRCam run was completed just after the first contact cleaning in October. It allowed us to measure the zero-points in the Y, J, H, and Ks bands and compare the results with previous zero-point measurements. These are shown in Figure 24. The last point added to the zero-point plots comes from the combined photometric standard star observations of the WIRCam run Q08 from October 16 to 21. The vertical dashed-lines are the different aluminizations. Note that prior to 2014 the zero-point calculation was slightly different and less accurate.

The results from the last measurement suggest that the improvement on the zero-points was significant: of order 5% in flux. The improvement also suggests that the mirror reflectivity and scattering properties are back to what we expect from the

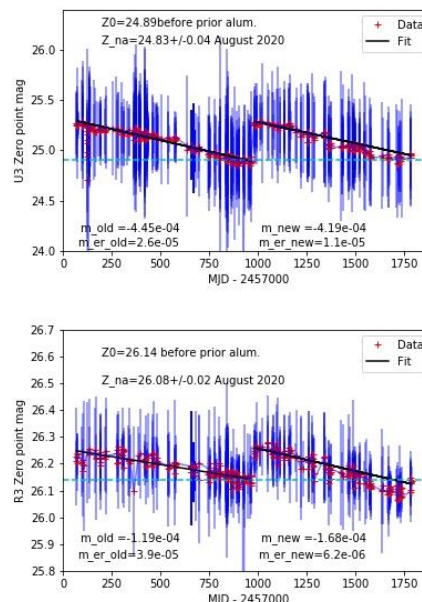


Figure 25 – MegaCam zero points for the previous post-recoating period, and the current period. Note the rightmost data point is after the mirror cleaning.



Figure 26 – First Contact applied to the primary mirror prior to peeling (left) and after peeling (right).

slope measured during the past coating period from 2014 to 2017. This is consistent with the result obtained more recently with MegaCam in the visible.

Also shown in Figure 25 are zero points for MegaCam including data from after the mirror wash. The results are fair to good for r and excellent for u , meaning that if one excludes the volcano-to-wash data points for u , the slope in the zero points is equal or slightly better than the u decline before the previous re-aluminization. For r , eliminating the same data points from the new slope estimates gives about the same slope or possibly slightly poorer slope. Error bars are estimated from the number of points used in the specific exposure used as a data point. The fits use least-square minimization with weights inversely proportional to the error bars. Attempts were made to remove the 3 sigma outliers from the fit and then the data were refitted to account for particularly good or poor conditions. This exercise has not significantly affected the results.

Coating Chamber Upgrade

The aluminizing chamber is original equipment and has deteriorated somewhat in the past 40 years. Risks were reported in the December 2018 Board of Directors meeting and the decision was made to upgrade the chamber to minimize risk. The following is an update to the status of the upgrade, which encompasses mostly rebuilding the frail and breaking electrodes.

In 2018, we proposed the idea of replacing the tips of the 224 electrodes in the large coating chamber with a new design that would not be subject to the kind of damage the old electrodes suffered.

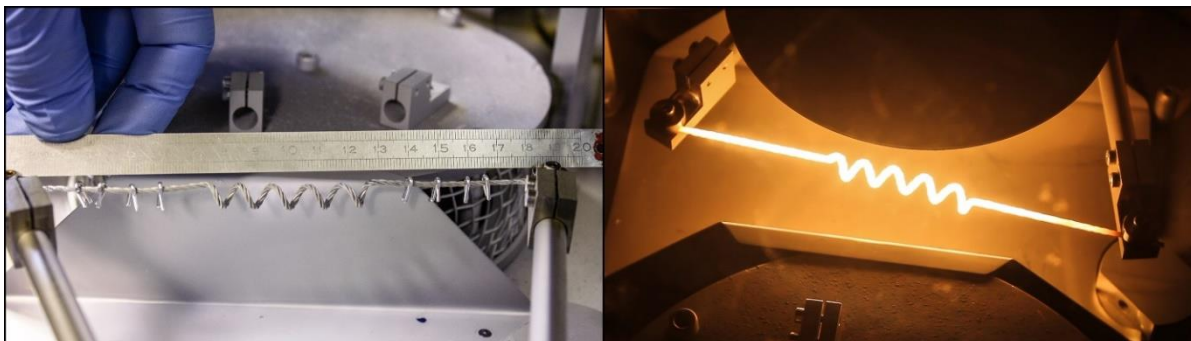


Figure 27 – Prototype electrodes placed in the small coating chamber. Several witness samples were coated to verify normal operation and demonstrated that the prototype electrodes performed well.

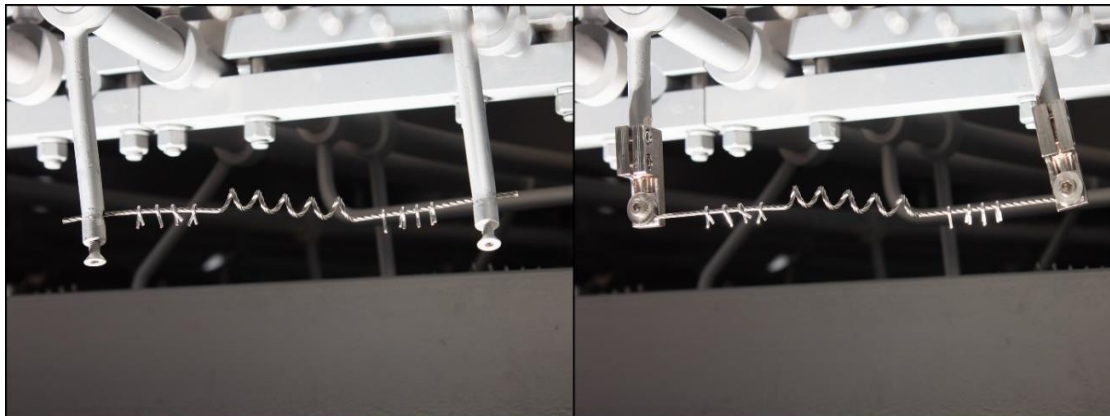


Figure 28 - New electrodes (right) replacing the old electrodes (left) in the large chamber and tested during the UKIRT recoating in September 2019. Note, only two of the electrodes were of the new design during this run, to minimize risk to the UKIRT coating run, while still verifying the new electrode design.

Steps in the 2018 plan include -

1. Fabricate prototype clamps in-house and install them in the small chamber for testing.
2. Upon successful testing in the small chamber, install the clamps on two of the more damaged electrodes in the large chamber. These should be selected so the new clamps fall inside the view of the upper chamber window.
3. Install the thickness profile test fixture in the large chamber and fire the chamber, recording video of the new clamps.
4. If the performance of the new clamps is acceptable, manufacture all remaining clamps and install them in the large chamber.
5. Fire the chamber again and compare coating thickness to the previous test.

The 2019 status of the project is summarized below –

Step 1 – Small Chamber Testing: May, 2019, we replaced the electrodes in the small coating chamber with the new prototypes and coated several witness samples to verify normal operation. The prototype electrodes performed well.

Steps 2-3 – Large Chamber Testing: The TMT protests delayed work on the large chamber until August. When we were able to return to work on the project, we replaced two of the electrode tips with the new design.

Earlier in the year, East Asian Observatory (EAO) contacted us to ask if we would be able to re-coat the UKIRT primary mirror in 2019. Rather than fire the chamber twice in the same year, once for our test and once for their mirror, we asked if they would be willing to test the new electrodes on their mirror. They agreed. The coating was a success and the new electrode tips performed well.

Step 4 – Retrofit: All of the new electrodes are in hand, replacement began in November, 2019 with an expected completion date in early 2020.

MSE Report

Summary and Overview

2019 began with a change in scientific leadership in the Project Office. Jennifer Marshall, new Project Scientist, brought her scientific knowledge, US and international project experience to MSE. As a result, we have made great progress in reaching the US astronomical community. This is evident in the growth of science team membership, 25% of the 400+ member are from the US, and the progress made in the Astro2020 survey with MSE selected for TRACE evaluation. We anticipate MSE will receive high ranking in the US and Canadian national strategic planning processes, with reports and recommendations slated for release in 2020 and 2021.

MSE also made excellent progress in the national Prospective planning process in France where we are anticipating the highest PO ranking for the facilities and infrastructure. 2019 saw a UK university consortium led by the UKATC join the Management Group (MG) as observer and Texas A&M University transitioned into a full member of the Management Group. MSE continued to maintain grassroots support in Canada for the next decadal Long Range Plan and, in addition, commitment for eight universities and industrial partners to support a \$20M CAD Canada Foundation for Innovation application.

A Partnership Model was developed to engage new partners. This model includes the basic rights and obligations of the MSE partnership regarding scientific leadership, science data access, voting authority and financial commitment. The MG will continue to develop a detailed partnership model in the upcoming year.

Project Office Activity - Science

Soon after her start, Jennifer Marshall (JM) was at work in organizing the PO's science tasks, and recruited Andreea Petric's (AP) help by formally recognizing her as the Deputy Project Scientist. They took over Alan McConnachie's (AM) responsibility in coordinating the Science Working Groups' work in refreshing the Detailed Science Case (DSC) for the NOAO co-sponsored Massively Multiplexed Spectroscopy with MSE: Science, Project and Vision meeting in February 2019.

At the February meeting, JM and Nicolas Flagey (NF) presented their plan to solicit from scientists an optimal set of requirements for spectral coverage, resolution, and target density. The PO's objective for consolidating a set of optimal science-driven design requirements is to facilitate feasible spectrograph optical designs for the low/moderate and high resolution modes. The Conceptual Design Phase spectrograph optical designs were recognized to be challenging. Even incremental relaxation in the science-driven design requirements may have positive impacts on their design feasibility.

After the meeting, NF devised a questionnaire for the science team to ascertain their optimal science requirements. After analyzing the questionnaire findings, he derived parametric top-level design requirements for the spectrograph design teams in the form of proposed trade studies. The outcomes of the trade studies will inform parametric models so the PO can iterate between the science and spectrograph design teams for a set of optimal design requirements that are scientifically effective and technically feasible. The trade studies are currently in progress by both low/moderate and high resolution spectrograph design teams.

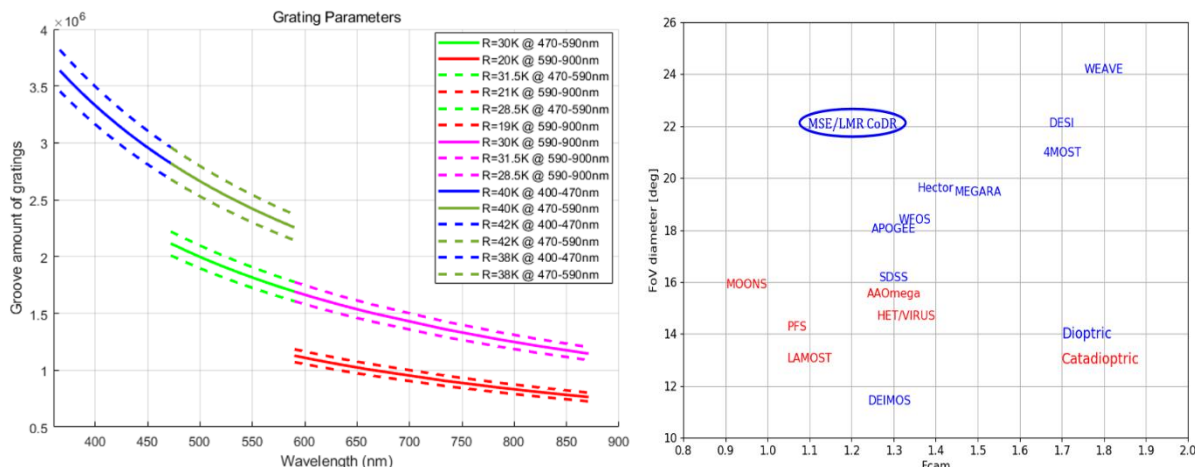


Figure 29 - Spectrograph trade studies - disperser line counts vs. spectral coverage for HR mode (left); demand on camera design vs. existing spectrographs LMR mode (right).

In parallel, AP and JM have been assessing the questionnaire findings for consistency against the science requirements derived from the DSC. Their work is also in progress, and depending on their findings, the top-level design requirements may be modified with additional iterations. The parallelization of their work with NF was motivated by expediency in engaging the design teams early in the process.

JM also began to plan the Design Reference Survey (DRS). The DRS is the system level conceptual design review panel’s recommended tool for validation of the conceptual design against “realistic” science observations. The current methodology is to produce a detailed first generation observing plan by combining the three most diverse science cases selected from the DSC. By executing the step-by-step observation plan we will identify any performance and functional design deficiencies in the conceptual design baseline configuration. Therefore, findings from the DRS will inform the improvements required in the Preliminary Design Phase (PDP).

The MSE science team continued to grow, from 336 members from 31 countries in 2018 to 409 members from 36 countries in 2019. The growth is attributed to the extensive science outreach under the leadership of JM. The breakdown of science team membership by countries is as follows, where * denotes participating MG countries:

- Australia* – 33
- Belgium – 7
- Canada* – 38
- Chile – 7
- China* – 32
- France* – 41
- Germany – 20
- India* – 12
- Italy – 12
- Korea – 5
- Spain – 14
- United Kingdom* – 36
- USA* – 106
- Other – 144

As mentioned earlier, the priority of the science team was to update the contents of the DSC document in time for the NOAO co-sponsored meeting. A new version of the DSC was released in early 2019. To facilitate this endeavor, with AM’s help, JM divided the work among the eight science working groups, with two co-leads appointed for each group.

The science topics, co-leads and their affiliations for the eight working groups are as follows –

- Exoplanets and stellar astrophysics
 - Maria Bergemann, MPIA Heidelberg
 - Daniel Huber, University of Hawai'i
- Chemical nucleosynthesis
 - Sivarani Thirupathi, Indian Institute of Astrophysics
 - David Yong, Australian National University
- Milky Way and resolved stellar populations
 - Carine Babusiaux, Observatoire de Paris
 - Sarah Martell, University of New South Wales
- Galaxy Formation and evolution
 - Kim-Vy Tran, Texas A&M University / University of New South Wales
 - Aaron Robotham, University of Western Australia
- AGN and supermassive black holes
 - Yue Shen, University of Illinois
 - Manda Banerji, Institute of Astronomy, Cambridge
- Astrophysical tests of dark matter
 - Ting Li, Carnegie Observatories
 - Manoj Kaplinghat, University of California @ Irvine
- Cosmology
 - Will Percival, University of Waterloo
 - Christophe Yèche, CEA
- Time domain astronomy and transients
 - Adam Burgasser, University of California @ San Diego
 - Daryl Haggard, McGill University

Project Office Activity - Engineering

2019 was recognized as an interim year before the start of significant PDP work. The proposed PO's tasks, listed in order of priority, were:

- Support the MG in their efforts to establish funding by continuing to promote MSE interest in the science and engineering communities
- Continue to engage new participants
- Closeout the M1 readiness review with recommendations and action plans to the MG
- Prepare the systems engineering products needed to support subsystem PDP work whenever a subsystem has secured in-kind contribution, including revision of the three Level 1 foundational design requirements documents, Observatory Architecture Document (OAD), Operations Concept Document (OCD) and Observatory Requirements Document (ORD), and implementation of the DOORS requirements management

Highlights of the PO activities for 2019 outside of outreach and promotion activities include -

- Completed the consolidated system budgets (throughput, injection efficiency, noise and image quality) document. This ensured the budget items are cohesive and consistent project wide and with the exposure time calculator. The consolidated system budgets will form the basis for refining the system-level design requirements during the PDP. (Led by NF)
- Incorporated the system level conceptual design review panel's recommendations by coordinating changes to the Level 1 design requirements documents. More significantly, the planned revision will streamline the requirements management process with the DOORS software. (Led by Alexis Hill - AH)
- Produced an end-to-end configuration management and reviews plan (CMRP) by adopting the best practices of similar projects but adjusting to the staffing level at the PO through MSE's project lifecycle. The plan is a comprehensive document that defines: the technical phases to execute the project; the configuration documentation required to fully describe the project baseline; and the corresponding configuration management procedures to safeguard the baseline in terms of scope, cost and schedule. Once finalized, the CMRP will become the PO's de facto operating manual. (Led by Kei Szeto - KS)
- Investigated alternative software tools to facilitate collaborative work within the geographically distributed PO and design teams. After several months of trial, Microsoft SharePoint was selected. Once fully implemented, SharePoint will augment the DocuShare document control center as the collaborative workspace for in-progress documents before they become formalized as released versions in DocuShare. (Led by AH)
- Liaised between the science team and the low/moderate and high resolution spectrograph design teams to define technically feasible design requirements. (Led by NF)
- Consolidated the subsystems' conceptual design reviews' action items and risk registers into Redmine, an open-source issue tracking software. (Led by AH)
- Revised the Program Execution System Architecture (PESA) product definitions to incorporate an object model concept and the product interface definitions; organized and hosted bidders' conference to solicit potential contributions where over 20 participants from more than ten organizations attended the conference, which had two separate sessions. (Led by NF)
- Drafted operations plan with annual operating cost and staff level. (Led by NF)
- Interacted with MG members to enquire about M1 System IP access from TMT and ELT. (Led by KS)

In-kind Contributions from MSE Participants

The chart below shows the distribution of the contributions by MSE participants since the inception of the Project in 2015. The total combined contribution is \$10,201,730 including the MSE PO effort. The distribution of in-kind contributions among the MSE participants includes the CFHT's MSE PO operating budget. Here, contributions from CFHT are distributed among Canada, France and Hawai'i (0.425:0.425:0.15).

Strategy Going Forward

For planning purposes, we have made the following assumptions about pending national strategic planning reports and associated funding availability. The reports are expected in Q1 2021 with rankings. Once the rankings are announced, we expect funding will be available starting in Q2 2021 to support PDP work through either direct national participation or routed through the current national participants.

The high-level technically paced schedule shows the PDP starting in mid-2021 with a two-year duration. The Construction Phase will follow. It includes a Detailed Design Phase, subsystems manufacturing and testing activities for a total duration of six and a half years. Once the subsystems are tested and accepted at the “factory”, they are shipped for Assembly, Integration and Verification (AIV) to become part of the MSE system. The AIV phase is seven and a half years long, including the deconstruction and refitting of the summit building and facilities, AIV activities for the industrial systems of enclosure and telescope mount structure, and AIV activities of the Science Instrument Package such as positioner system, spectrograph systems and science calibration system, etc. Science operations will start in 2034 at the mid-phase of a two-year science commissioning process. The phases in the schedule overlap in order to shorten the total duration.

Four milestones framing the assumed schedule are:

- Master lease renewal by mid-2023
- MSE construction permit approval by mid-2024
- CFHT deconstruction starting in 2026
- Science operations commencing in 2034

Project science work will continue to focus on leading the science team, development of the Design Reference Survey, and refinement of the low/moderate and high resolution spectrographs’ design requirements with respect to the optimal science requirements. Specifically, AP will support scientific aspects related to the low/moderate spectrograph such as the characterization and modelling of the Maunakea sky in the NIR, and NF will coordinate the development and enhancement of the primary simulation tools essential for the DRS, such as the survey scheduler, exposure time calculator and fiber allocator.

The DRS development will be the main science endeavor for the coming year. It will enable fine-tuning of the low/moderate and high spectrographs’ design requirements and lead to feasible design solutions, and understanding of the constraints that the spectrographs impose on the system performance budgets. Working with the PO and science team, JM will lead the process of reconciling the MSE science requirements with the spectrographs’ performance. The expected resolution may be a combination of science and design requirements revisions in order to reach full performance compliance.

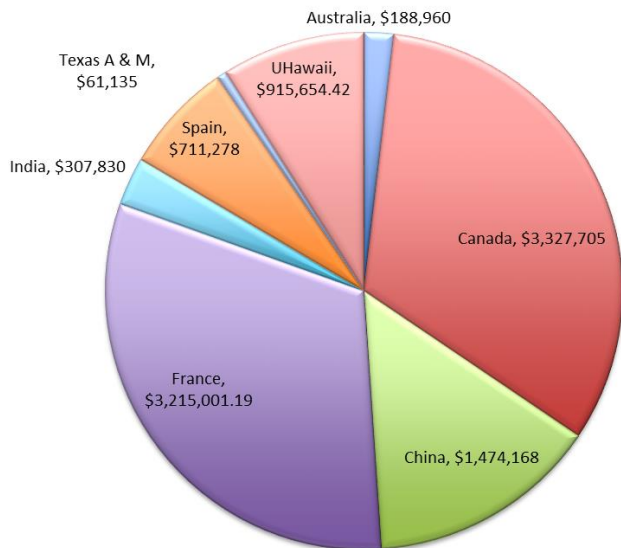


Figure 30 - The distribution of contributions among the MSE participants is shown including the CFHT’s MSE PO operating budget. Here, contributions from CFHT are distributed among Canada, France and Hawai’i (0.425 : 0.425 : 0.15), and contributed effort is valued at \$110/hr.

Administration Report

Overview

The Finance & Administration Department supports the mission of CFHT by providing and overseeing all shared service functions of the observatory: Finance, Human Resources, Safety, Office Services, and Fleet and Building Maintenance. The goal of the Administrative group is to be helpful to the organization and provide outstanding service to our internal customers.

Summary of 2019 Finances

CFHT continues to operate in a challenging economic environment of limited member agency contributions compounded with inflationary cost pressures. For 2019, member agency contributions increased 1.8% from the prior year. During the last 5 years, agency contributions have grown an average of 1% per year. Personnel costs represent the largest portion of CFHT's budget, with average annual inflation pressure on salaries and benefits of between 2.5% to 3% per year. To date, CFHT has been able to successfully balance these cost pressures and maintain a balanced budget due to a strategic focus on efficiency improvements in both personnel and operating costs and a disciplined eye on expenditures.

Agency Contributions (US\$)		
	2019	2018
NRC	3,358,000	3,300,000
CNRS	3,358,000	3,300,000
UH	778,664	765,214
Total	7,494,664	7,365,214

Table 1 - Contributions from CFHT partners increased 1.8% from 2018 to 2019.

Table 2 shows our 2019 Operating Fund expenditures on a comparative basis with 2018. In spite of the budget constraints, we have been able to maintain a balanced budget in both years with nominal amounts unspent and transferred to reserves. These results are due to conscientious and targeted cost containment in several categories. As we look towards the future, CFHT will continue to work closely with its member agencies to maintain stable and efficient operations while continuing to deliver world class service.

Operating Fund Expenditures (US\$)		
	2019	2018
Maunakea Facility and Operations	496,722	487,909
Base Facility and Operations	149,325	137,917
Services	278,501	377,579
Mauankea Support Services	129,154	135,198
Management & General	459,225	435,313
Staffing	5,558,414	5,551,289
Outreach	88,609	74,567
Instrumentation	90,339	57,858
Science	58,757	64,101
Transfer to Reserve	185,618	43,483
Total	7,494,664	7,365,214

Table 2 - Operating expenditures broken down by cost categories.

In addition to member agency contributions, CFHT receives payments under collaborative agreements with other agencies as reimbursement for costs associated with their use of CFHT facilities. In 2019, CFHT received \$361,500 and \$353,250 from the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) and the National Astronomical Observatory of China (NAOC), respectively. Money received under collaborative agreements with these agencies is used to fund instrument and project development costs, with the

current focus on MSE. Efforts are ongoing to seek additional collaborative agreements and partner with agencies throughout the world.

Staff Safety

CFHT has a designated Safety Committee with members representing all departments across the observatory to address safety concerns or issues. The Committee meets at least monthly. Additionally, health, safety and environmental surveys are conducted at observatory facilities as well as ongoing reviews of programs and processes.

During 2019, we experienced one OSHA recordable injury. An employee suffered a potential back sprain while moving equipment. The incident resulted in one day of lost work time. The employee was limited to light duty work for a few days before resuming normal duties. This accident, along with any near miss or non-recordable incidents, are addressed promptly to identify opportunities for improvement in our operating processes or training.

For the last two years, CFHT has used outsourced safety management services in coordination with its internal Safety Committee. However, management has determined that additional resources are needed to oversee broader environmental and health needs in addition to safety management. As such, CFHT will hire a full time Environment, Health and Safety Manager in 2020.

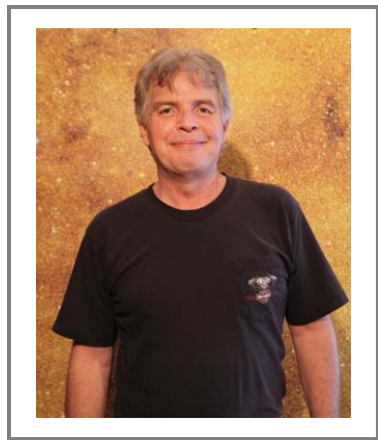
	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010
Injuries	1	1	0	0	2	2	0	0	1	0
Lost work days	1	0	0	0	0	10.5	0	0	1	0

Table 3 – A decade of top-level statistics pertaining to safety are listed above.

Arrivals and Departures

During 2019 we bid farewell to three of our staff 'ohana who have chosen to move on to their next adventures in life. We welcomed four new individuals as well as promoted two of our long standing staff members. At the end of 2019 we had two vacant permanent positions that will be actively recruited. We wish to pay tribute and extend our best wishes to those who have moved on and provide a warm welcome to our new staff members.

Farewell



David Woodworth

David retired as a remote observer in early 2019 after a 22-year career with CFHT. Prior to CFHT, he was an observer at the University of Hawai'i 88" telescope. Over the years, David has seen many significant changes to astronomy on Maunakea in his role – from supporting classical observing runs on the mountain with visiting astronomers to modern remote observing in queue mode. His knowledge and experience have been passed on to the next generation of observers following in his footsteps. At the time of his retirement, David was planning on spending a great deal of his well-earned retirement time touring the country on his motorcycle. We look forward to hearing about his new adventures when he comes back to visit us.

Claire Moutou

Claire was a Resident Astronomer from 2013 through 2019. She served CFHT in this capacity through two 3-years terms on assignment from CNRS. Upon completion of her second term, she has returned to CNRS. While here, Claire was a lead astronomer on the development, installation and commissioning of SPIRou. We are excited to hear that her involvement and use of SPIRou continues in her work from France.



Alexis Hill



Alexis joined the MSE project office in 2016 as an Engineer on temporary assignment from the Herzberg Astronomy and Astrophysics Research Centre (HAA) in Victoria, Canada. Her temporary assignment ended in 2019 and she returned to HAA. We are extremely fortunate, however, in that she continues to be dedicated full time to the MSE project from Victoria. One of Alexis' most meaningful contributions during her time in Waimea was supporting the completion of the conceptual design phase of the MSE project and developing the project plan book. Her work now continues in preparing for and executing the preliminary design phase of the project.

Welcome



Carolyn Castaneda

Carolyn joined CFHT in January 2019 as a Finance and Administrative support specialist. She supports all the activities of our front office administrative team and is the lead on all accounts payable and credit card activity. Carolyn is a life-long resident of Waimea with deep family roots across the Island. She has over 20 years of experience in industries ranging from hospitality to construction. In her short time with the CFHT, Carolyn has quickly become integrated in supporting staff across all departments and made many meaningful contributions to streamline our administrative functions.

Helen Januszewski

Helen joined CFHT as a Remote Observer to fill the vacancy left by the retirement of David Woodworth. Helen is from Ann Arbor, Michigan and is a recent graduate of the University of Michigan. She completed an internship in 2018 at the Gemini North Observatory. That experience convinced her that she wanted to be an observer on Maunakea. The Big Island suits Helen well with her active hobbies including hiking, camping and dog walking.



Raycen Wong

Raycen was hired in December, 2019 as a Mechanical Engineer. He graduated from the University of Hawai'i in 2016. As part of his studies, he completed an Akamai internship at CFHT in 2015. His internship project was focused on heat mitigation for WIRCam. Raycen was born and raised in Hilo, Hawai'i. His hobbies include racing cars, riding motorcycles, fishing and camping. Prior to joining CFHT he was an engineer at the Pearl Harbor Naval Shipyards while waiting to find the perfect engineering position on Island to enable him to return home. We are very excited and feel fortunate to be able to hire experienced talent that participated in our workforce development initiatives through the Akamai Internship program.



Luc Arnold

Luc joined CFHT as a Resident Astronomer on assignment from CNRS, filling the vacancy left by the return of Claire Moutou. Luc completed his PhD in 1995 at Observatoire de la Côte d'Azur, and continued his postdoc work focused on instrumentation at Observatoire de Haute Provence (OHP). Since that time, Luc has had the opportunity to work on a wide range of worldwide projects with an interest in exoplanetary research. His primary instrument focus at CFHT will be with SPIRou. Luc and his wife, Bettina, came to Hawai'i with their two teenage daughters and look forward to experiencing all that Hawai'i has to offer while on assignment here.

Promotions

Tom Benedict

Tom was promoted to the position of Instrument Engineer from the role of Instrument Technician. His distinguished 18-year career has given him the depth of experience in all aspects of observatory and instrument maintenance needed to transition to engineer seamlessly. Tom has a contagious enthusiasm for all aspects of his job and loves to get his hands dirty on the mountain at the observatory. Some of Tom's recent significant accomplishments include key roles in the installation and commissioning of SPIRou and leading multiple mirror coatings for both CFHT and other observatories in Hawai'i.



Mary Beth Laychak

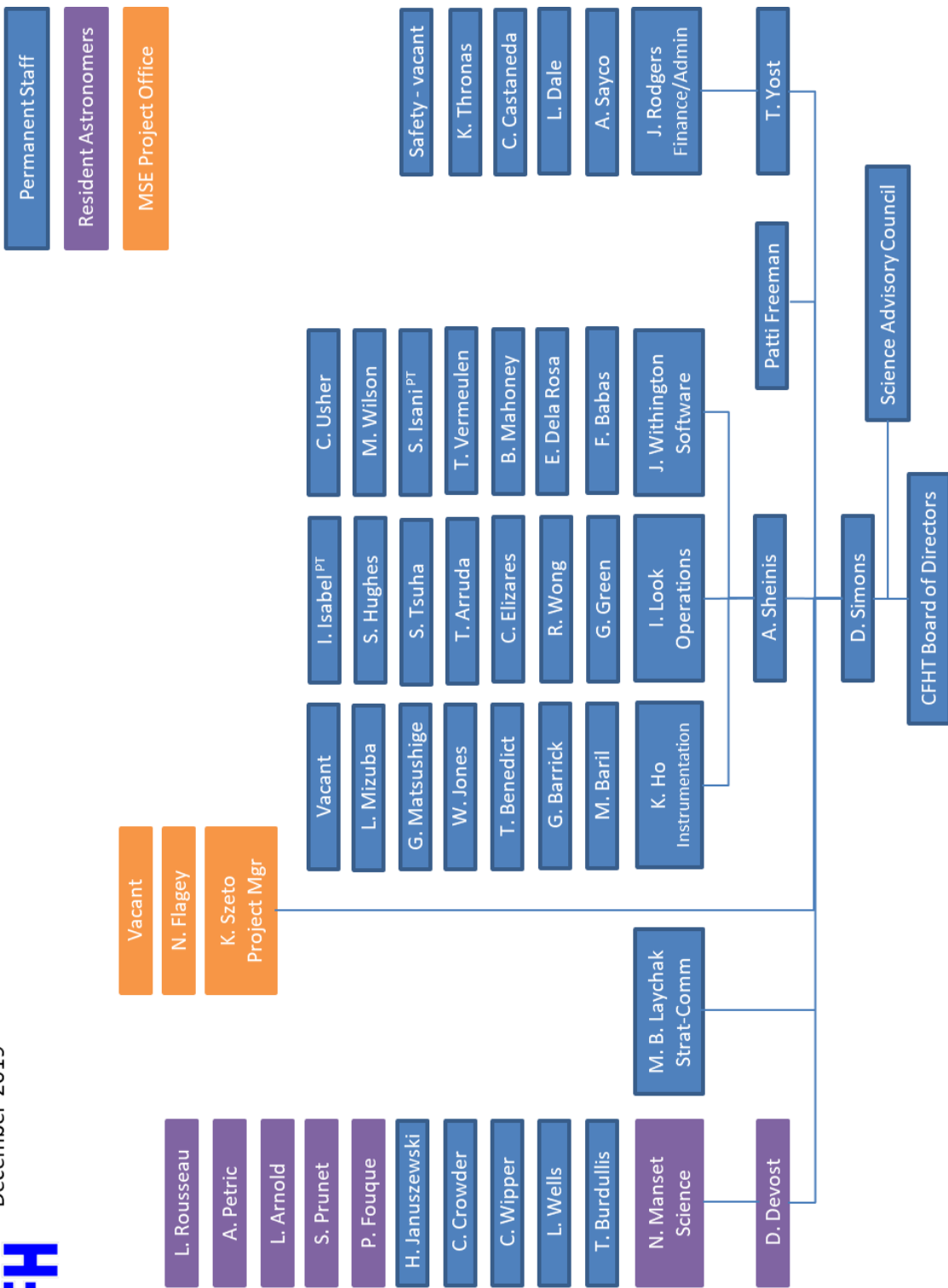
Mary Beth has served for many years as our Manager of Outreach and Public Relations. One of her most significant accomplishments in this role was the development and expansion of Maunakea Scholars, a program designed for public high school students to conduct research programs utilizing multiple observatories on Maunakea. As CFHT's presence in the community and involvement in many visible initiatives within the Maunakea Observatory Community grew, we promoted Mary Beth to the role of Director of Strategic Communications. In this expanded position, she will create a comprehensive communications plan for CFHT's interaction with the public and serve as a primary point of contact for external communications with our local community.





Canada-France-Hawaii Telescope Corporation
Organizational Chart
December 2019

Organization Chart



Staff List at the End of 2019

Name	Position	Name	Position
Arnold, Luc	Resident Astronomer	Look, Ivan	Operations Manager
Arruda, Tyson	Mechanical Technician	Mahoney, Billy	Database Specialist
Babas, Ferdinand	System Administrator	Manset, Nadine	QSO Manager/Resident Astronomer
Baril, Marc	Instrument Engineer	Matsushige, Grant	Sr. Instrument Specialist
Barrick, Gregory	Optical Engineer	Mizuba, Les	Instrument Specialist
Benedict, Tom	Instrument Engineer	Petric, Andreea	Resident Astronomer
Burdullis, Todd	QSO Operations Specialist	Prunet, Simon	Resident Astronomer
Castaneda, Carolyn	Administrative Specialist	Rodgers, Jane	Finance Manager
Crowder, Callie	Remote Observer	Rousseau-Nepton, Laurie	Resident Astronomer
Dale, Laurie	Administrative Specialist	Sayco, Arturo	Accountant
Dela Rosa, Eric	System Administrator	Sheinis, Andy	Director of Engineering
Devost, Daniel	Director of Science Operations	Simons, Doug	Executive Director
Elizares, Casey	Summit Operations Manager	Szeto, Kei	MSE Project Engineer
Flagey, Nicolas	MSE Systems Scientist	Thronas, Kahea	Vehicle/Facility Maint. Specialist
Fouqué, Pascal	Resident Astronomer	Tsuha, Seizan	Mechanical Technician
Freeman, Patti	Assistant to the Exec Director	Usher, Christopher	Software Programmer
Green, Greg	Mech Designer/Instr. Maker	Vermeulen, Tom	System Programmer
Ho, Kevin	Instrument Manager	Wells, Lisa	Remote Observer
Hughes, Steve	Electrician	Wilson, Matt	Computer Software Eng.
Isabel, Ilima	Custodian	Wipper, Cameron	Remote Observer
Isani, Sidik	Software Engineer	Withington, Kanoa	Software Manager
Januszewski, Helen	Remote Observer	Wong, Raycen	Mechanical Engineer
Jones, Windell	Instrument Engineer	Yost, Tracy	Director of Finance and Admin.
Laychak, Mary Beth	Director of Strategic Communications		

Outreach Report

Outreach in Canada

CFHT continued writing a column in the bi-monthly Royal Canadian Astronomical Society's journal, entitled "CFHT Chronicles" which debuted in the June 2015 edition. The column focuses on all aspects of CFHT; instrumentation, staff and science. Our strategy with the column is to make the work of CFHT relatable to the predominately amateur astronomy community readership and cultivate a sense of connection with CFHT. We have received nice feedback from RASC members who enjoy reading the column. In 2019, the columns highlighted scientific contributions from CFHT's 40 year history combined with current work. The partnership also provided opportunities for CFHT to set the record straight on the protest impacts in Hawai'i. One of the editors works for the CBC and reached out to Mary Beth Laychak (MBL) for impacts on the Starlink satellites on Hawai'i astronomy.



Figure 31 - Julie Boldoc-Duval introducing the CASCA teacher's workshop.

CFHT continued to partner with Discover the Universe on our 5th annual teacher's workshop at the June 2019 CASCA meeting. The workshop was free of cost to participants and focused on hands-on activities they can use in their classrooms. We hosted one workshop in Montreal. The timing of the CASCA meeting was during the last week of school, so we had fewer teachers able to attend than in years prior. The bulk of the presentations to the teachers were in French, which according to the workshop evaluations, was appreciated.

MBL and Laurie Rousseau-Nepton (LR-N) partnered with Ismael Moumen from Université Laval on the Astronomy for Canadian Indigenous People (ACIP) project. They visited two First Nations schools and reserves near Québec City. LR-N spoke to the students and community about her First Nations background, career path and science as a precursor to visits by the students to Mont Mégantic Observatory later in the summer. The ACIP project was funded again for 2020 and CFHT will continue to support the program.

MBL and LR-N both gave presentations during the CFHT User's meeting as part of the Montreal Pint of Science week. The talks were well attended.

CFHT is a sponsor of Canada's "Name ExoWorlds" competition for the IAU. MBL serves on the organizing committee and LR-N served as one of



Figure 32 - Laurie Rousseau-Nepton speaking with students on the reserve where her father lives.

the astronomers tasked with selecting the finalists from the public suggestions. CFHT donated fifty calendars to honorable mentions and thirty minutes of director's discretionary time on ESPaDONs to take a spectrum of the star hosting the exoplanet being named.

In 2020, we plan a similar outreach strategy, using CASCA as a gateway for opportunities for outreach in Eastern Canada. We are aiming to set up talks in visits to First Nations' Reservations and other potential collaborations. MBL has a tentative trip planned to Victoria in February to meet with the RASC chapter there. We will continue to work with Discover the Universe on Teacher Workshops and continue to work with the Friends of the DAO to support initiatives in Victoria.

Outreach in France

CFHT was approached by Alain Cirou, editor of Ciel et Espace and Dom Perignon to provide summit tours for Dom Perignon as part of their Plenitude 2 event in Hawai'i in April. The tours went well, and we plan on trying to continue to work with Alain and Dom Perignon in the future.

CFHT hosted a booth at the 2019 SF2A meeting in Nice. The booth showcased the MSE virtual reality headset as well as CFHT's current suite of instrumentation. The booth was well attended and was featured on the school's news program.

We plan to continue to look for additional contacts in France. With the SF2A meeting in Paris this year, we will reach out to Alain to try and leverage that connection to expand our reach into France. We will propose another booth at the meeting in 2020.

Outreach in Hawai'i

CFHT participated in the usual assortment of community events, school visits, portable planetarium shows and summit tours. At each community event, our booth featured hands on activities designed to explain who we are and what we do. Our displays were visited by ~7000 people over the course of the year, similar numbers to last year.

As part of CFHT's effort to reach local school students, we have several projects in the works with schools statewide. We have partnered with Honoka'a Intermediate and High School. Currently, MBL serves on the School and Community Council for two local schools and offers support to the new STEM building built at Waimea Middle School. She also served on the North Hawai'i School Advisory Council for facility upgrades statewide. These connections give CFHT a prominent role in the local education community.



Figure 33 – Top: Mary Beth at the Dom Perignon star gazing event. Bottom: The CFHT/MSE booth at the 2019 SF2A meeting. The MSE VR system made a large impact.

Matt Wilson expanded his after school coding class into working with teachers at Waimea Elementary Schools in the classroom. The lessons developed by Matt and his collaborators teach the students to program in Python using Minecraft. Matt works with the IT lead for WES to run the program. Earlier in 2019 we hosted a workshop at CFHT for local teachers and Matt is working with a curriculum specialist to develop the lessons into classroom ready learning modules for teachers.

2019 continued the expansion of the North Hawai'i Journey Through the Universe. We partnered with Honokaa Elementary, Intermediate and High School, Waimea Elementary School and Paauilo to visit over 1800 students during Journey week. Staff from the Keck Observatory and UH's Institute for Astronomy joined our efforts. Between Journey Through the Universe and other classroom visits, CFHT staff directly interacted with over 3500 students, K-12. Our primary focus remains our North Hawai'i schools, but we are working with teachers across the island.



Figure 34 – Callie Crowder representing CFHT at Hilo Career Fair.

For the 2019-2020 school year, Maunakea Scholars added one additional school, Laupahoehoe Public Conversion Charter School, bringing our total to thirteen schools, reaching schools on every major Hawaiian Island, the first fully statewide astronomy outreach program. We have twelve mentors, primarily graduate students from the University of Hawai'i's Institute for Astronomy. 'Imiloa garnered funding to provide cultural and Polynesian wayfinding presentations to the students and communities in all of our participating schools. All of the Maunakea Observatories contributed time to the MKS program.



Figure 35 – A local 4th grade teacher at Waimea Elementary School at the Coding for Classrooms workshop.

In July, we awarded the second Hōkūala Scholarship to JC Dumaslan at a public event at 'Imiloa. The scholarship is awarded to a senior who participated in the MKS program and plans on majoring in astronomy in college. JC is attending UH Mānoa.

MKS received one grant this year - a \$80,000 grant from the Hawai'i Community Foundation. The HCF grant continued the MKS online astronomy class in partnership with UH Mānoa for students at our participating Big Island MKS

schools. The course will be held in Spring and Summer 2020. We expect to receive the remainder of the two year First Hawaiian Bank grant by the end of 2019. Mary Beth is organizing Maunakea Scholar’s participation in “Giving Tuesday” a national day of fundraising for non profit organizations.

CFHT sponsored three major community events this year: the CFHT 40th anniversary event on September 28th, the Waimea Solar System Walk held on October 26th and the Winter Star Party on December 7th. Over 400 people attended the anniversary event. We rented a dunk tank and bounce castle slide, had a complimentary BBQ, face painting, music and a birthday cake donated by a local grocery store (KTA). The dunk tank raised money for our Maunakea Scholars program and Waimea Elementary School. The event received statewide media coverage and very positive responses.



Figure 36 – Mary Beth with JC, the 2019 Hokuāia recipient.

The party capped off over a week of activities. CFHT’s director Doug Simons (DS) kicked the celebrations off with a talk on September 20th at ‘Imiloa Astronomy Center in Hilo. He covered the discoveries, instruments, and people of CFHT over the past 40 years. CFHT staff marched in the 44th Annual Paniolo Parade in Waimea. The parade, chaired by one of our retired staff members Moani Akana, celebrates the cowboy culture and history of Waimea. CFHT also donated books to our local public library and a few local schools, sponsored and volunteered at the weekly Waimea Community Meal, and treated our local

teachers to chocolate covered macadamia nuts. We also bought our local crossing guard breakfast and learned she went to Waimea school with the daughter of one of our early directors, René Racine.



Figure 37 – CFHT staff volunteering at the 40th anniversary event on September 28th. Birthday party volunteers wore our new CFHT t-shirts. CFHT’s graphic design intern designed the shirts.

The Solar System Walk was organized in conjunction with Keck Observatory and IfA Hilo and focused on the contributions the Maunakea Observatories have made towards our understanding of the solar system. Roughly 300 people participated in the walk, which received coverage on state television news broadcasts and in Big Island newspapers.



Figure 38 – Akamai interns with Doug Simons (left to right Kaiaka, Danielle, and Aliyah).

Eight of the Maunakea Observatories, 'Imiloa and University of Hawai'i continued the Kama'aina Observatory Experience summit tours until the closure of the Maunakea Access Road in July due to protests. Prior to the stoppage, CFHT played an active role in the organization and coordination of the tours. The program is very successful - reservations book quickly each month and the post visit reviews are stellar.

AstroDay Hilo is a Big Island event occurring every May for the past 16 years. This year the Maunakea Observatories expanded the event to West Hawai'i for the second time on

November 3rd. The venue used last year was not available, but we worked with Kealakehe high school to hold the event the same day as their robotics tournament. We estimate 750 people attended. Astro Day West received statewide coverage on television and Big Island newspapers.

We offer a variety of unpaid internships and volunteer opportunities to local high school students. The students are all interested in astronomy or engineering and find mentor support from the CFHT staff. CFHT had three Akamai interns over the summer. Kaiaka Kepa-Alama worked with Ivan Look and Grant Matsushige to design a scaled down dome vent prototype for testing solutions to the dome vent icing issues. The prototype was fabricated in Hilo. Danielle Young worked with Greg Barrick and Tom Benedict on improved insulation for SPIrou. Aliyah Pana worked with Windell Jones and Simon Prunet on the astrometric camera. All three students' projects were impacted by the loss of summit access, more so for Danielle and Aliyah.

CFHT hosted a graphic design intern for the second summer through the STEMWorks program. Amanda Schiff worked with MBL to design CFHT t-shirts, film and edit videos of CFHT staff, finalize the new CFHT business cards and develop social media assets. Amanda continues to work with MBL on projects as she finishes her senior year of high school. MBL recently took on another intern, Naomi Schubert a senior at Kamehameha Schools. Naomi will be researching potential grant opportunities for Maunakea Scholars.

Social Media

The CFHT FaceBook page grew from ~2,775 followers last year to 3,570 as of this report. Posts are made daily Monday-Friday and focus on good news coming out of CFHT with emphasis on the staff, science, instrumentation and outreach. We started several new social media initiatives this year, most notably "Better Know a CFHT Staff Member" video series and the very popular "Pets of CFHT" photos. These posts are designed to highlight the diversity of the CFHT staff while putting a face on the facility. The CFHT cloud cams and webcams prove popular and are often reposted or used by media to show snow in Hawai'i.

CFHT continues to maintain a Twitter presence. The content is more astronomy focused since many of our PIs are on Twitter, but we are often retweeted by the Hawai'i State Department of Education. Our

followers have increased from 988 in 2019 to 1,450 followers today. We added a CFHT Instagram account in spring 2020 where we have 380 followers.

During the height of the protests, managing the CFHT social media presence required three people - MBL, Nadine Manset (NM) and Callie Crowder (CC). We had to manage and comment on all posts during the protests ensuring that the CFHT page remained as civil as possible. As

the social media storm quieted, MBL returned to managing the FaceBook and Twitter account while CC continues to post on Instagram for CFHT. The content on all three accounts are complementary.

MSE

2019 saw the creation of the MSE Education and Public Outreach working group. The EPO WG is co-chaired by Mary Beth and Kelly Lepo from McGill University. It is comprised of representatives from each of the MSE partners. The MSE EPO working group was charged by the MSE Management Group with analyzing the EPO needs and expectations of each partner, performing a survey of EPO activities at other comparable astronomical observatories, and recommending a broad MSE outreach strategy - including preliminary budget estimates - to the Management Group. The group will submit their preliminary document to the MSE MG at the December meeting along with a presentation by MBL at the meeting.

MSE and the MSE VR tours were heavily featured at the AAS, MSE, CASCA, and SF2A meetings as the signature component of the CFHT booth. At all four conferences, the VR made an impression and many people commented on the high quality of the rendering.

CFHT and MSE are featured on the SolidWorks website and are the subject of a six and a half minute long video by the company. Greg Green attended the SolidWorks 2019 launch and was interviewed extensively for all of the SolidWorks materials. We received considerable social media attention throughout the year due to SolidWorks.

Awards

In June MBL was among the Pacific Business News “40 Under 40” awardees – an honor that goes to the forty most influential people in Hawai’i under the age of 40. She was recognized for her work on Maunakea Scholars and strategic communications for the Maunakea Observatories. She is the first person from the Hawai’i astronomy community to be honored in this way. In July she was also awarded the prestigious Pūalu Award from the Kona-Kohala Chamber of Commerce for her work in community education.

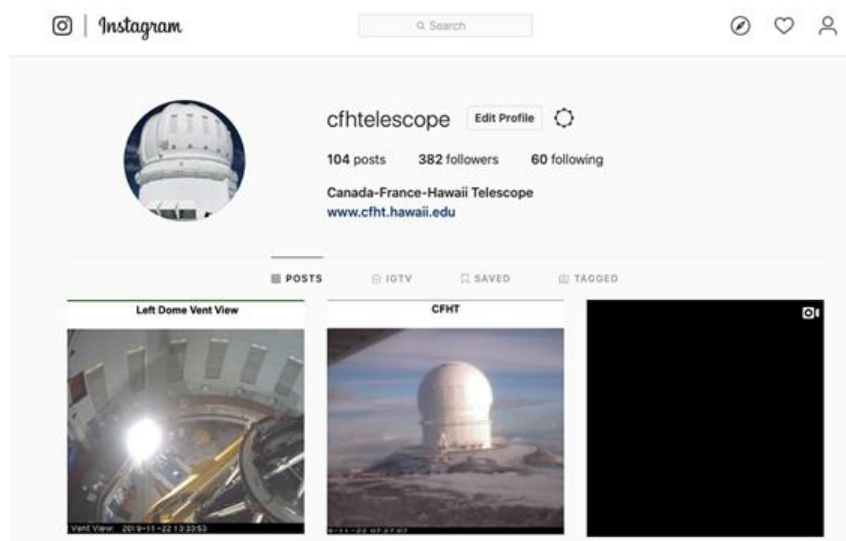


Figure 39 – Photos from CFHT’s Instagram account are shown.

MKO-Wide Communications

Joint Maunakea Observatories communications efforts took a tremendous amount of time and effort over the course of 2019. NM, MBL and DS coordinated with key stakeholders inside and outside of the observatory community to prepare for and ultimately manage the MKO response to the TMT protests.

NM is the chair of the Maunakea Observatories Crisis Communications (MKCCWG) working group, an extension of her role as the Maunakea Astronomy Outreach Committee chair, a position she has held for over five years. The MKCCWG formed in the wake of the 2015 protests and was reactivated in the spring in anticipation of the protests related to TMT. The MKCCWG is comprised of representatives from each existing MKO and IfA with TMT, UH System and ‘Imiloa as guest members. The MKCCWG is responsible for managing the internal and external communications for the Maunakea Observatories as a collective. CFHT staff were involved in the creation of all MKCCWG documentation in conjunction with the Bennet Group and representatives from Keck, Gemini and EAO.

During the heights of the protests, the CCWG met daily to coordinate communications efforts across the MKOs, field press inquiries, arrange interviews, manage social media, write talking points, and update the communications plan based on the ever-changing landscape. CFHT communications leads were constants in the emergency communications operations center, one of them was present at all times during the first month of the protests.

In preparation for the anticipated protests, CFHT and Bennet Group conducted staff briefings at CFHT, Keck, Hale Pōhaku, and two combined briefings in Hilo for the Hilo based facilities to run through the communications plan with staff and address any concerns. Two additional trainings were held for front office staff in anticipation of concerning phone calls or visits. TMT also attended some of the sessions to share what they could about TMT communications plans. CFHT spearheaded the creation of the all MKO email listserv and text message alert system. The system allows a single authorized individual to send preapproved emails and text alerts to MKO staff regarding road closures and protest conditions. The system was successfully used several times up to the evacuation of the summit and remains active.



Figure 40 – Top: Mary Beth Laychak received the Pūalu Community Education Award from the Kona-Kohala Chamber of Commerce and (bottom) the Pacific Business News “40 Under 40” award, which is a statewide competition.

In July and August, numerous CFHT staff were interviewed by media regarding access issues, CFHT lost science, staff impact, etc. The impact of the collective MKO interviews is summarized in the graphic below. The two peaks correspond to the days immediately following the withdrawal of all MKO staff from the summit (first peak) and the announcement of going back to operations (second peak).

Since August, core members of the CCWG continued to be active behind the scenes. NM hosted twice weekly telecons where members of the CCWG stay updated on media and legislative engagement opportunities, coordinate resources when important events occurred, and created/compiled shared resources.

NM and MBL organized and executed another round of MKO staff visits with sessions in Waimea, HP and Hilo. They met with roughly half of the total MKO staff. The purpose of the presentation was to update staff on efforts to reopen the Maunakea Access Road, touch base with staff concerns, and present the efforts of the CCWG towards giving the MKOs a voice in the preceding months.



Figure 41 – Global media hits pertaining to the Maunakea conflict during July – September 2019 is plotted. The first peak corresponds to the initial protests while the second peak stems significantly from the coordinated communications of the Maunakea Observatories.

2019 Publications Including CFHT Data

The past year was another productive one from a publications standpoint with 75 papers stemming from PI and Large Programs (facility papers), another 70 papers coming from CFHT's data archive, and 73 papers including CFHT cataloged data. Totalling 212 unique publications, on a per telescope basis CFHT continues to be among the leading sources of ground-based astronomy publications. This is a tribute to our international team including scientists, instrument builders, funders, and of course, CFHT's staff that keeps our Maunakea and Waimea facilities in excellent shape.

Facility papers (75)

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