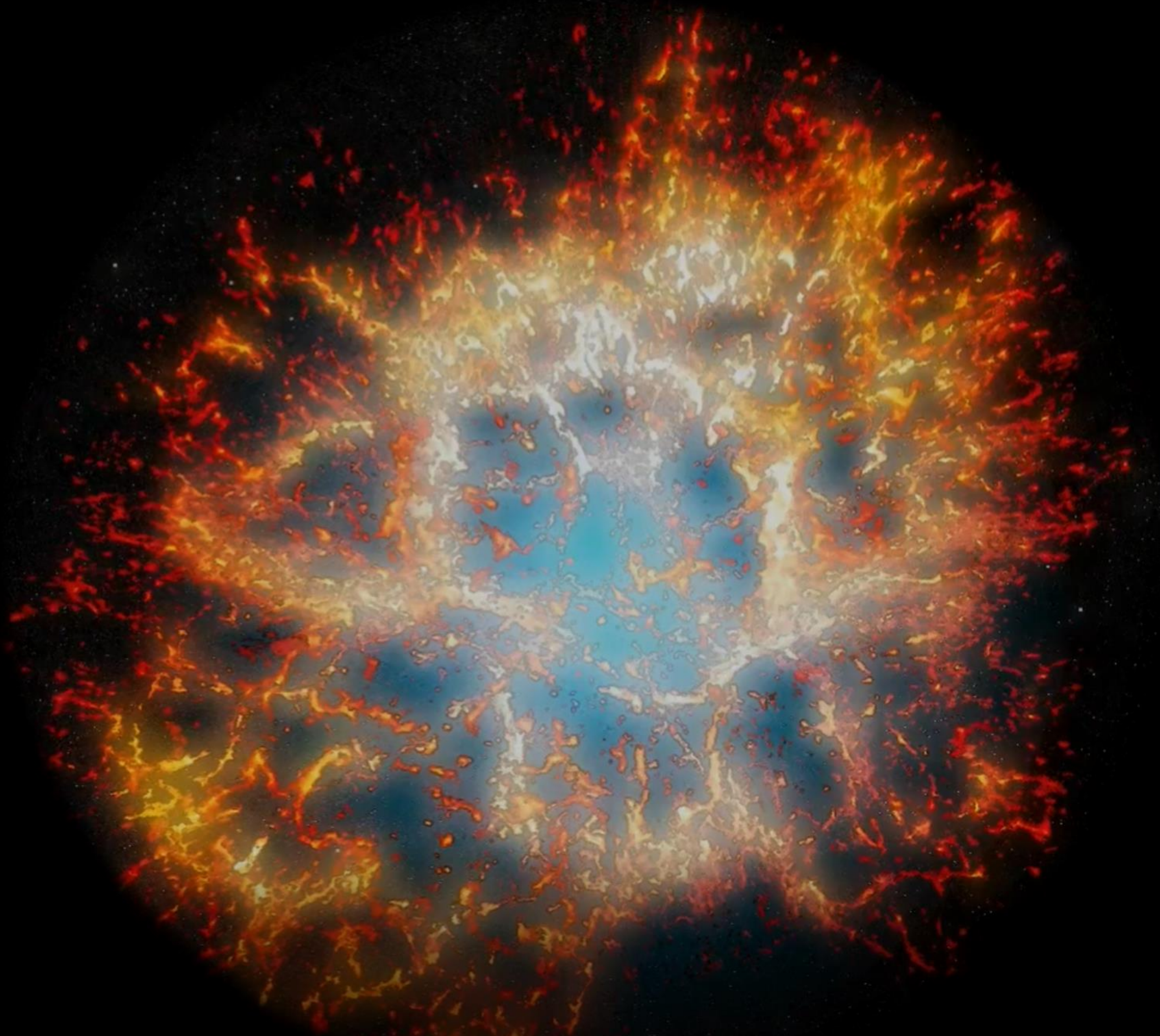
2020 CFHT Annual Report



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Front and back covers: On the front is a computer rendering of the Crab Nebula (M1) derived from SITELLE data which were used to generate a sophisticated 3D model of this supernova remnant. This dramatic example of SITELLE data shows the promise of the world's first imaging FTS working at optical wavelengths at a major observatory. On the back cover is a sunrise from Maunakea taken a few weeks into the COVID shutdown of all Maunakea Observatories in April 2020. Details can be found in the Director's message.

Director's Message

The year 2020 was certainly one of the most challenging in the 40+ year history of CFHT, as a slow motion global natural disaster washed upon our shores, devastating the Hawai'i Island economy, forcing the Maunakea Observatories to shut down and then adapt to completely new operating models with most staff working from home. The once-per-century pandemic had numerous ripple effects across CFHT and our community. With the termination of trans-Pacific flights, Hawai'i's tourism industry (among the largest economic sectors in the State) was decimated, leading to thousands of workers being laid off across Hawai'i Island. The Maunakea Observatories all suspended operations in late March in concert with emergency proclamations from State and County agencies. It was an eerie time, with a billion dollar research complex on Maunakea going from full throttle to idle in just a couple of days. There was great uncertainty about when we would resume operations, how many might contract COVID-19 across the island, and what so many people in our community would do without incomes for a long time.

CFHT had some advantages to adapting, with fully remote operations in place for years, all instruments relying upon cryo-coolers (instead of LN2) to be kept cold, and 24/7 telemetry available to monitor critical summit systems. Our software team launched a herculean effort to support everyone working from home, with Slack, Zoom, and other communications systems enabled like never before. A few weeks into the shutdown, feeling rather stir crazy with all the observatories closed, businesses shuttered, and no tourists


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COVID-19 shutters Mauna Kea telescopes

By Timothy Hurley
thurley@staradvertiser.com

The observatories on Mauna Kea have shut down their operations in response to Gov. David Ige's stay-at-home order aimed at preventing the spread of COVID-19.

This is the second time in less than a year the world-class science produced by the dozen or so observatories atop Hawaii's tallest mountain have ground to a halt.

The first time was last summer at the beginning of the protest against the Thirty Meter Telescope, when Mauna Kea Access Road was blocked and deemed unsafe to travel for nearly four weeks.

"It's deja vu," said Doug Simons, director of Canada-France-Hawaii Telescope. "We know the drill."

Like last summer, the latest shutdown will affect more than 500 technicians, astronomers, instrument scientists, engineers and support staff who work at both the summit and the observatory bases down below.

Most of the work is federally funded and therefore few, if any, employees will be laid off or furloughed for the time being, Simons said.

The largest impact will be on the science. Last year's monthlong shutdown interrupted hundreds of observing programs run by scientists from around the world and affected about 100 scientific publications that would have used Mauna Kea-generated data.

STAR-ADVERTISER
Doug Simons

Simons said he would expect the same thing to happen now for every month the facility is out of operation.

"It's a big blow," he said, adding that it's likely some scientific discoveries also will be lost. "We don't know things we miss because we weren't looking."

Another setback is the cancellation of the upcoming second run of the Event Horizon Telescope, the global array that includes the James Clerk Maxwell Telescope on Mauna Kea.

The array of telescopes, which last year offered up the first-ever image of a black hole, was due to start observations at the end of March to build on the first set of results. A combination of weather patterns and celestial mechanics makes it impossible to perform the observation at any part of the year other than a period from late March to early April.

Despite the devastating impact on science, Simons said the observatory directors didn't hesitate to shutter operations in response to the governor's mandate.

"The health and safety of our staff and community will always be our highest priority," he said. "We understand the necessity of doing whatever we can to stunt the spread of COVID-19. That's why our teams are staying home."

Employees have been asked to dedicate themselves to work that can be accomplished without having to travel to the summit or the office.

Any interaction at the facilities will be limited to emergency response and essential functions, provided that social distancing requirements are maintained. Emergency responses might include fire alarms, power

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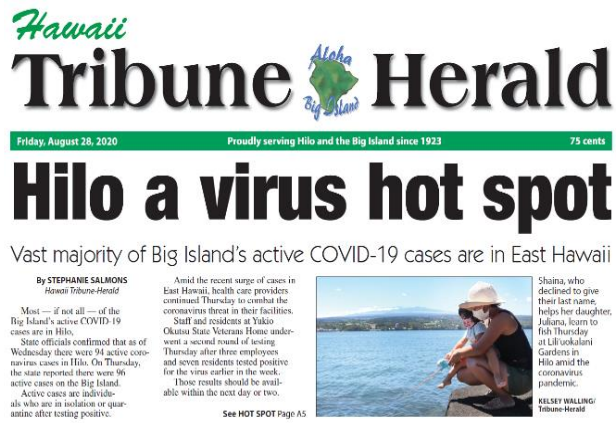
Hawaii Tribune Herald
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Hilo a virus hot spot

Vast majority of Big Island's active COVID-19 cases are in East Hawaii

By STEPHANIE SALMONS
Hawaii Tribune-Herald

Most — if not all — of the Big Island's active COVID-19 cases are in Hilo.

State officials confirmed that as of Wednesday there were 94 active coronavirus cases in Hilo. On Thursday, the state reported there were 96 active cases on the Big Island.

Active cases are individuals who are in isolation or quarantine after testing positive.

Amid the recent surge of cases in East Hawaii, health care providers continued Thursday to combat the coronavirus threat in their facilities.

Staff and residents at Yukio Okutsu State Veterans Home underwent a second round of testing Thursday after three employees and seven residents tested positive for the virus earlier in the week.

Those results should be available within the next day or two.

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Shaina, who declined to give their last name, helps her daughter, Juliana, learn to fish Thursday at Lili'uokalani Gardens in Hilo amid the coronavirus pandemic.

KELSEY WALLING/ Tribune-Herald

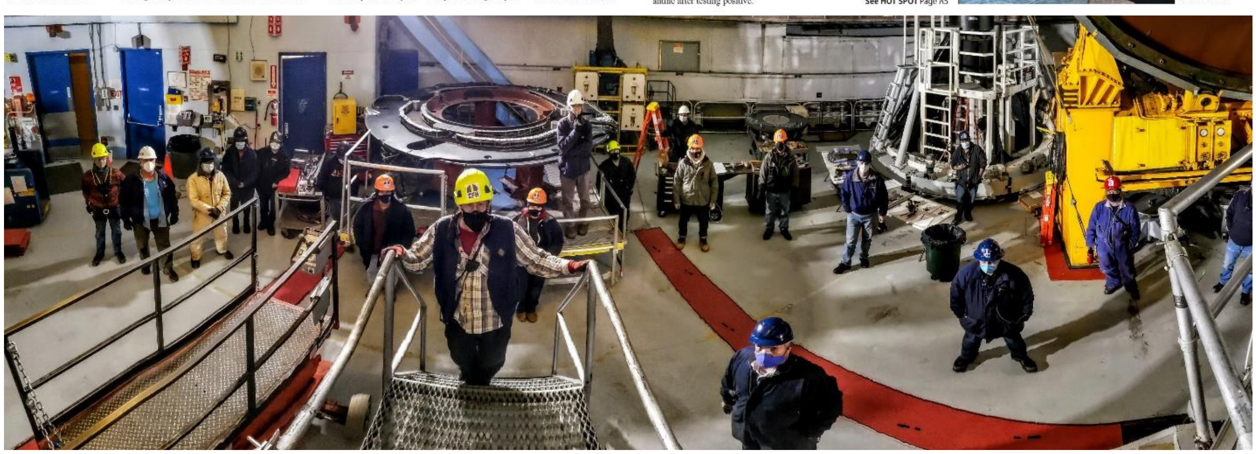


Figure 1 – Headlines and images that captured some key moments in 2020 as CFHT braced for and adapted to functioning in the midst of a pandemic. Across the top, spring and summer brought waves of COVID through Hawai'i that closed all Maunakea Observatories for the better part of 2 months. At the bottom is CFHT's engineering team, undertaking a delicate and complex shutdown to recoat CFHT's primary mirror during September 2020.

around, I realized it would be a unique time to visit the summit and reconnect on my way to pick up something from the office in Waimea. So I drove up to the summit in my truck before dawn one April morning equipped with a thermos of coffee and my camera. It was one of the most memorable and surreal times I've ever had on Maunakea since my first trip there 35 years ago. At that moment I was literally the only person on the world's tallest mountain, watching a riveting sunrise, witnessing intense colors erupt on the eastern horizon. Shivering in a cold wind, with eyes watering from the cold and emotion of the moment, the serenity and power of the mauna never spoke to me more profoundly than that quiet time, in the early days of the Great Pandemic of 2020. The photo on the back cover of this year's Annual Report was taken during that very personal visit to the summit of Maunakea.

Figure 2 – These photos show some of the many ways CFHT engaged the COVID storm. At top is one of many illustrations from the Keiki Heroes program which focused on helping young children understand COVID and protect themselves and their families. In the middle, CFHT ʻohana members (left to right) Patti Freeman, Lisa Wells, and Arturo Sayco are seen packing kupuna food boxes at the Hilo Food Basket warehouse. Along the bottom is a screenshot of the first fully online SAC meeting – a complete success.

Roughly 6 weeks later, working with the Governor's and Mayor's offices, the Maunakea Observatories were allowed to resume operations, albeit with numerous restrictions to protect the health of our staffs. CFHT was among the first observatories on Maunakea to resume operations, creating some level of normalcy in an otherwise extremely abnormal situation. Like many organizations, just keeping a sense of personal connection between staff members when long duration physical isolation was required was a basic concern of mine. Since then we have relied upon weekly "talk story" sessions to remind us all how we sound and what we look like. Someday I will relight the grills at the office and the CFHT ʻohana will reunite in person, again.

CFHT's story was a fortunate one in a sea of despair on Hawaiʻi Island with >25% unemployment, literally all resorts closed, and staggering food lines forming around the island. CFHT, like all the Maunakea Observatories, responded by rewiring our outreach programs and focusing on food security and PPE for the community. Staff packed food for delivery to needy elders, used CFHT fleet trucks to distribute thousands of pounds of food, designed and built custom PPE for use in hospitals, fire departments, and schools, and created the Keiki Heroes program - one of the largest community education programs ever undertaken by the observatories. Keiki Heroes filled a void in COVID education by helping teach K-5 students about COVID and how they can help protect themselves and their families. These programs had nothing to do with astronomy and everything to do with being deeply committed members of our community. They deserve an entire chapter in the future chronicles of CFHT as an example of the heart of our staff and their ability to rapidly adapt to a public crisis while sustaining operations and keeping safe.

Science Report

CFHT Explores New Frontiers in Multi-Messenger Astronomy

Using MegaCam a Canadian-led team of researchers placed one of the tightest limits to date on the light produced by the first observed high-probability merger between a neutron star and a black hole.

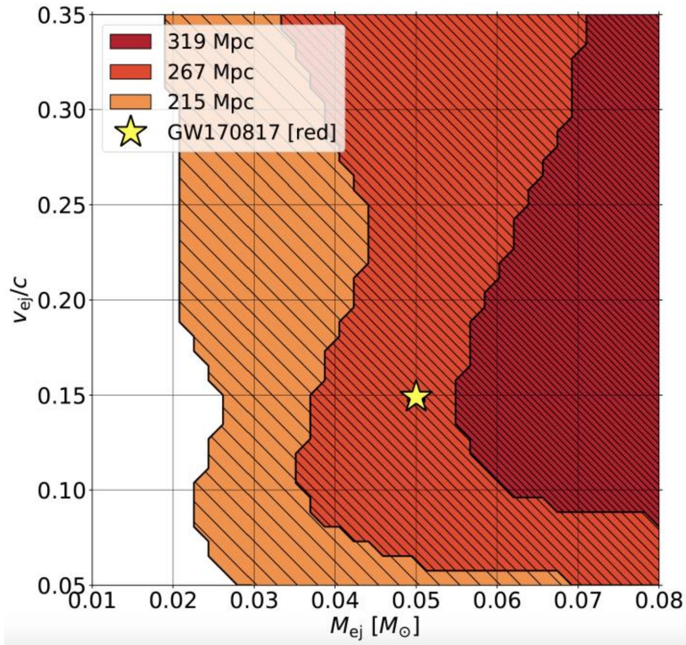


Figure 3 – Allowed parameters for the "ejecta" (material ejected during the merger): the ejecta mass in solar masses and the velocity of the ejecta as a fraction of the speed of light. Regions which are colored are those which were ruled out by deep CFHT MegaCam observations. The regions which are not allowed depend on the distance to the source, measured within a range of ~100 Mpc (300 million light years) by LIGO/Virgo. Here, the constraints are shown for distances of 215 Mpc (700 million light years), 267 Mpc (870 million light years), and 319 Mpc (1 billion light years). The yellow star shows the parameters measured for the "red" (material in the ejecta which shines mostly in the near-infrared) component of the kilonova associated with the binary neutron star merger GW170817. A GW170817-like kilonova is ruled out to 267 Mpc, and the mass of the total ejecta is constrained to less than 0.04 solar masses. For a typical neutron star with mass 1.4 times that of our Sun, this indicates that over 97% of the original neutron star was immediately consumed by the black hole during the merger.

On 14 August 2019, a gravitational wave signal was detected by both the Laser Interferometer Gravitational-Wave Observatory (LIGO) and its European counterpart Virgo. This signal was likely produced during the last moments of the in-spiral of a neutron star and its companion black hole, followed by the merging of the two objects. The gravitational waves – ripples in the fabric of space-time itself – created by the merger travelled almost 900 million light years before reaching the two LIGO detectors in Hanford, Washington and Livingston, Louisiana and the Virgo detector near Pisa, Italy. This type of signal is aptly named a “chirp.” Gravitational waves cannot be observed by conventional telescopes that detect light, but can be detected by the specially designed LIGO and Virgo interferometers.

The detected signal, named GW190814, was one of the strongest gravitational wave signals ever measured. The odds of the detection being a false alarm were incredibly remote: 1 in 10^{25} years, or 1 in a million, billion times the age of the Universe. The LIGO-Virgo collaboration traced the event to a 27 square degree region in the sky – approximately the size of a fist held at arm’s length – and promptly announced their detection so astronomers using conventional telescopes could join the observations.

“The merger between a neutron star and a black hole, the most exciting scenario for this case of GW190814, sits at a new frontier in astronomy” said Nicholas Vieira, lead author on the new paper. “Events like GW190814 can be ‘multi-messenger’, in which we learn about the detailed astrophysics of the merger by linking one cosmic messenger, the gravitational waves detected by LIGO and Virgo, to another cosmic messenger, in this case the light we can observe with a telescope like CFHT.”

During the merging of a pair of neutron stars or a neutron star and a black hole, the violent tides in the system tear apart one or both of the neutron stars and fling away extremely neutron-rich material. This neutron-rich material produces radioactive forms of the heaviest elements, including gold and platinum. Neutron star mergers may be the dominant site for the production of these heavy elements across the Universe. These elements radioactively decay, powering a rapidly-evolving, short-lived event called a kilonova. These objects typically reach their peak brightness in visible light within ~2 days of the merger and in the infrared over the next 5 - 10 days. The first and only unambiguous kilonova to-date was observed on 17 August 2017 in the landmark binary neutron star merger GW170817.

John Ruan (PI of the CFHT program), Daryl Haggard of McGill University, and Maria Drout of University of Toronto led this new campaign to try and nail down an electromagnetic counterpart to the gravitational waves with CFHT's MegaCam. The team started their observations less than two days after the detection of gravitational waves and continued up to nine days after the detection. They took advantage of MegaCam's large field of view of ~1 square degree to tile the region of the sky with a 50% probability of finding the gravitational wave source and used targeted observations of known galaxies in the 90% probability region to search for a kilonova event. Owing to the excellent depth reached by CFHT and the large field of view of MegaCam, these observations are among the deepest and most useful searches for an optical counterpart to GW190814 to date.

No such optical counterpart was discovered by the authors or any other teams. However, the depths achieved by CFHT MegaCam's exquisite images can be understood as upper limits on the brightness of a kilonova. These limits on the brightness of the source can then be translated into limits on the amount of material which was swallowed by the black hole and the amount which escaped this fate. The team was able to use their observations to calculate the mass that escaped was less than 0.04 solar masses, or less than 4% the mass of the Sun. For a typical neutron star, which has a mass around 1.4 times that of the Sun, this means that at least 97% of the star was immediately swallowed by the black hole. This mass limit, which is the strictest presented to date, tells us that the neutron star companion must have been almost or completely gobbled up by the black hole. Alternative explanations, such as the possibility that the lighter object in the merger was not in fact a neutron star but actually a very low-mass black hole, are also being considered. Ultimately, an announcement from the LIGO-Virgo collaboration on the details of GW190814 may help settle these questions. The insights of LIGO-Virgo and CFHT MegaCam observations in conjunction are much more than the sum of their parts.

"While the team didn't detect an optical counterpart to this event, their follow-up observations show the importance of wide field cameras like MegaCam in this new era of multi-messenger astronomy" said Daniel Devost, director of science operations at CFHT. "We look forward to CFHT playing a leading role in this new exploration of the Universe in the coming years". The team involved institutions from Canada and the United States. More information can be found in their paper.

Galactic Census Reveals Origin of Most "Extreme" Galaxies

Astronomers have found that the key to understanding galaxies with "extreme" sizes, either small or large, may lie in their surroundings. In two related studies, an international team found that galaxies that are either "ultra-compact" or "ultra-diffuse" relative to normal galaxies of comparable brightness appear to reside in dense environments, i.e., regions that contain large numbers of galaxies. This has led the team to speculate that these "extreme" objects could have started out resembling normal galaxies, but then evolved to have unusual sizes through interactions with other galaxies.

The team identified both ultra-compact and ultra-diffuse galaxies as part of an unprecedented census of galaxies residing in the nearby Virgo cluster. The investigation used data from the Next Generation Virgo Cluster Survey (NGVS) using MegaCam. At a distance of 50 million light years, Virgo is the galaxy cluster nearest to the Milky Way, and contains several thousand member galaxies, the majority of which are revealed, for the first time, in the NGVS data.

Astronomers discovered ultra-compact dwarf galaxies (UCDs) a quarter century ago, and they are the densest known galaxies in the Universe. Competing theories describe UCDs as either large star clusters, or as the remnants of larger galaxies that have been stripped of their stellar envelopes.

"We found hundreds of UCDs in the nearby Virgo galaxy cluster, and at least some of them appear to have started their lives as larger galaxies," said Dr. Chengze Liu of Shanghai Jiao Tong University, lead author of the first study.

While UCDs are similar in appearance to a large star cluster, a number of UCDs in this study were found with faint stellar envelopes surrounding the central, compact core. These envelopes could be the last remnants of a galaxy that has gradually been stripped away by gravitational tidal forces from neighboring galaxies. Additionally, UCDs were found to inhabit preferentially the regions of the Virgo cluster with the highest galaxy densities. Together, these pieces of evidence point to an environmentally-induced transformation as being responsible for producing some UCDs. Ultra-diffuse galaxies (UDGs) are a mystery at the other end of the size spectrum. They are much larger, and more diffuse, than typical galaxies with similar brightness. Some theories suggest that UDGs are massive galaxies whose gas --- the fuel for their star formation --- was removed before many stars could form. Others suggest that they were once normal galaxies that have been made more diffuse through mergers and interactions.

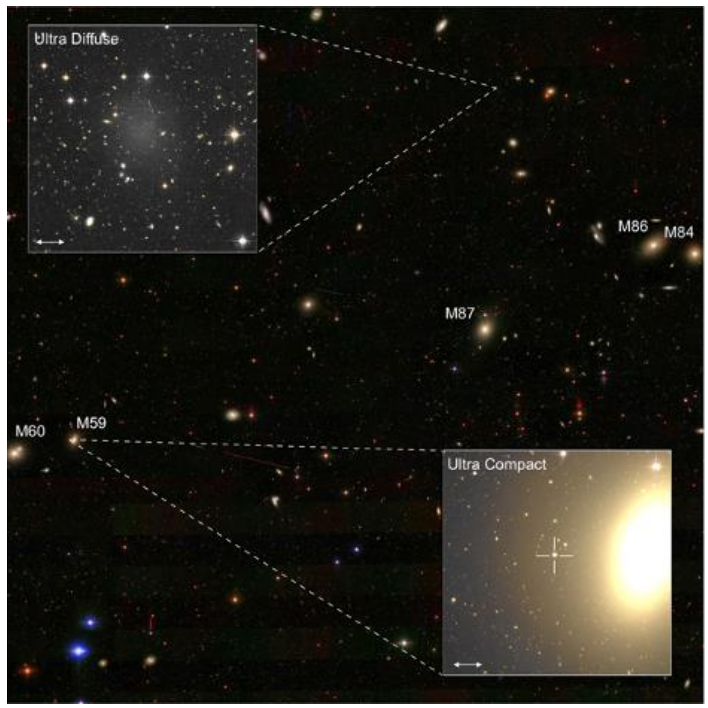


Figure 4 - A wide field view of the central region of the Virgo Cluster, measuring 4.4 million light years on each side, from the Sloan Digital Sky Survey. Some of Virgo's brightest member galaxies are labeled, including Messier 87, or M87, which is located close to the cluster center. Insets show deep images of two structurally extreme galaxies, taken with the MegaCam instrument on CFHT as part of the Next Generation Virgo Cluster Survey. An ultra-compact dwarf is within the crosshairs in the lower inset, while an ultra-diffuse galaxy is featured in the upper inset. These galaxies are nearly a thousand times fainter than the bright galaxies visible on this image. Although the compact and diffuse galaxies contain roughly the same number of stars, and their total brightness is similar, they differ in area by a factor of more than 20,000. The scale bars in each inset represent a distance of 10,000 light years. Image credits: Sloan Digital Sky Survey, Canada-France-Hawaii Telescope and the NGVS team.

"We found that the ultra-diffuse galaxies in the Virgo cluster are more concentrated toward the dense cluster core, indicating that a dense environment may be important for their formation," said Dr. Sungsoon Lim of the University of Tampa, and the lead author of the second study. "The diversity in their properties indicate that while no single process has given rise to all objects within the UDG class, at least some UDGs have appearances suggesting their diffuse nature is due to tidal interactions or to the merger of low-mass galaxies."

Another mystery is that some ultra-diffuse galaxies were found to contain significant populations of globular star clusters. "The intense star-forming events needed to make globular clusters generally make a galaxy less, rather than more diffuse, so understanding how we get globular clusters in ultra-diffuse galaxies is an interesting challenge," said Prof. Eric Peng of Peking University's Kavli Institute for Astronomy and Astrophysics, and co-author on both studies.

"To find galaxies that are truly unusual, you first need to understand the properties of so-called normal galaxies," said Dr. Patrick Côté of the National Research Council of Canada's Herzberg Astronomy and Astrophysics Research Center, and an author on both studies. "NGVS provides the deepest, most complete look at the entirety of the Virgo cluster galaxy population, allowing us to find the most compact and most diffuse galaxies, advancing our understanding of how they fit into the general picture of galaxy formation."

These research results have been presented in two papers that were published recently in the Astrophysical Journal (Lim et al. 2020; Liu et al. 2020).

New Machine Learning Applications for SITELLE

Machine learning, a new technology revolutionizing the analysis of large data sets, has gained traction in the astronomical community for the past decade. A team of researchers led by Carter Rhea from the Université de Montréal and Laurie Rousseau-Nepton of the Canada-France-Hawaii Telescope are spearheading efforts to bring machine learning into the flow of SITELLE data analysis. In the first paper of the series, the team shares their application of a convolutional neural network to SITELLE spectra to estimate kinematic parameters.

SITELLE, CFHT's unique imaging Fourier Transform Spectrograph, is capable of generating 3D data cubes containing more than 4 million spatial pixels and a spectral resolving power of 10,000 resulting in a total of over 40 billion spectral pixels or spaxels. Analysis on this volume of data requires a dedicated suite of tools designed specifically for SITELLE by Thomas Martin, astronomer at the Université Laval. The ORCS (Outils de Réduction de Cubes Spectraux) software package was designed precisely for this reason; using ORCS, an astronomer can fit each spectrum in the data cube. SITELLE measures the amount of light, or photons, that hits each pixel during the exposure. ORCS "fits" those photon counts into a scientifically usable spectrum, enabling astronomers to learn about the complex physics in planetary nebulae and HII regions.

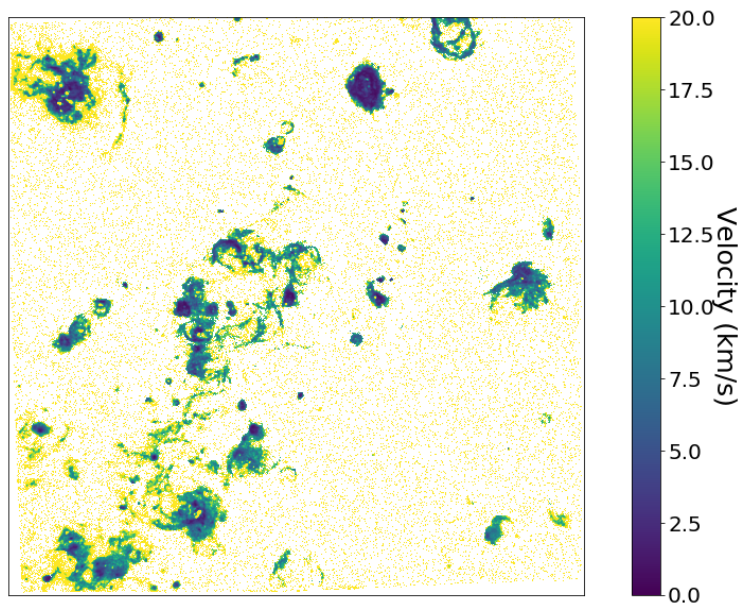


Figure 5 - Residual map of the recovered velocity parameter in the Southwest field of M33. The residual was calculated by taking the difference between the network's estimate and that of the ORCS fitting software.

Before fitting a spectrum, ORCS requires the user to input an initial estimate for the velocity and broadening parameters. Astronomers rely on previous studies of their objects to determine these initial estimates. However, these estimates frequently come from older, potentially outdated, research which may not be appropriate or available for all nebulae. An inaccurate initial estimate triggers a series of unsound calculations ultimately leading to an incorrect solution. Prior to the team's works, SITELLE users did not have a standard method for determining initial estimate values.

"When we started this project, we were hoping to capitalize on recent successes employing a machine learning technique known as a convolutional neural network to calculate spectral parameters," says Simon Prunet, CFHT resident astronomer. "Convolutional neural networks are becoming increasingly common in the field of image processing including recent success in astronomy."

These networks take spectra and break them down into their most important components, learning to extract key parameters from the input. Convolutional neural networks are trained with labeled data through a process known as supervised learning where the networks learn to associate patterns in the input images with corresponding output parameters. The networks are trained on pre-labeled data until they properly categorize inputs based on their labels. In the case of SITELLE, the team trained their algorithm on a suite of synthetic spectra specifically tailored to mimic actual data from the instrument. The synthetic data were generated using preexisting tools in another custom designed SITELLE software package, ORBS (Outils de Réduction Binoculaire pour SITELLE). After training the algorithm, it was extensively tested on freshly generated synthetic spectra. Once the algorithm demonstrated its capability of accurately estimating the velocity and broadening parameters of emission-lines in SITELLE spectra, the team progressed their testing to include real observations taken by SITELLE. The network was applied to a SITELLE field from the galaxy M33. The team selected M33, a spiral galaxy hosting an assortment of emission-line nebulae, supernovae remnants, and planetary nebulae, due to M33's well established velocity and line broadening input estimates. The results indicate that the network recovers the broadening and velocity values with errors similar to those found by ORCS.

"This type of analysis is a game-changer for astronomers using SITELLE," says Laurie Rousseau-Nepton, CFHT resident astronomer and SITELLE instrument scientist. "The network analyzes the data in a fraction of the time previously required, greatly speeding up the time it takes to reduce the enormous amounts of data generated by projects like our large program SIGNALS."

Carter Rhea, the machine learning project's lead and graduate student at Université de Montréal, notes that "This is the beginning of what we can do with machine learning to revolutionize data analysis from instruments such as SITELLE. It is incredibly exciting for me to work on the intersection of machine learning and astronomical data sets."

The team's paper is the first in a series of papers on machine learning applications towards SITELLE data. Learn more about the SIGNALS large program on their website.

New M92 Stellar Stream Discovered

A team of astronomers using the Canada-France-Hawaii Telescope discovered a new stellar stream emanating from the M92 globular cluster. This new stream suggests that M92 is actively being disrupted by tidal forces caused by our Milky Way Galaxy. This discovery utilized high quality data obtained as part of the Canada-France-Imaging-Survey (CFIS) using MegaCam at CFHT and from the Pan-STARRS 1 (PS1) survey on Haleakalā, Maui. The discovery of a stellar stream around M92 raises the question of the cluster's origin and could be used in the future to probe the innermost region of our Galaxy. The team estimates that the stellar stream has a mass equivalent to ~10% of the mass of the entire M92 cluster.

Stellar streams are long thin streams of stars formed as globular clusters or dwarf galaxies are ripped apart by the immense gravity of the Milky Way. The structures formed by these tidal forces are stable over many billions of years. Their longevity allows astronomers to use their presence to better understand the formation of galaxies like the Milky Way as a guide to determine the role of galactic cannibalism in galaxy formation. Additionally, stellar streams are excellent tools to probe the gravitational potential of our Galaxy and study the distribution of dark matter around it.

The team identified the 17° long stellar stream from the M92 globular cluster using an improved matched-filter method. This method aims to highlight a specific known signal in a noisy dataset and proves to be an extremely efficient tool to detect stellar streams around the Milky Way Galaxy.

Despite previous observations in this region, the newly discovered M92 stellar stream was hidden by the high number of foreground stars from the Milky Way disk. It was discovered because of the combination of high quality images from both CFIS and Pan-STARRS. The team also used proper motions obtained by the European space mission Gaia to confirm the existence of the stream.

The Canada-France Imaging Survey is an ongoing large program at CFHT using MegaCam. Allocated 271 nights, CFIS aims to address some of the most fundamental questions in astronomy including the assembly of the Milky Way, properties of dark matter and dark energy, and the growth of structure in the Universe from galaxies to clusters.

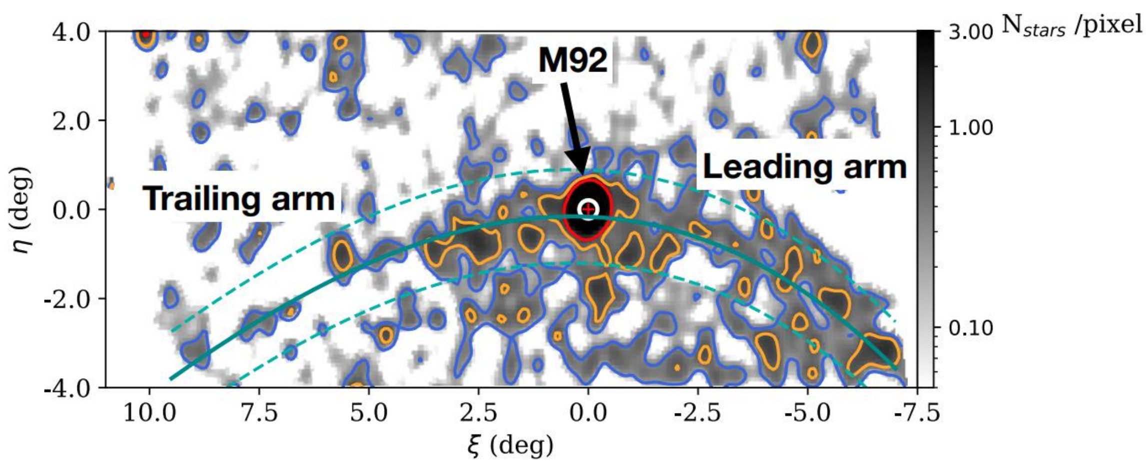


Figure 6 - Residual map of the number of stars per pixel along the M92 stream. The residual was obtained by applying the matched-filter techniques to the CFIS/PS1 data. The cyan line represents the center of the M92 stellar stream path. Image credit: CFIS team.

Engineering Report

Re-Coating Shutdown, Coating Chamber and Mirror System Improvements

The CFHT primary mirror was successfully re-coated and then reintegrated with the overall telescope structure in October 2020. The entire process took seven days at the summit to complete. The operation was broken into several teams based on task organization and the need to isolate people due to COVID-19. The coating team demonstrated a significant improvement in coating thickness, and at ~1000 Å, it is likely that this is the thickest coating to have been placed onto the mirror to date. The process actually started many months earlier as explained below.

Figure 7 - A happy coating team shows off a freshly coated primary mirror. Due to improvements in the coating chamber, the coating thickness for this runs exceeds all previous coatings by ~30-50%.

Filament electrode modifications: In May 2020 work resumed on the large coating chamber and in July replacement of the electrodes was finished. Once the work was completed, the chamber was test fired on a test fixture to establish the new radial thickness profile. While the new electrodes appear to produce a more even filament temperature across the chamber, the resulting coating from our test in early August was still thinner than desired. It should be noted that the coating thickness, although lower than average, was nevertheless within the range of past coatings.

Figure 8 - Modification of the chamber filament baffles.

Modelling of the chamber coating profile: In order to determine what changes could be made to improve the coating thickness, a model of the coating thickness surface distribution for the chamber was developed in Python. The measured coating profile obtained in August, as well as the last measured coating profile obtained in 2010, was consistent with the model except for the model's overestimate of the thickness at the 1.2 m radius of the mirror.

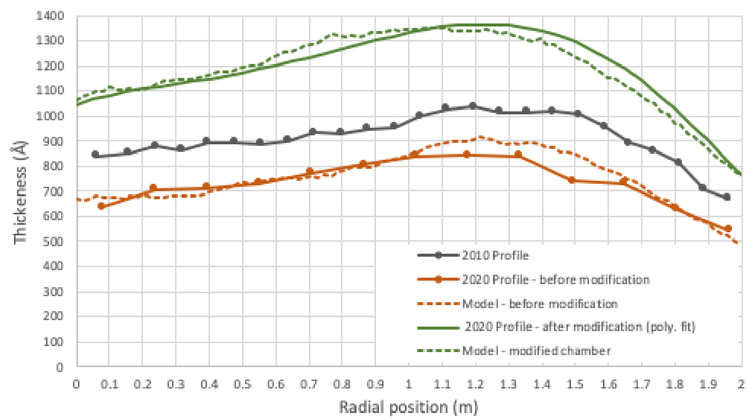


Figure 9 - Comparison of radial coating thickness profiles for the CFHT aluminizing chamber.

Analysis of the model indicated that much of the evaporated aluminum was being vignetted by the tungsten filament baffles and that increasing the un-vignetted solid angle seen by the filaments, either by increasing the diameter of the baffle tubes, or by shortening them, would lead to a much thicker coating with little risk of affecting the coating process details (e.g., increasing the filament aluminum load can lead to "drips"). Although the non-uniformity of the coating would increase, modeling in Zemax indicated that this would have no significant impact on the IQ. The worst case coating non-uniformity predicted was 70 nm, peak-to-valley, however the error on the wavefront is roughly half of this when the focus term is removed.

Investigation of the baffle door mounts indicated that raising the baffle doors and shortening the baffles by 4 cm (1.5" nominal) was a practical mechanical limit. The model indicated that this would lead to an improvement in the thickness by a factor of 1.7 near the edge of the mirror. Due to this change having a low risk of affecting the chamber operation with a potentially large gain in thickness, the baffle doors were removed, the baffles shortened and reinstalled in the chamber – all within a one week time-frame to allow a second test of the chamber.

As can be seen in Figure 9, the improvement in thickness gained by modifying the baffles over even the 2010 coating (which was a typical "thick" coating), is substantial – achieving for the first time >1000 Å in thickness over the entire mirror. This gives us substantial margin in producing a good coating.

Dry Air Mirror Purge System

Optical condensation sensor: An optical condensation sensor was installed on the telescope during the coating shutdown. This sensor consists of a camera mounted under the west-side mirror covers and aimed at the mirror surface. Lights mounted on either side of the camera provide illumination. The intention is only to use this sensor during daylight hours to establish a safe dead-band around the dew point values calculated from the relative humidity sensors near the mirror.

A target pattern was painted on the bottom of the mirror covers to help increase the contrast change in the camera image due to condensation on the mirror.

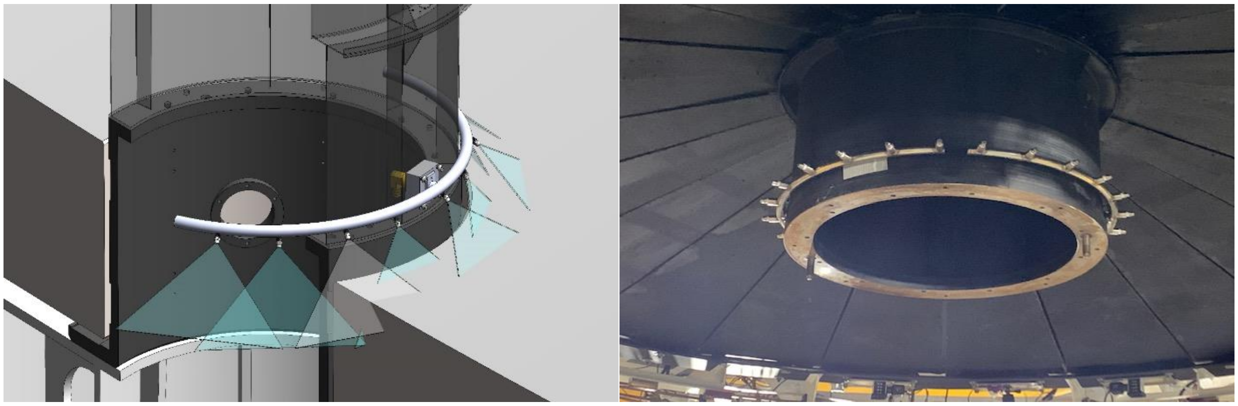


Figure 10 - (Left) Solidworks model view of the primary mirror dry air delivery ring mounted on the central spigot. Note that the CFD indicates that the orientation of the nozzles, delivery pattern or position of the ring above the mirror is not critical to the flushing time, or the distribution of water vapor concentration over the mirror after a few minutes of operation. (Right) Real view of the primary mirror dry air delivery ring mounted on the central spigot and installed on the telescope.

As a test of the system, on September 23rd humidity in the dome spiked and the dew point rose above the temperature of the mirror. Staff at the summit looked at the mirror and confirmed that water had condensed on the surface. Even though we didn't have the target pattern painted on the mirror covers, the effect of condensation in the condensation camera image was visually obvious. With the target now painted on the bottom of the mirror covers, another high humidity event will allow evaluation of several possible algorithms to determine which most reliably detects condensation.

Mirror dry-air purge system: A feasibility study was undertaken to determine what would be required to maintain the dew point of the air above the primary mirror surface below the mirror temperature. A computational fluid dynamics (CFD) model was developed in COMSOL Multiphysics to determine the flushing time of the cavity between the primary mirror and the mirror covers, as a function of the dry-air flow rate into this cavity. The model assumed a source of dry air near the central "spigot", with air flow outwards across the mirror and out of the gap between the primary mirror and cover.

The CFD model indicated that a flow of 5 l/s (10 CFM) would be sufficient to reduce the water vapor content in the cavity to a safe level, under most circumstances, in under 10 minutes. We have the dry compressed-air capacity to deliver this flow by turning on our backup air compressor. Once flushed, nominally after ten minutes, we plan to reduce the flow to 0.5 l/s, to maintain the relative humidity above the mirror in a safe range, as validated by the CFD model. Eventually, a bank of relative humidity sensors placed around the edge of the mirror will provide feedback that can be used to actively throttle the high and low dry air flow.

It is important to note that this system is primarily intended to keep the mirror dry. Although, it could be used to dry the mirror more quickly in the case of a condensation event, its predicted efficiency in doing so is unknown. The goal was to have the system working as soon as possible after the mirror was recoated to avoid condensation on the new coating. Most of what remains to complete is the implementation of the control scheme using the OAP software framework.

Hydraulic System Update

The original telescope hydraulic system failed in late 2019 after many years of intermittent failures and heroic efforts by the operations staff to keep the system running. This failure resulted in 45 days of lost observing time.

CFHT developed and implemented a temporary hydraulic system early in 2020. This system bypassed much of the failed components and used many new components which are themselves spares for the new system. The bypass system ran flawlessly since its installation in January 2020.

Figure 11 - The completed new hydraulic power system in Waimea.

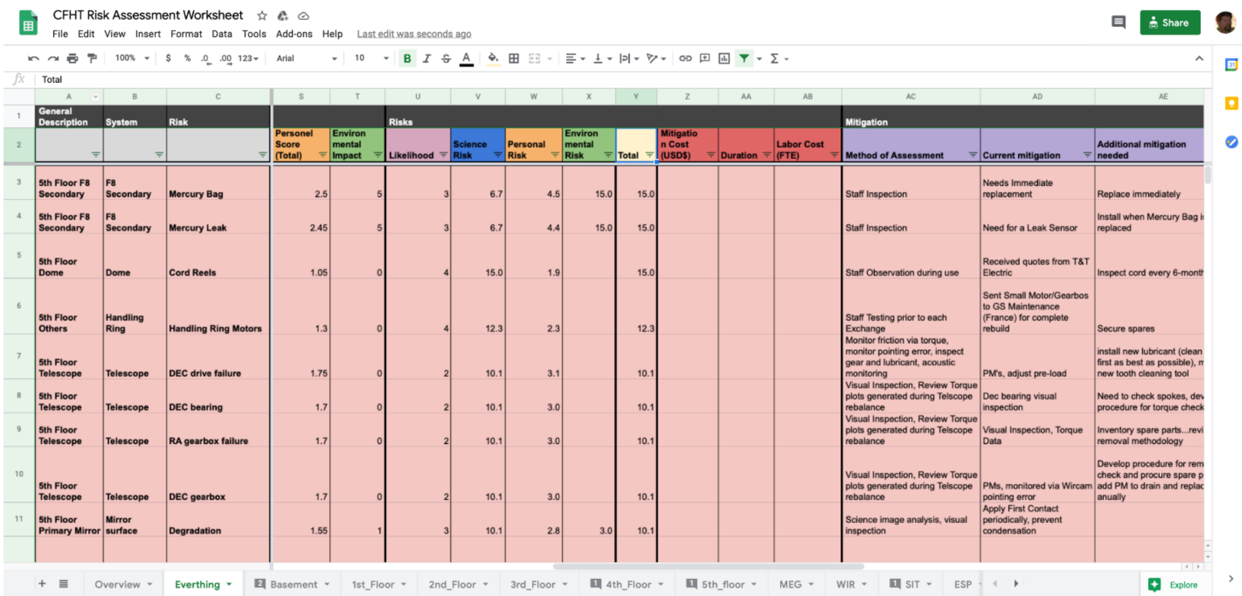
In parallel a completely new, custom, stand-alone hydraulic system was developed in partnership with Atlantic Hydraulic Systems of New York (AHS). Final design efforts between AHS and CFHT were conducted in late May 2020. System fabrication began in June 2020 and was completed in September 2020. The new hydraulic system was delivered to CFHT and will be integrated into the telescope hydraulic lines in 2021.

As part of the process the obsolete dome hydraulic system was removed from the summit to make space for the new telescope hydraulic system once it is at the summit. With the decision to perform recoating of the primary mirror in October it was decided that the hydraulic power plant would remain in Waimea until the recoating shutdown was complete. The system will initially be installed in parallel with the bypass system so that either one can feed the telescope hydrostatic bearings. This ensures that no telescope time will be lost in the unlikely event of a premature failure of any components in the new system. Once the new system is "broken in" the bypass system will be dismantled, approximately 6 months after installation of the new system.

Observatory Risk Assessment and Mitigation (RAM)

The engineering group implemented a risk and mitigation working group made up of representatives from all departments of the observatory including Operations, Instrumentation, Software, Astronomy, Administration and Safety. The working group meets regularly and is chaired by the Director of Engineering. The primary charge of this group is to update the existing risk register and to use the output from the risk register to set Observatory priorities. This includes detailed mitigation strategies as well as cost and schedule constraints associated with those strategies.

Sample output from the Risk Register is shown in Figure 12. Risk elements are listed by floor in the observatory and by instruments for the instrumentation risks. Telescope and IT risks are listed separately on their own pages. Likelihoods are evaluated and impacts are analyzed under 3 criteria: Personnel (Health or injury), Environmental and Risk to Science (Observing). The risk values are calculated by multiplying likelihood against impact and then all risks are sorted on the single "Everything" page. This page is then evaluated biweekly or monthly by the engineering managers in the context of staff priorities. The everything page is also evaluated monthly by the RAM working group for missing elements and progress on mitigation.



CFHT Risk Assessment Worksheet

	General Description	System	Risk	Personel Score (Total)	Environ mental Impact	Likelihood	Science Risk	Personal Risk	Environ mental Risk	Total	Mitigation Cost (USD$)	Duration	Labor Cost (FTE)	Method of Assessment	Current mitigation	Additional mitigation needed
3	5th Floor F8 Secondary	F8 Secondary	Mercury Bag	2.5	5	3	6.7	4.5	15.0	15.0				Staff Inspection	Needs Immediate replacement	Replace immediately
4	5th Floor F8 Secondary	F8 Secondary	Mercury Leak	2.45	5	3	6.7	4.4	15.0	15.0				Staff Inspection	Need for a Leak Sensor	Install when Mercury Bag i replaced
5	5th Floor Dome	Dome	Cord Reels	1.05	0	4	15.0	1.9		15.0				Staff Observation during use	Received quotes from T&T Electric	Inspect cord every 6-mont
6	5th Floor Others	Handling Ring	Handling Ring Motors	1.3	0	4	12.3	2.3		12.3				Staff Testing prior to each Exchange	Sent Small Motor/Gearbos to GS Maintenance (France) for complete rebuild	Secure spares
7	5th Floor Telescope	Telescope	DEC drive failure	1.75	0	2	10.1	3.1		10.1				Monitor friction via torque, monitor pointing error, inspect gear and lubricant, acoustic monitoring	PM's, adjust pre-load	install new lubricant (clean first as best as possible), n new tooth cleaning tool
8	5th Floor Telescope	Telescope	DEC bearing	1.7	0	2	10.1	3.0		10.1				Visual Inspection, Review Torque plots generated during Telscope rebalance	Dec bearing visual inspection	Need to check spokes, dev procedure for torque check
9	5th Floor Telescope	Telescope	RA gearbox failure	1.7	0	2	10.1	3.0		10.1				Visual Inspection, Review Torque plots generated during Telscope rebalance	Visual Inspection, Torque Data	Inventory spare parts...revi removal methodology
10	5th Floor Telescope	Telescope	DEC gearbox	1.7	0	2	10.1	3.0		10.1				Visual Inspection, Review Torque plots generated during Telscope rebalance	PMs, monitored via Wircam pointing error	Develop procedure for rem check and procure spare p add PM to drain and replac anually
11	5th Floor Primary Mirror	Mirror surface	Degradation	1.55	1	3	10.1	2.8	3.0	10.1				Science image analysis, visual inspection	Apply First Contact periodically, prevent condensation	

Figure 12 - A page from the CFHT Risk Register showing some of the highest risk items for the observatory. The register contains a separate page for each floor and each instrument.

Currently we believe that all major risks have been identified. Detailed mitigation strategies are ongoing and high priority risks from the Risk Register have been and are being folded into the Observatory priorities list.

MegaCam Update

As previously reported, 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 use 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 boards with a GigE interface, a communications industry standard used by many applications including commercial cameras. The new GigE system has been designed and built. During 2020 the last spare SLINK board failed in MegaCam, so while we have enough boards to run MegaCam, we no longer have any viable spares. Therefore, the decision was made to install the GigE into MegaCam during the November downtime between runs.

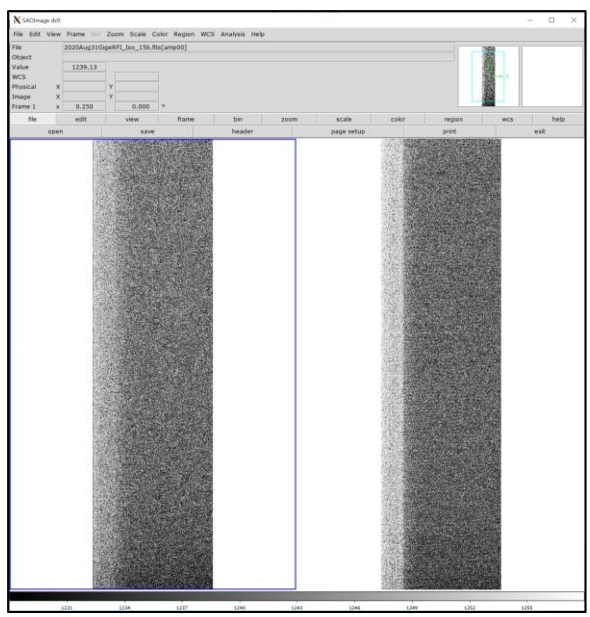


Figure 13 - Images of Amp 00 in the GigE (left) and SLINK (right) configurations. The images appear to be very similar with no Moiré noise pattern visible. RMS noise is nearly identical.

With the GigE installed, a series of tests were performed including comparison by the MegaCam instrument scientist of the bias images taken with the GigE interface and the SLINK interface. No observable differences in noise or gain characteristics were found. Readout noise performance with the GigE interface is nearly identical to that with the SLINK interface, and the Moiré pattern in the bias images have disappeared as shown in Figure 13. More on-sky information was derived from the MegaCam run in December 2020. It is not expected that we will require engineering time or shared risk observations to fully implement the GigE system due to the careful and detailed development process used to build it.

Bridge Crane

The bridge crane access platform upgrade has been placed on hold by the onset of the coronavirus pandemic coupled with a shift in project priorities. The platform fabrication is 95% complete, primarily awaiting final inspection by a local certified inspector. Pacific Overhead Crane (POC) has resumed outer island service and was able to address most of the crane issues that were identified previously: repairing the crane brake assemblies, certifying use of the 12-ton hoist, and inspection/certification of the 25-ton crane (required for primary mirror recoating). POC also installed a new 2-speed (Lo/Hi) 3-ton jib crane for use in the Observatory hatchway. This upgrade will prove extremely useful as we continue to assist other observatories with their mirror recoating, such as Las Cumbres Observatory (Haleakalā, Maui).

Currently the heaviest routine lift (upper end exchange) appears to be over the capacity of the 12 ton crane by ½ ton based on measurements using our out-of-calibration scale. While this overcapacity lift has been certified by POC, CFHT is currently working with POC to secure two calibrated crane scales to recalibrate our heaviest lift. Once this load-limit situation is addressed, CFHT will continue the variable frequency drive (VFD) crane-controller upgrades previously presented. The VFD upgrade proposal provided by POC is designed to reduce all identified “hard start/stops” that currently exist as well as replace the crane with a more reliable, safe, and well deserved upgrade to an aging system.

Figure 14 - (top) Existing bridge crane access and (bottom) SolidWorks model of new crane access.

Software Activities

A wide variety of software activities occurred in 2020 including –

- **The transition to a fully distributed workforce** happened in just a few weeks. This was perhaps less elegant than the other examples like CFHT's transition from classical to service-observing, and subsequently from summit to remote observing, where the transition had careful planning and over a year to execute. Nonetheless, the transition was just as successful, essentially without interruption or loss of capability to the observatory and the organization, with weather still being the main reason for lost observing time. The demand on staff has been formidable. Personal and operational adaptations, as well as group collaboration tools were needed. In addition, a higher level of network security and service reliability was required while expanding remote access and new network services.
- **Astrometric camera** on-sky tests have enabled the development of an integrated guider display while a new mount is being fabricated. The display shows estimated offsets and visual overlays indicating proper motions from GAIA catalogs giving observers powerful tools to quickly and accurately point the telescope.
- **A new display tool for the Spirou H4RG** science detector provides an enhanced and annotated view of the raw echellogram. These new visualization tools work over secure network connections and enable support staff to follow observing, including guider and exposure meter views, in real-time from home.
- **Hosted a group** of machine learning experts investigating dome seeing and attempting instantaneous predictions based on sensor data and the configuration of telescope, dome and vents. Results are in preparation and are encouraging for further study.
- **The AIRFLOW site study is on hold**, a consequence of shifting internal priorities. That study directly measures the local optical turbulence of dome seeing and is complementary to the machine learning study of dome seeing. For example, the present Machine Learning analysis gives insight to the principal components of dome seeing which inform decisions about the placement of instruments for future AIRFLOW site studies.
- **Operational Issue Tracking (now Technical Observing Support, TOS).** Concluding a multi-year study of system-level workflows and experiments with issue tracking in various applied methodologies, we emerged with an active and comprehensive issue tracking system implemented in Jira that records all reported errors during observing, establishes a life-cycle management for reported issues and establishes protocols for managing their life-cycle. This fulfills the majority of our requirements in this domain. Cam Wipper, the RO who implemented most of the system, was promoted to the newly created position of "Technical Observing Support Coordinator" within the technical staff. The purpose of that role is to continue to develop the TOS concept to the extent that records are sufficiently structured that analytic software can be used to search for patterns and predictive models that might be missed by conventional review. This will help coordinate the shift-to-shift activities of the observers with the objective of promoting continuity and comprehensive error reporting, providing front-line technical support to observers, and advocating among the technical staff for action on high-impact issues instead of responding to error reports in an occasionally ad-hoc manner.
- **Data Access Policy**: CFHT has implemented a relatively simple data access policy to formalize SAC recommendations, secure the observatory operations network and provide a secure mechanism to exchange data with external collaborators. The policy essentially describes the process by which CFHT data products outside of the science data archive (mostly engineering sequences) can

be shared with collaborators. Access to science data under embargo of the proprietary period are handled by CADC through their 'group access' tools.

- **Operational Metrics**: the exercise of combining Machine Learning methods and historical metrics highlighted the fact that, despite some progress in this area, a lot of work remains before we have a consistent and usable database for the 20+ years of digital site monitoring at CFHT.

SITELLE Update

In 2020 we noted an anomalously high rate of high-energy particle events on both SITELLE detectors that coincided with the installation of the new flat fielding lenses on the cryostats. The rate increase was estimated to be a factor of 6 to 8 greater than in the past and was proving to be problematic for the spectroscopic reduction.

We were unable to get a clear indication from the glass manufacturer, Ohara, that radioactive isotope contamination was a problem with the S-FSL5 glass used in these lenses. In consultation with Université Laval, we decided to replace the S-FSL5 lenses with lenses made of high purity fused silica. Optimization of the design with fused silica indicated effectively no impact on the image quality of the instrument. Since the cost of fabricating the lenses was low (~$5k), we decided to pursue fabrication and installation immediately without making further efforts to narrow down the source of contamination (the coatings remained a possibility).

The new lenses were installed in July and long dark images indicated a reduction in the high energy particle count rate by a factor of 7, a return to the level seen before installation of the S-FSL5 cryostat lenses. The cameras were refocused to optimize fringe contrast off-sky, and on-sky testing during the October 2020 SITELLE run indicated no effect on the IQ from the new lenses.

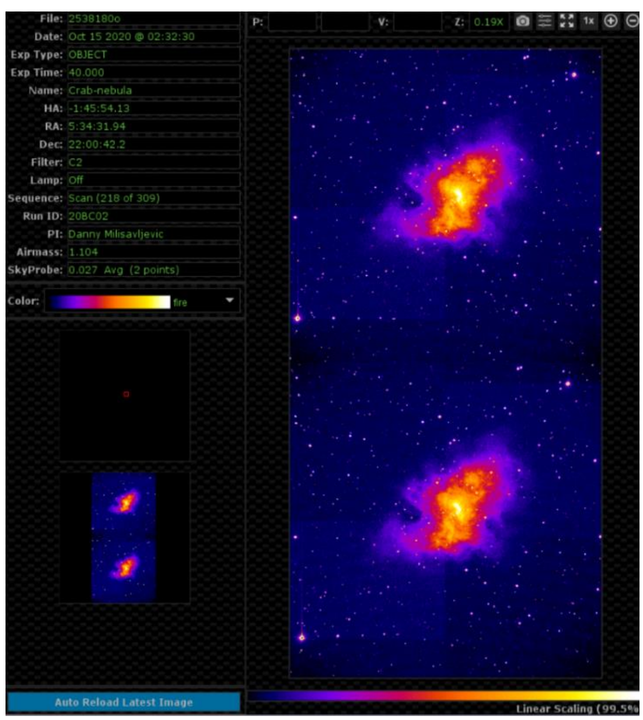


Figure 15 - New display tool for observers showing the readout of both SITELLE detectors with scaling parameters, detail view (ROI not shown), metadata and annotations.

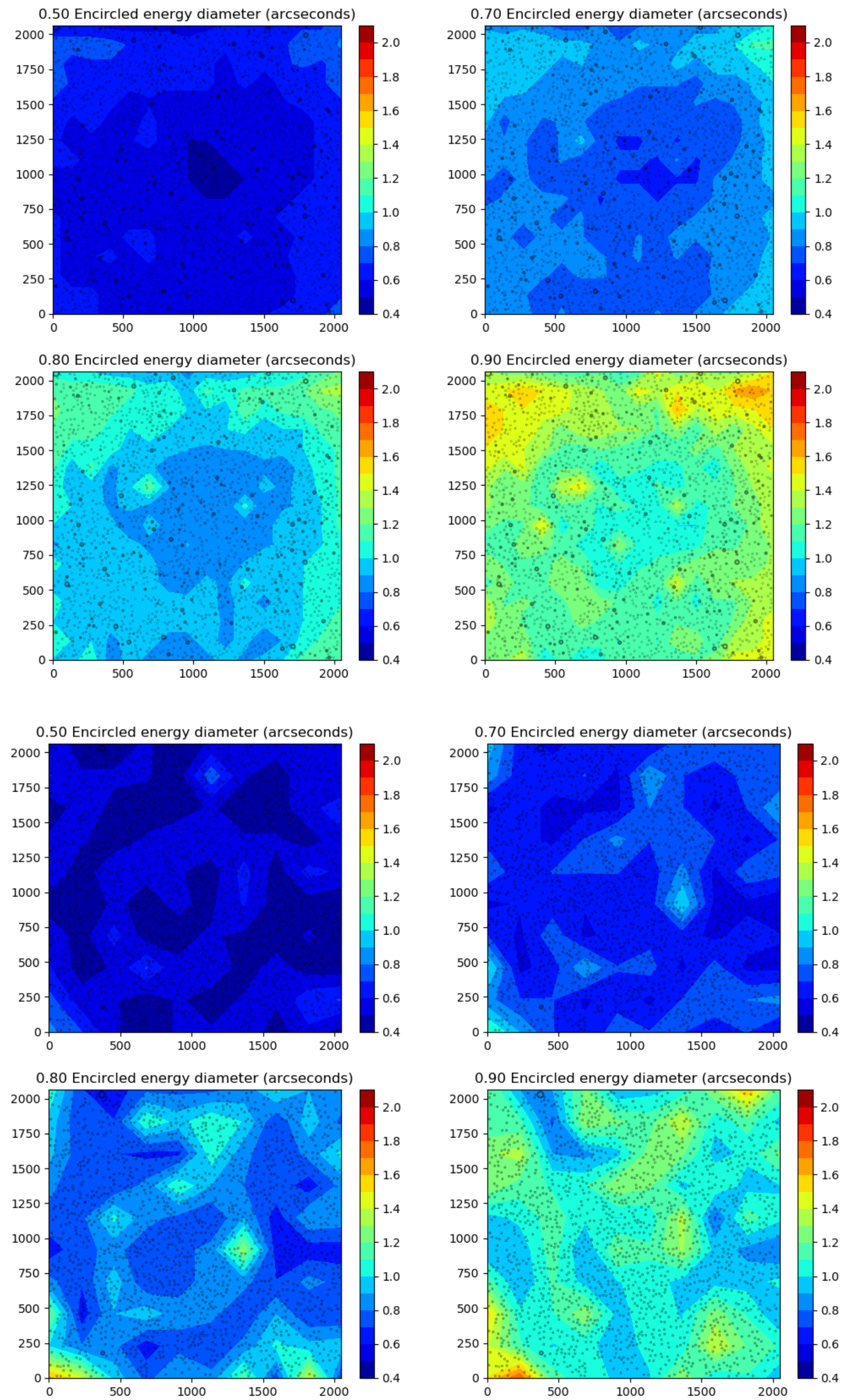


Figure 16 - Comparison of encircled energy radius maps from before the fused silica corrector installation (4 panels at top), and after (4 panels at bottom), all for Camera 1. The colored scale is the radius in arc-seconds corresponding to the indicated encircled energy fraction of the specific map. Note that the 50% encircled energy metric is equivalent to the FWHM metric for a Gaussian PSF. Therefore, at 0.6" over the entire field, the IQ is well within the sub 1" FWHM specification at the edge of the field, and sub 0.8" FWHM specification in the central 5'.

SPIRou Update

Operations with SPIRou in 2020 were smooth with very few technical issues. At the same time, improvements continue to be made and progress on plans for further improvements continue to develop.

Rhombs: After many iterations, much improved blue transmission is seen with the installation of a new set of rhombs fabricated by Winlight and using new ZnSe material from a new supplier. Despite at least one more rhomb adhesion failure, we now have three rhombs with good transmission and low image wobble that have maintained their adhesion for several months in the cold. The improved transmission is the result of better ZnSe material and improved coatings. The image wobble improvement is due to better alignment of the rhomb input.

Agitators: The new control and sensing system for the SPIRou agitators has been installed and is working well. In addition to a more robust, faster control system, the arm length is now producing an appropriate throw on the fibers for best mode scrambling as determined by the IRAP development team. A new agitator has also been added at the Cassegrain Unit to provide mode scrambling for the calibration fiber just prior to insertion into the Cassegrain unit.

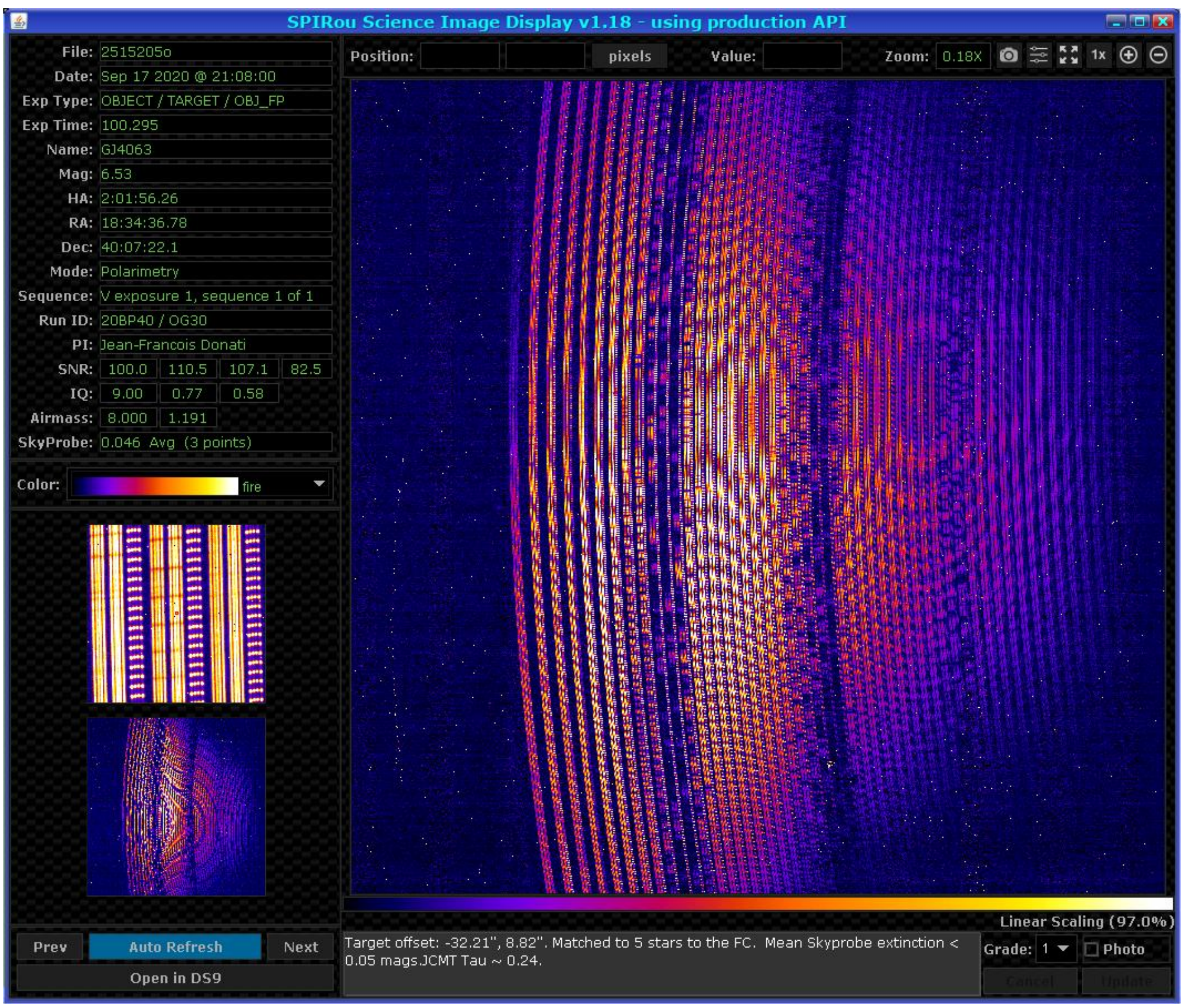


Figure 17 - New display tool for observers showing the SPIRou H4RG slope/intercept output and visual scaling parameters, detail view, metadata and annotations.

Cassegrain Unit Lens Stabilization: Unfortunately, little progress has been made on the Cassegrain lens stabilization issue, due to lack of resources. It will be necessary to stabilize these lenses prior to cooling the Cassegrain unit as the alignment of the field mirror to the fibers is currently temperature dependent.

Cassegrain Unit Cooling: A design for chilled glycol cold plates has been developed to cool the SPIRou Cassegrain unit in order to reduce the thermal background in SPIRou spectra. The goal is to lower the temperature of the Cassegrain unit to around 0° C during operations. The design consists of 8 separate custom copper cold plates which will be glued, using a thermally conductive adhesive, to the sides of the Cassegrain unit (see Figure 18). Easily removable insulation will be installed around the Cassegrain unit to reduce convection and prevent frosting of the unit. Dry air will be used to keep the inside of the unit moisture free.

A thin (3 mm) G10/FR4 spacer will be placed between the Cassegrain unit and the end-to-end unit (mounting spacer) to thermally isolate the Cassegrain unit from the telescope. This has been found, through simulations, to be necessary to achieve the desired temperatures throughout the unit. Calculations show that the spacer will not introduce significant additional flexure in the system or degrade the image quality.

Simulations indicated the system should cool down the entire Cassegrain unit to 0° C or lower using 3.8 liters/minute of glycol at -3° C with an ambient temperature of 5° C and no insulation on the outside.

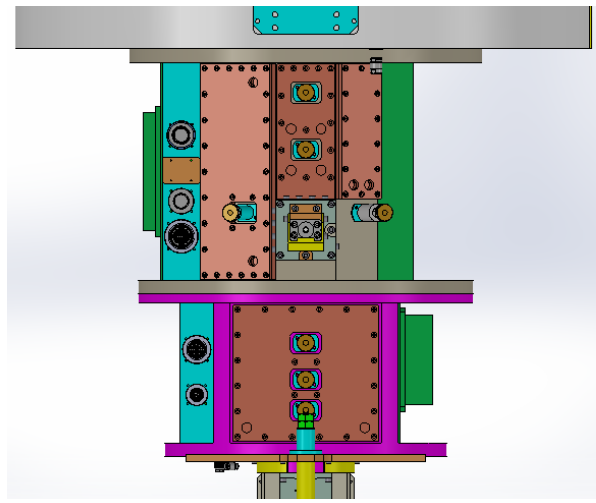


Figure 18 - 3D model of the Cassegrain unit west side with new cold plates.

A test plate has been made to be sure that the simulations are approximately correct and to test the adhesives to be used before committing to the process. The test is currently on hold awaiting delivery of the thermal adhesive required to glue the cold plates to the Cassegrain unit.

RV Reference Source: The RV reference source, a thermally stabilized Fabry-Perot (FP) system, has had some minor improvements to increase the stability of the system. First, the insulation around the top of the source has been improved to reduce this remaining source of heat within the slit room. Second, the FP was seen to vary in temperature with the ambient room temperature. To improve the temperature stability of the FP, the thermal control loop of the system was modified to keep the temperature stable to within 1-2 mK.

Laser Frequency Comb: Some improvements in the Laser Frequency Comb (LFC) have been made by Menlo Systems that has kept the system running more reliably, but there are still issues with the system that keep it from being used as an RV reference source on-sky. IRAP and Menlo are still working on these, but at the moment, the LFC is only used during calibrations.

Absolute RV Drift: A significant absolute RV drift in the spectrograph with changes in Coudé room temperature was noticed. While this drift can be removed using the RV reference source or, eventually, the LFC, it is desirable to reduce the absolute drift as much as possible.

A test was done to try warming the exterior of the cryostat only while monitoring the RV drift of the system. This test, unfortunately, did not show a direct correlation with the heating of the cryostat or with any other variable that could be easily measured except the ambient room temperature. Further testing will be done to see if additional insulation or stabilization of the Coudé room temperature is needed.

Data Reduction Software: A new and improved version (V0.6) of the SPIRou data reduction software (DRS) arrived at CFHT some time ago. After a substantial effort to integrate the new software into the CFHT systems, the new version is now in use reducing SPIRou data. Discussions are happening with the Université de Montréal to try to make subsequent versions of the DRS easier to transition to CFHT.

Collaboration with the SPIRou DRS team resulted in multiple DRS releases and significant improvements to calibration. Starting to re-process historical data with DRS 0.6 batch processing is slow and there are multiple factors that limit scaling/distributed processing. The DRS team as well as CFHT and CADC staff are actively working on this. The current 0.6 version does not, to our knowledge, extract polarization signatures. Maintaining a working installation of the DRS, including the functional interfaces and FITS packaging software, is more demanding than anticipated. Nonetheless, the DRS team is collaborative and very hard working. The software group at CFHT is short of staff and collaboration on DRS development, while productive, must come at the expense of other priorities.

Replacement of the Calibration Unit Chiller: The chiller provides heat extraction for a Peltier cooler inside the Calibration Unit. Since one of the two chiller units received with SPIRou has failed and the expense to repair it is significant, a background project has been started to develop a heat exchanger system to passively remove the heat and exhaust it into the slit room air. Changing to such a system would also reduce the power consumption and net heat exhaust in the slit room. The project is progressing nicely, though slowly, since it is not a high priority task.

Co-Mount ESPaDOnS and SPIRou

A polarization design study was conducted in order to evaluate the feasibility of the first design concept, whose efficacy hinges on the ability of pairs of dichroic folds to self-compensate for polarization shifts. The analysis was conducted over the summer/fall by (remote) internship student, Arthur Soutenain, a student at The Institut d'Optique in Paris. The primary goal of this internship was to quantify the cross-talk between linear and circular polarization components introduced by the dichroic beam splitter and fold mirrors. The problem was tackled using a combination of Zemax and Python. Zemax provided the tool to trace rays and track polarization changes through the system, and Python provided a convenient way to analyze the results.

While CFHT staff are still digesting the study, the initial result suggests that the polarization state can be affected by more than a few percent in transmission, and very significantly in reflection. It is possible that the transmission side can be corrected by applying a careful calibration, without much loss in polarization sensitivity. However, in reflection, it appears that the dichroic beam-splitter introduces a loss of polarization signal of up to 60% which would significantly reduce the polarimetric sensitivity of ESPaDOnS.

The final results of this study and the possible plan for moving forward with the less ambitious option of mounting both instruments on translations stages to facilitate quick exchange, are under review.

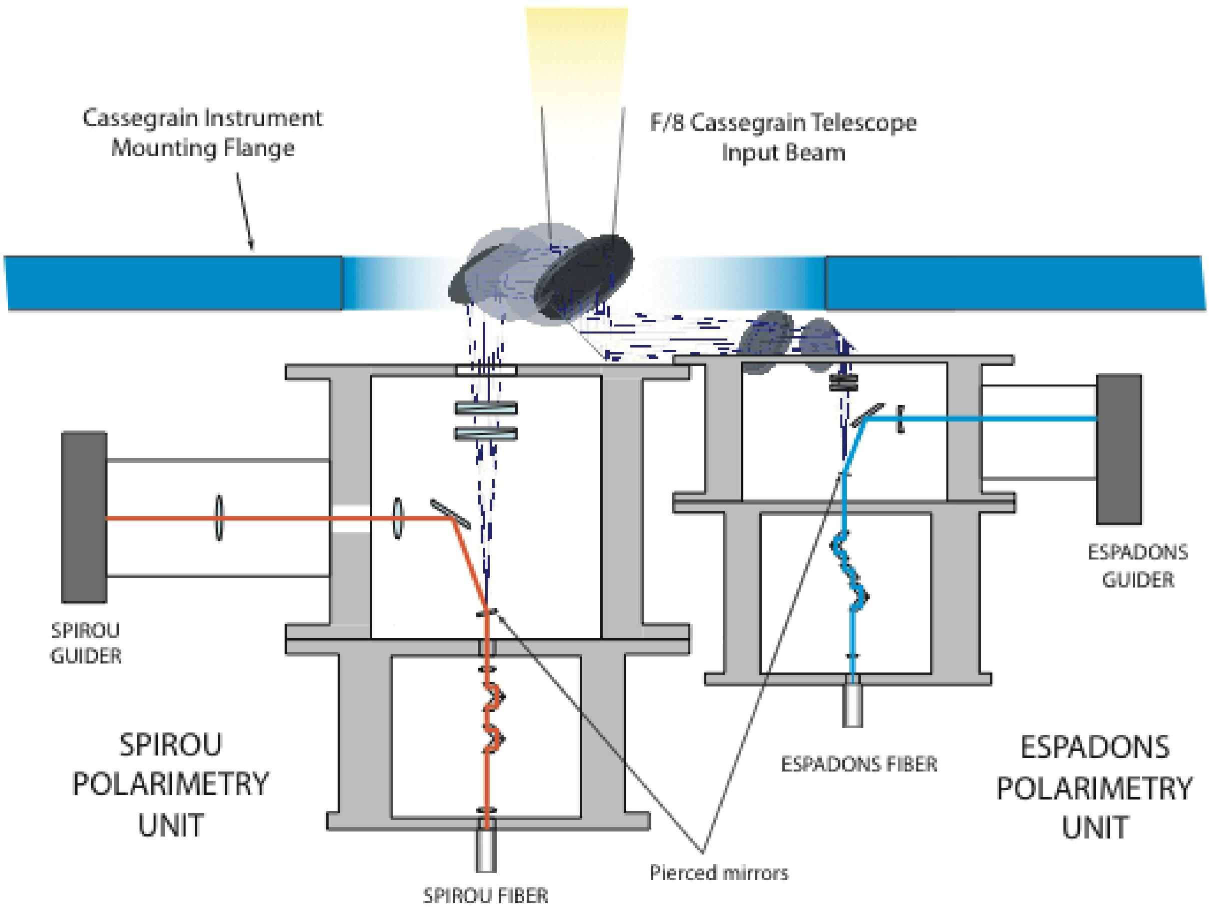


Figure 19 - Co-mounting ESPaDOnS and SPIRou concept.

MSE Report

2020 Project Adjustments

Like many organizations during the COVID pandemic, the Project Office (PO) learned to adapt and advance MSE science, technology and program execution. Figure 20 shows the meeting changes in 2020 where the organizers of many planned promotional meetings were canceled and then some were restructured into virtual meetings. Due to the elimination of physical travel, we adjusted and were able to add more meetings and increase our presence, virtually. However, the effectiveness of a virtual presence is unclear at this time.

In lieu of a traditional all-hands October meeting in France, as originally planned, Jennifer Marshall organized a series of four virtual meetings through the month of October. Each session lasted 1.5 hours and alternated between European and Asian time zones. These meetings brought the distributed and extended MSE community up-to-date with the latest news, project progress, partnership engagement updates and more. The virtual meetings became discussion forums stimulated by short presentations linking Science Case requirements with technical design development.

In anticipation of endorsement for wide field multi-object spectroscopic facilities in the Astro2020 report, Joan Najita, Management Group member from NSF's NOIRLab, planned a series of community meetings to consolidate common support. In addition to MSE, representatives from ESO SpecTel, Mega Mapper, and Keck's FOBOS, etc. were invited. The meeting objective was to promote collaboration and minimize detrimental competitions among these likeminded facilities.

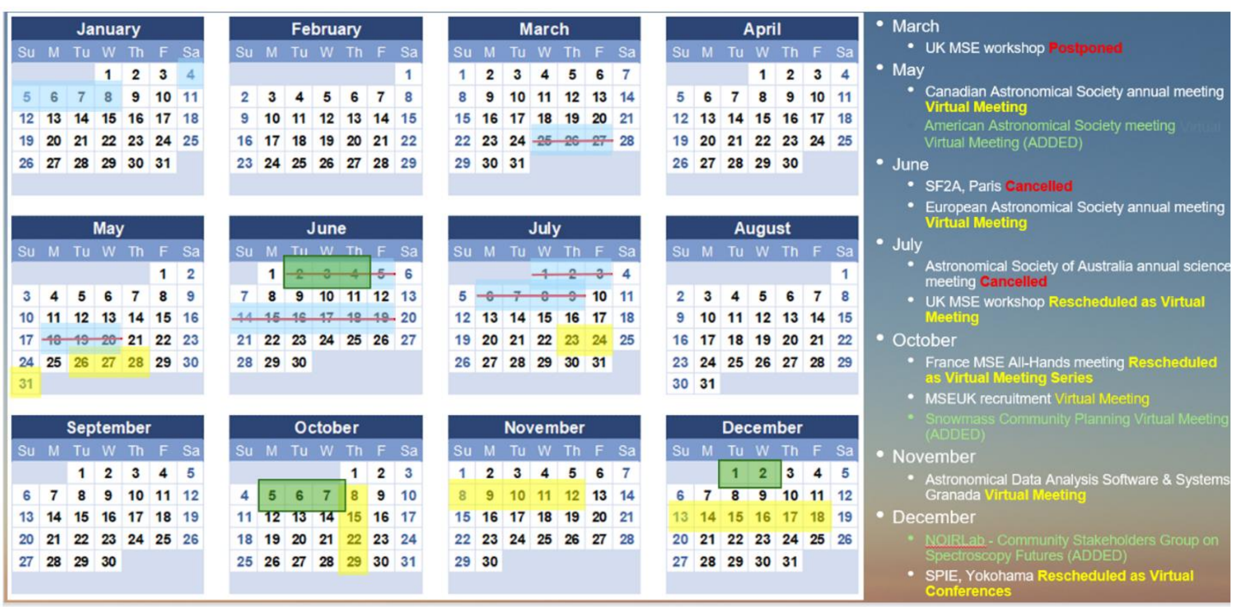


Figure 20 - Changes in planned promotional events in the 2020 calendar: blue blocks indicate original meetings, yellow blocks indicate reorganized virtual meetings, and green blocks indicate added meetings from previous planning.

Project Office 2020 Staffing

Some PO staffing changes occurred in 2020. Sam Barden joined as the new Systems Engineer and Kei Szeto moved back to NRC/HAA. Andreea Petric and Nicolas Flagey left the PO though Andreea continues as the Deputy Project Scientist on a part-time basis. In addition, Christian Surace from the Laboratoire d'Astrophysique de Marseille has joined the PO as the technical lead, at 0.25 FTE, for the Program Execution Software Architecture (PESA) conceptual design over the next year. Working remotely from France, Christian brings his experience and expertise from leading the Astrophysical Data Center of Marseille, CeSAM, to MSE.

The recruitment of a System Scientist to replace Nicolas was completed by the end of 2020 with the arrival of Jennifer Sobeck, who will bring her SDSS-IV project experience to MSE. A new Project Administrator recruitment was also underway by year's end. The addition of a new Systems Scientist and Project Administrator will certainly increase the capacity of the PO going into the Preliminary Design Phase of the project.

2020 Project Highlights

Figure 21 - Core Project Office team - Barden joined in February, Flagey departed in September, and Surace started in November.

Advancements in partnership, national strategic planning, science, and engineering are highlighted below.

MSE Partnership

Kyung Hee University (South Korea) joined the MSE Management Group via their in-kind contribution in the Exposure Time Calculator prototype development. Currently there are eight participants and two observers in the MSE program -

<u>Participant</u>

- Australian Astronomical Optics Macquarie
- National Astronomical Observatories, Chinese Academy of Sciences
- Centre National de la Recherche Scientifique
- Institute for Astronomy, University of Hawaiʻi
- India Institute of Astrophysics
- Kyung Hee University
- Texas A&M University

<u>Observer</u>

- US NSF's NOIRLab
- UK university consortium, led by the Astronomy Technology Centre

National Strategic Planning

A summary of national astronomy long rang prioritization processes includes –

- Australian mid-term review of its Decadal Plan 2015 stated their top priority remains joining ESO full membership, from current associate member, while MSE or wide-field multi-object spectroscopic facilities were highlighted as potential opportunities.
- Canadian Long Range Plan 2020 panel released their final finding on astronomical facilities recommending that Canada should play a leading and substantive role in a next-generation wide-field spectroscopic survey facility with MSE as the best option currently.
- Science Team submitted 20+ science white papers and PO submitted a facility white paper to the US Astro2020 Decadal Survey. The final report is expected in mid-2021.
- Science team submitted Letters of Interest in the topics of dark matter, dark energy and facilities to the US Snowmass 2021, a.k.a. US Particle Physics Community Planning Exercise. This is a multi-year strategic planning process for US particle physics priorities during the next decade.

Science Team Expansion

The Science Team grew to 422 members from 39 countries. Five new Science Working Group co-leads replaced the outgoing co-leads of the eight SWGs. Design Reference Survey development is underway to produce a detailed survey plan that combines four diverse science cases: Milky Way halo star metallicities, "Cosmic noon" survey, Cosmology, and AGN reverberation mapping to inform design improvements for the Preliminary Design Phase. Updating the Science Case based requirements to facilitate LMR and HR spectrograph optical designs is on-going (see Engineering highlight below for additional information).

Figure 22 – MSE Science Team international composition.

In addition, we welcomed 3 new Science Working Group co-leads including:

- Xiaotin Fu (Kavli Institute for Astronomy and Astrophysics, Peking University). Xiaoting will join Sarah Martell to co-lead the Milky Way and Resolved Stellar Populations Working Group. She brings significant experience from her study of stellar populations in our Galaxy, in particular seeking to answer questions about the lithium problem as well as chemical abundance connections among stars, stellar clusters, and the Milky Way.
- Chien-Hsiu Lee (NOAO/NOIRLab) will join Adam Burgasser to co-lead the Time Domain Astronomy and Transients Working Group. His science interests are in variable stars, stellar explosions, and moving objects. He is heavily involved in the time-domain broker ANTARES that sifts through millions of alerts raised by the Rubin Observatory to hunt for the rarest of the rare targets that merit follow-up with MSE.
- Ricardo Schiavon (Liverpool John Moores University) will join Charli Sakari to co-lead the Chemical Nucleosynthesis Working Group. Ricardo served as the APOGEE Survey Scientist. He is currently a co-leader of the ESO-MOONS Galactic Surveys Tools Working Group, and a member of the WEAVE science team. His scientific interests are broadly in the area of galaxy formation but focusing on Galactic archaeology towards understanding the history of the Milky Way and its position in the cosmological context.

Engineering Progress

Figure 23 – New Science Working Group co-leads, from left to right - Xiaotin Fu, Chien-Hsiu Lee, and Ricardo Schiavon

Work focused on establishing direct links between the Science Case and spectrograph capabilities in order to prioritize optical design and functional requirements for wavelength coverage, spectral resolution, and multiplexing. Reducing technical risks that were identified by the LMR and HR spectrograph design review panels was also pursued via exploring alternative optical designs. The Science Calibration (SCal) system conceptual design progressed by identifying all contributors affecting spectra's SNR. Figure 24 shows science calibration considerations under the work package agreement with Texas A&M University to develop the SCal system. Implementing requirement management software (DOORS) was also completed. This helps enforce procedures to ensure traceability and flow-down of science and system-level requirements. Finally, PESA work commenced by recruiting a technical lead, Christian Surace, organizing an advisory council with volunteer members from similar spectroscopic projects (PFS, 4MOST, WEAVE and MOONS) and executing a work package agreement with Kyung Hee University to develop the ETC prototype.

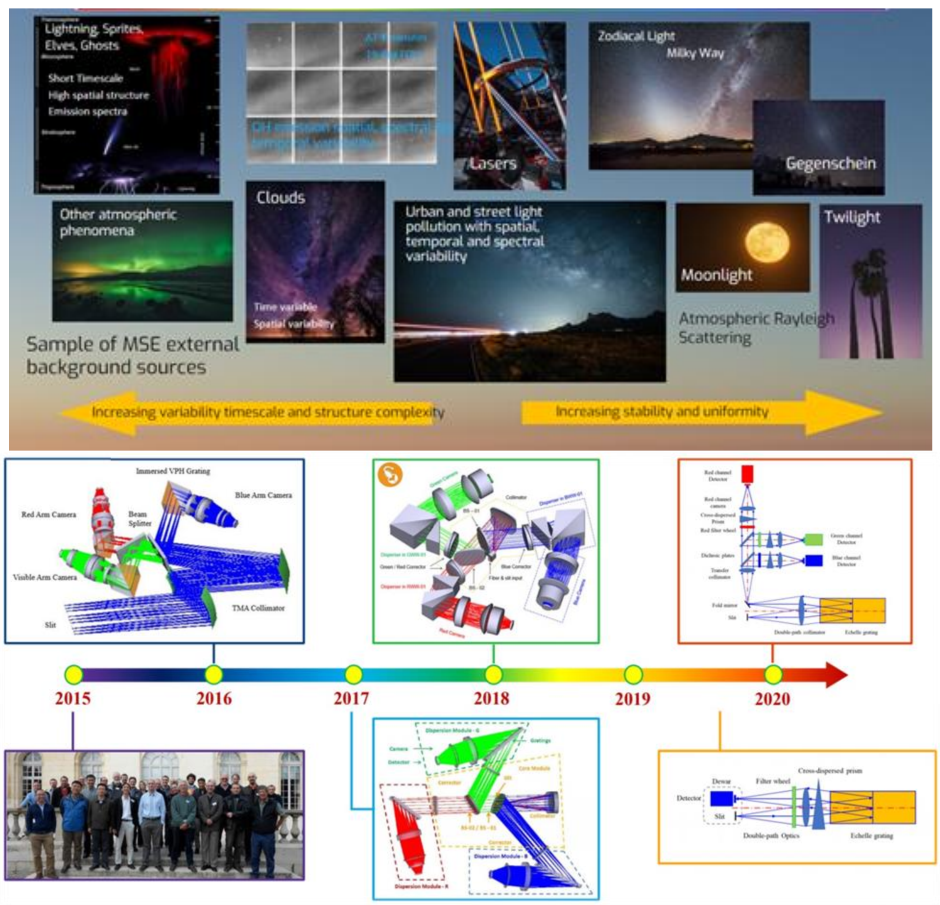


Figure 24 – Top - Sky background sources dominate faint object spectroscopy with sky levels nominally swamping the faintest signals by a factor of 50 to 100 with spectral, temporal and spatial variability across the field. Bottom - HR spectrograph optical design is driving the desire to improve the dispersing element fabrication feasibility and operations flexibility to adjust the available observed spectral windows without replacing dispersing elements.

Project Office 2021 Direction

In August, the PO proposed a Preliminary Design Phase Readiness Review (PDPRR) at the end of 2021. The PDPRR will use an external review panel to determine if the PO has the requisite system-level documents, processes and procedures in place to lead the subsystem design teams and ensure a successful and effective preliminary design endeavor. Being PDP-ready is vital to instill confidence in funding agencies that their investments are well managed for effective science return. As seen in Figure 25, despite not having a definitive PDP start date, the Review will be a concrete and ambitious goal for the PO with 49 deliverables required via PDPRR documentation.

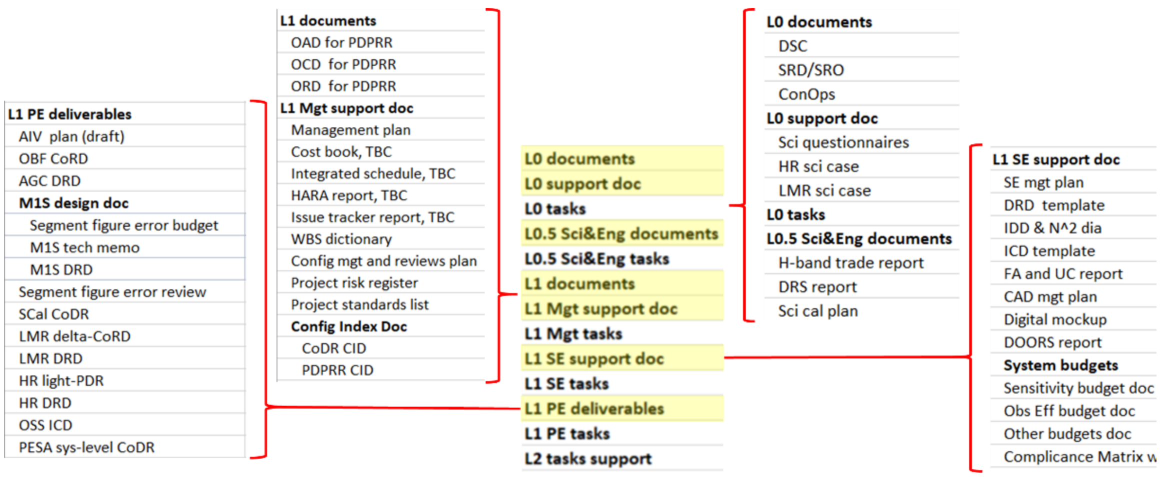


Figure 25 - 49 items are contained in the seven sets of deliverables to be completed by PDPRR

Preparation for the PDPRR is the leading and central work objective for 2021. The PO will include the parallel PDPRR development threads:

- Design Reference Survey and its associated Exposure Time Calculator and Scheduler observing performance simulation tools
- Readiness for five subsystem design reviews - Observatory Building Facilities Conceptual Design Review (CoDR), SCal CoDR, LMR spectrograph delta-CoDR, HR spectrograph interim Preliminary Design Review, and PESA CoDR
- Primary mirror design report with segment IQ error budget

In-kind and CFHT Contributions Summary

We continue to record both contributed effort (hours) and cost. Figure 26 shows the distribution of contributions by MSE participants at the end of Q3 2020, accumulated since the inception of the Project in 2015. The total combined contribution is $12,188,687, including the direct CFHT contribution and the Spanish contribution which ended in 2017. In this chart, the in-kind contribution and Project Office contribution made by CFHT have been allocated to Canada (42.5%), France (42.5%) and Hawai'i (15%).

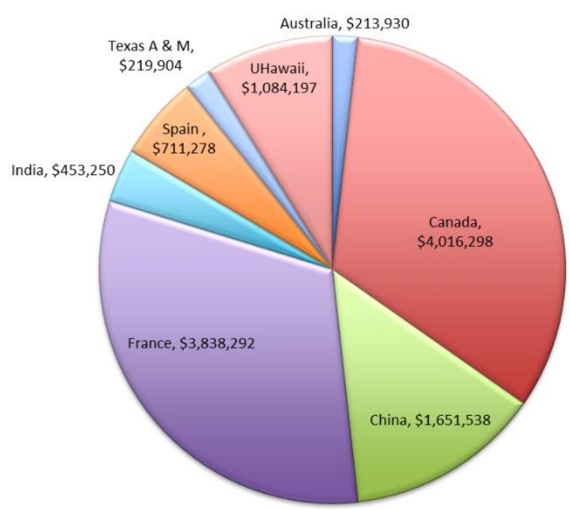


Figure 26 - Contributions of MSE participants since the project inception in 2015.

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 2020 Finances

CFHT continues to operate in a challenging economic environment of limited member agency contributions compounded with inflationary cost pressures. During the last 5 years, agency contributions have grown an average of 1.5% per year. For 2020, member agency contributions increased 3% from the prior 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$)		
	2020	2019
NRC	3,458,740	3,358,000
CNRS	3,458,740	3,358,000
UH	802,024	778,664
Total	7,719,504	7,494,664

Table 1 - Contributions from CFHT partners increased 3% from 2019 to 2020.

Table 2 shows our 2020 Operating Fund expenditures on a comparative basis with 2019. The significant increase in our 2020 annual contributions from our member agencies was intended to provide additional funding for needed deferred maintenance and cover our baseline operations. Due to the effects of the COVID pandemic, we significantly underspent in our Management and General Services cost categories. Based on our original budget expectations, we anticipated drawing from reserves in 2020. Due to the unanticipated underspending, we added slightly to our financial reserves. As such, we have been able to maintain a balanced budget in both 2020 and 2019 with nominal amounts unspent and transferred to reserves. 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 science.

Operating Fund Expenditures (US$)		
	2020	2019
Maunakea Facility and Operations	769,415	496,722
Base Facility and Operations	209,075	149,325
Services	344,842	278,501
Maunakea Support Services	122,115	129,154
Management & General	160,108	459,225
Staffing	5,805,956	5,558,414
Outreach	58,857	88,609
Instrumentation	113,579	90,339
Science	31,829	58,757
Transfer to Reserve	103,728	185,618
Total	7,719,504	7,494,664

Table 2 - Operating expenditures broken down by cost categories.

In addition to member agency contributions, CFHT receives payments under Associate Partnership collaborative agreements with other agencies as reimbursement for costs associated with their use of CFHT facilities. In 2020, CFHT received $273,000 and $358,000 from the Academia Sinica Institute of

Astronomy and Astrophysics (ASIAA) and the National Astronomical Observatory of China (NAOC), respectively. Funds received under these collaborative agreements are 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.

Environmental, Health and Safety Oversight

For the two years prior to 2020, CFHT had used outsourced safety management services in coordination with its internal Safety Committee. However, at the end of 2019 management determined that additional resources are needed to consolidate environment, health and safety oversight into a central role. At the beginning of 2020, we hired an Environmental, Health and Safety (EHS) Manager. This action has provided a more robust, broad based training program and better coordination and transparency of various environment and health initiatives.

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, environmental, health, and safety surveys are conducted at observatory facilities as well as ongoing reviews of programs and processes.

During 2020, there were no OSHA recordable injuries. In an effort to continuously improve the safety environment and culture, the observatory identifies and evaluates near miss and early symptom incidents in an effort to prevent more serious issues. The Safety Committee takes an active role with the EHS Manager in identifying and correcting potential safety issues.

	2020	2019	2018	2017	2016	2015	2014	2013	2012	2011
Injuries	0	1	1	0	0	2	2	0	0	1
Lost work days	0	1	0	0	0	0	10.5	0	0	1

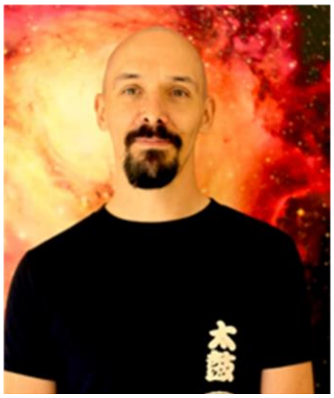
Table 3 – A decade of top-level statistics pertaining to safety are listed above.

The year 2020 brought with it some very unique challenges to staff health and safety due to the COVID pandemic. As with the rest of the world in early 2020, we entered a period of lock downs, quarantines, loss of personal connections and heightened anxiety. After a short shut down period, CFHT modified its operations to limit access to the summit and our base facility offices. We instituted work from home arrangements for as many staff as possible. Throughout all of these challenges, we strived to continue delivering high quality data for our international research community while making pandemic safety a top priority. At the time of this report we still are operating under modified work arrangements and adjust our practices based on the best available guidance provided by health and government agencies.

Arrivals and Departures

Over the last year we bid farewell to five of our staff 'ohana and welcomed six new members. In addition, we promoted two of our long standing employees. As of year-end 2020, three of our Resident Astronomer positions remain open, two from France and one from University of Hawaii. We anticipate those positions will be appointed and filled in 2021. 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



Nicolas Flagey

Nicolas Flagey worked in our MSE project office from 2015 through 2020 in the role of System & Operations Scientist. He has been an instrumental member of the MSE Project Office team from its inception through completion of the conceptual design phase and helped establish the foundation for commencing the preliminary design phase of the project. Nicolas was actively engaged in advocating for MSE in the international community and represented the project through numerous venues. Nicolas accepted a position at the Space Telescope Science Institute. While we are saddened by his departure, we are excited for his new professional opportunities focused on space based astronomy and projects.

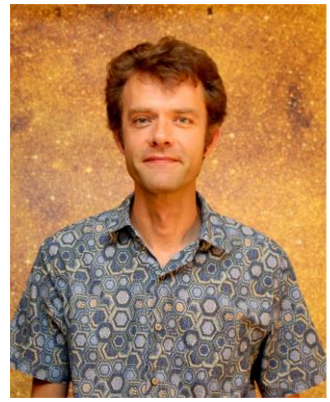
Pascal Fouqué

Pascal was a Resident Astronomer at CFHT since 2013, serving on assignment from CNRS. He started as the WIRCam Instrument Scientist and put his vast knowledge of NIR observing to work by greatly enhancing the instrument's photometric calibration. His work led to the detection of zero point variation due to mirror aluminizing in the NIR, a first at CFHT. After the departure of Claire Moutou, Pascal became the SPIRou Instrument Scientist and worked mainly on improving the instrument's Data Reduction Software and also handled many requests from our engineering and science team for instrument testing.

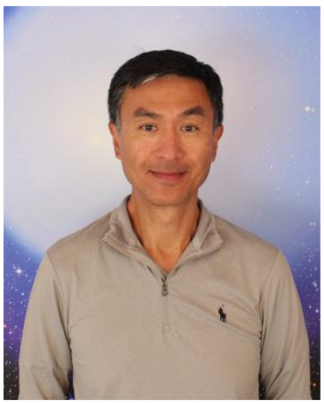
Andreea Petric

Andreea has been serving at CFHT as the UH Resident Astronomer since 2016. In addition to her responsibilities in that capacity, Andreea dedicated significant time as a volunteer to many educational and community support events. She was deeply involved in the MSE project, filling the role of Deputy Project Scientist. Though Andreea accepted a position at the Space Telescope Science Institute she continues to be involved with and support the MSE project, retaining her role as MSE Deputy Project Scientist. We are grateful and excited for her continued involvement in the MSE project.

Simon Prunet



Simon was a Resident Astronomer on assignment from CNRS since 2013. He served as Instrument Scientist for both MegaCam and SITELLE. Simon's contributions to CFHT were numerous. He routinely tackled difficult problems, among the most notable being rewriting the fringe correction for MegaCam and providing crucial help with SITELLE's alignment challenges. His exceptional mathematical analytical skills had many applications at CFHT. Given his curious nature, Simon often participated in many endeavors and activities across the observatory – his multifaceted engagement and skills will be missed.



Kei Szeto

Kei joined the MSE project in early 2015 on temporary assignment from the Herzberg Astronomy and Astrophysics Research Centre (HAA) in Victoria, Canada. He began as the Project Engineer and then subsequently assumed the role of MSE Project Manager. His temporary assignment in Waimea ended in 2020 when he returned to HAA. Fortunately for CFHT/MSE, he continues to be dedicated to MSE on a full-time basis and still serves at the Project Manager. During his time on-site he successfully steered the project through a complex conceptual design phase and organized an extensive portfolio of project documentation. His work is now focused on preparing for and executing the preliminary design phase of the project.

Welcome

Virginia Aragon-Barnes

Virginia joined CFHT in February 2020 in the role of Environmental, Health and Safety (EHS) Manager. While her responsibilities are first and foremost focused on employee safety, in this new expanded role, we have consolidated health and environmental oversight into a central position. Prior to working at CFHT, Virginia worked at Thirty Meter Telescope as the EHS Compliance Engineer and at Hawaii Electric Light Company as Safety Administrator. Virginia has been actively engaged in astronomy related educational outreach throughout her career, a passion that she will continue to cultivate at CFHT.

Samuel Barden

Sam joined the MSE Project as Systems Engineer just weeks before the pandemic forced the shutdown of our offices. When he is not working on MSE from his home office, he has taken up the hobby of building telescopes and cameras in his garage. Sam brings an incredible depth of expertise to the Project Office. He previously was a project engineer associated with the 4MOST instrument and was a work package manager for the DKIST adaptive optics group. Sam was head of engineering at the Anglo-Australian Observatory, and a scientist at NOAO. We consider ourselves very fortunate to have him as a member of the MSE project team.

Christy Cunningham

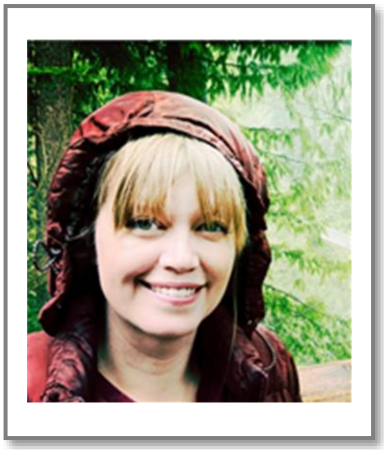
Christy just joined CFHT at the beginning of 2021 as a Remote Observer. Originally born and raised in Alaska as a fisherwoman, she fell in love with the Hawaiian sky and sea, and made this her home. Christy holds a BS in astronomy from Northern Arizona University and an MS in Applied Physics from the University of Oregon. She has found her passion as an observer on Maunakea. Prior to joining CFHT she has a combined 7 years of experience at SMA and Gemini. She still stays true to her Alaskan roots by taking her 13-foot whaler from Kona to chase marlin, tuna and ono any chance she gets.

Heather Flewelling

Heather joined the Astronomy Group as an Instrument Support Scientist on a temporary contract as a result of the voids created by the departure of several resident astronomers. Heather’s primary focus is supporting MegaCam. She earned her PhD from the University of Michigan. Heather has worked for the last 10 years in a variety of positions at the University of Hawaii, Institute for Astronomy. She served as a researcher on Pan-STARRS, building the world’s largest astronomical database, and the ATLAS Planetary Defense project. Her background is a perfect match for supporting MegaCam.

Barbara Small

Barbara Small joined the MSE Project Office as Project Administrator. With a master’s degree in computer science and a bachelor’s degree in journalism, Barbara hails from Memphis where she spent a decade in IT project management with International Paper. She moved to Hawaii in 2015 to become an Interpretive Guide at the Onizuka Center for International Astronomy, Visitor Information Station. Barbara brings her love of Maunakea and passion for its stewardship, her scientific curiosity, and her project management and communications skills to the team.



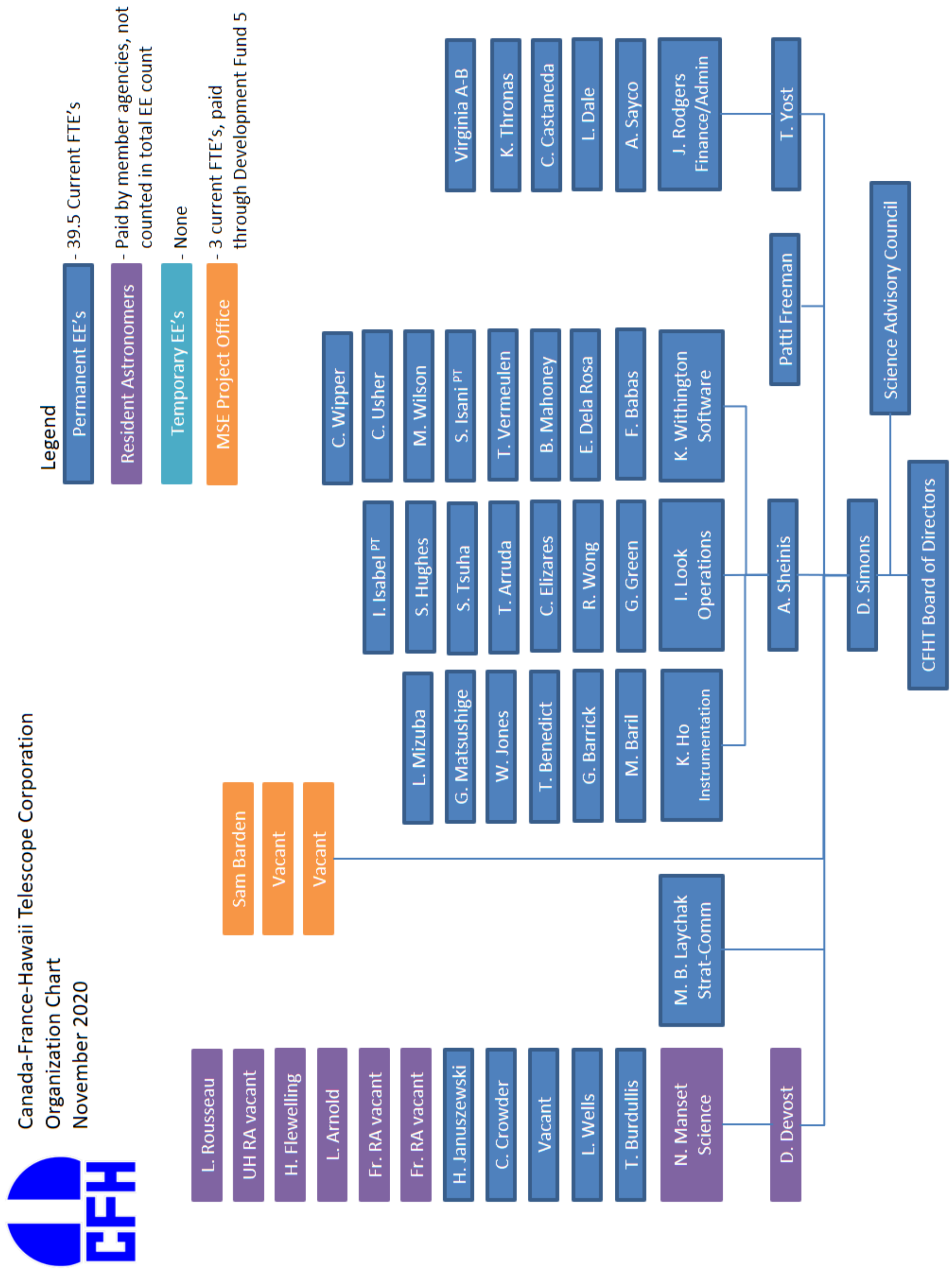
Jennifer Sobeck
Jennifer joined the MSE Project Office as the System Scientist after a 7-year tenure with the Sloan Digital Sky Survey IV (SDSS-IV). She served as the Project Manager for one of its cornerstone projects, the Apache Point Galactic Evolution Experiment 2 (APOGEE-2), and additionally managed SDSS-IV Operations at Las Campanas Observatory. Jennifer was a member of the team that built the second APOGEE instrument which acquires multi-object, high-resolution spectral data in the near-infrared. Jennifer studied at the University of Texas at Austin and received BS, MA, and PhD degrees in Physics. She completed postdoctoral positions at the European Southern Observatory, the University of Chicago, and the Observatoire de la Côte d'Azur, before undertaking research scientist roles at the University of Virginia and the University of Washington.

Promotions

Greg Green
Greg was promoted to the position of Senior Mechanical Designer/Instrument Maker. In addition, with this promotion Greg has been reassigned from the Operations Group to the Instrumentation Group to better align his skills and expertise with the needs of the organization. Greg has been a valuable member of the CFHT ‘ohana since 2012. His machining capabilities, combined with his CAD expertise, prove invaluable across a wide spectrum of projects. Among some of his most recent accomplishments are the design and manufacture of a new access platform to the dome bridge crane and machining a new dry air purge system to reduce condensation on the primary mirror. Greg also contributes to the MSE project by creating the CAD models for the planned facility.

Arturo Sayco
Arturo has served as CFHT’s accountant since 2016. Jane Rodgers, our current controller, recently announced her planned retirement in early 2021. Moving Arturo into the role of Controller to replace Jane was a natural progression given his significant contributions and experience. He was promoted to the role effective January 1, 2021 in order to transition with Jane prior to her retirement. Arturo is well prepared for the role with a broad and deep level of expertise. Over his career he has worked in internal audit, corporate planning, budgeting and reporting, and financial analysis. Arturo has made many significant contributions to streamlining existing business processes and we look forward to further contributions as CFHT moves into the future.

Organization Chart



Staff List at the End of 2020

Name	Position	Name	Position
Aragon-Barnes, Virginia	Environmental, Health, & Safety Manager	**Laychak, Mary Beth**	Director of Strategic Communications
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
Barden, Sam	MSE System Engineer	**Marshall, Jennifer**	MSE Project Scientist
Baril, Marc	Instrument Engineer	**Matsushige, Grant**	Sr. Instrument Specialist
Barrick, Gregory	Optical Engineer	**Mizuba, Les**	Instrument Specialist
Benedict, Tom	Instrument Engineer	**Rodgers, Jane**	Finance Manager
Burdullis, Todd	QSO Operations Specialist	**Rousseau-Nepton, Laurie**	Resident Astronomer
Castaneda, Carolyn	Administrative Specialist	**Sayco, Arturo**	Accountant
Crowder, Callie	Remote Observer	**Sheinis, Andy**	Director of Engineering
Dale, Laurie	Administrative Specialist	**Simons, Doug**	Executive Director
Dela Rosa, Eric	System Administrator	**Sobeck, Jennifer**	MSE System Scientist
Devost, Daniel	Director of Science Operations	**Szeto, Kei**	MSE Project Manager
Elizares, Casey	Summit Operations Manager	**Thronas, Kahea**	Vehicle/Facility Maint. Specialist
Flewelling, Heather	Instrument Support Scientist	**Tsuha, Seizen**	Mechanical Technician
Freeman, Patti	Assistant to the Exec Director	**Usher, Christopher**	Software Programmer
Green, Greg	Mech Designer/Instr. Maker	**Vermeulen, Tom**	System Programmer
Hill, Alexis	Project Engineer	**Wells, Lisa**	Remote Observer
Ho, Kevin	Instrument Manager	**Wilson, Matt**	Computer Software Eng.
Hughes, Steve	Electrician	**Wipper, Cameron**	Remote Observer
Isabel, Ilima	Custodian	**Withington, Kanoa**	Software Manager
Isani, Sidik	Software Engineer	**Wong, Raycen**	Mechanical Engineer
Januszewski, Helen	Remote Observer	**Yost, Tracy**	Director of Finance and Admin.
Jones, Windell	Instrument Engineer		

Communications & Outreach Report

Communications Program

The focus of the joint Maunakea Observatories (MKOs) communications efforts transitioned in 2020 from focusing on responses to protests to coordinated COVID-19 messaging and community support, monitoring of kia'i efforts away from Maunakea, bolstering public perception of the Maunakea Observatories, and virtual public engagement.

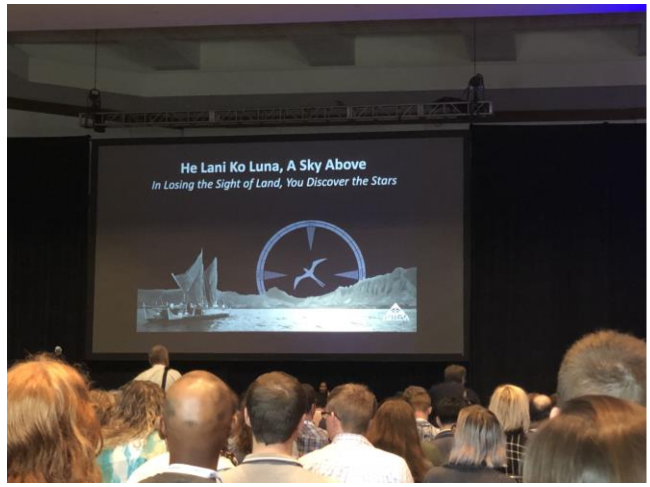


Figure 27 – AAS conference plenary talk by master navigator Kalepa Baybayan.

The AAS held their annual winter meeting in Honolulu in January of 2020. CFHT and MSE had a booth along with the majority of the Maunakea Observatories. For the first time, the MKOs sponsored a joint Maunakea Astronomy booth. The dedicated MKO booth acted as a concierge of Hawai'i Astronomy, directing inquires to the appropriate booths, answering general questions about the "Hawai'i situation" and providing the occasional dinner recommendation to visiting astronomers.

Coordination of the AAS meeting required significant effort from Mary Beth Laychak, Doug Simons and Nadine Manset. Mary Beth took the lead along with W.M. Keck Observatory in organizing the joint Maunakea Observatories booth along with all printed materials, MKO wide staff trainings, and coordination among the MKOs, UH, IfA and 'Imiloa. She served as the primary contact for the AAS regarding the MKO block of booths and public relations with the convention center.

Doug and Mary Beth spearheaded two successful AAS special sessions dedicated to Hawai'i Astronomy - Innovative Collaborations of Integrity with the Hawaiian Community and The Many Facets of Hawai'i Astronomy along with an evening public talk "The Physics of Pō" by Doug and Dr. Larry Kimura, Hawaiian language expert. They worked with the AAS to schedule two Native Hawaiian Plenary sessions, one by master navigator Kalepa Baybayan and the other by Hawaiian language and culture expert Amy Kalili. The "Evening with the Maunakea Observatories" open house organized by Mary Beth and John O'Meara from the W. M. Keck Observatory was a success and heavily attended.

In addition to contributing to the joint MKO booth and efforts, CFHT and MSE hosted a booth for the 3rd consecutive year. The booth focused on MSE while highlighting CFHT's current suite of instrumentation. MSE's special session and evening event were well attended. The goal of the events and booth was to emphasize a positive future for CFHT and MSE.

The AAS meeting received significant coverage on statewide news. Hawaii News Now, the largest news outlet in the state, conducted live interviews from the conference every half hour throughout their morning news one day and sent a crew to cover "The Physics of Pō and the Pō of Physics" evening talk by Doug and Dr. Kimura.

Nadine continues to chair the Maunakea Observatories Crisis Communications working group (MKCCWG), an extension of her role as the Maunakea Astronomy Outreach Committee chair, a position she has held

Figure 28 - AAS booths-- (left) Kei Szeto at the CFHT/MSE booth (right) Joint MKO booth.

for over six years. The MKCCWG formed in the wake of the 2015 protests and was reactivated in the spring in anticipation of more protests related to TMT. The MKCCWG is comprised of representatives from each existing MKO and IfA with TMT, UH system and ʻImiloa as guest members. The MKCCWG is responsible for managing the internal and external communications for the Maunakea Observatories as a collective. CFHT staff, specifically Mary Beth, Nadine, and Doug, were involved in the creation of all MKCCWG documentation in conjunction with the Bennet Group and representatives from W. M. Keck Observatory, Gemini, and EAO.

The MKCCWG meets weekly, reviewing any significant issues or crises related to the Maunakea Observatories. In the spring, the group's efforts focused on the MKO response to COVID-19, specifically the public-facing announcements surrounding the hiatus of MKO operations mountain wide and the subsequent return to observations.

2020 saw the creation of the Maunakea Strategic Communications working group, chaired by Mary Beth and charged with executing the joint MKO communications plans developed in conjunction with the Bennet Group and approved by the MKO directors. The group was assembled to address the long-term communications needs of the MKOs with an emphasis on Master Lease renewal. As chair of the MKCCWG, Nadine sits on the MKSCG to ensure smooth communications and coordinated efforts between the two groups.

Mary Beth oversees the management of the MKO social media channels. The success of the MKO social media during the AAS meeting and launch of MKO@Home required a new strategy to maintain interest. The overall social media strategy was developed in collaboration with the Bennet Group and representatives across the MKOs. Mary Beth's virtual summer intern created a structure and repository for MKO representatives to upload images from their facilities. Mary Beth organized the MKO social media committee in fall 2020 to handle the daily management of the pages. The committee will begin implementation by the end of the year.

Doug and Mary Beth joined Rich Matsuda (W. M. Keck Observatory), Jessica Dempsey (EAO), Christine Matsuda (Bennet Group), and community consultants, Noe Kalipi (Kalipi Enterprises) and Susan Maddox (Friends of the Future), to develop a MKO plan for community engagement building off of the success of EnVision Maunakea. COVID and meeting fatigue on the part of the community, combined with many parallel efforts on the part of the US National Science Foundation, state, and University of Hawaiʻi led to a revamping of the planned project in the fall. Implementation of the community engagement strategy is underway.

Canada

CFHT continued writing a column in the bi-monthly Royal Canadian Astronomical Society's journal, entitled "CFHT Chronicles." The CFHT Chronicles 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 received nice feedback from RASC members who enjoy reading the column.

In February 2020, Mary Beth visited Victoria and Vancouver, giving talks to the RASC chapters of both cities, graduate and undergraduate students at the University of Victoria, and the Centre of the Universe. She also met with Kathryn MacLeod from the NRC Communications department to provide updates on CFHT and plan future collaborations.

CFHT planned to partner with Discover the Universe during our 5th annual teacher's workshop at the June CASCA meeting, but the meeting's move to a virtual platform cancelled the workshop. Instead, CFHT staff including Mary Beth and Laurie Rousseau-Nepton participated in the Discover the Universe's Astro at Home program. Running weekdays from March 17-May 29, Astro at Home offered a daily French and English thirty minute, live astronomy talk targeted at keiki ages 8-12.

In November, CFHT was one of the sponsors of the McGill University Hack-a-thon. Nadine created a small coding challenge, identifying spectral lines and calculating the area under the curve for absorption/emission lines in ESPaDOnS data. The winning code will be reviewed and potentially used by Maunakea Scholars students who have ESPaDOnS data. Mary Beth gave a talk on software careers at CFHT featuring a video interview with CFHT software engineer Matt Wilson.

Understanding that travel will again be limited in 2021 at least through the first half of the year, our evaluation of how to engage groups that CFHT missed in 2020 (e.g., First Nations groups, teachers, undergrad/graduate students, etc.) is ongoing.

France

COVID-19 derailed all plans for French outreach, including connecting with Alain Cirou, former editor of Ciel et Espace, whom we connected with in 2019. Similar to our Canadian outreach, we evaluate on a continual basis how to connect with the community in France.

Figure 29 – Screenshot from one of Laurie Rousseau-Nepton's Astro at Home Talks.

Hawai'i

CFHT participated in the usual assortment of community events, school visits, portable planetarium shows and summit tours before everything came to a halt in March 2020. Much of our outreach efforts in 2020 focused on virtual events and responding to the needs of the community due to COVID.

Journey Through the Universe occurred the first two weeks of March. Journey Through the Universe is a Gemini led initiative in East Hawaiʻi where observatory staff visit K-12 classrooms presenting science and career talks. Several CFHT staff volunteered for the East Hawaiʻi classroom visits, including a career panel organized by Doug Simons at Waiakea High School. The bulk of the CFHT Journey Through the Universe visits occurred in North Hawaiʻi where the program is organized by CFHT with support from the W. M. Keck Observatory. The program reached approximately 1200 students before being suspended due to COVID-19.

With the cancellation of not only Journey Through the Universe classroom visits, but all scheduled Spring outreach events, the Maunakea Observatories started MKO@Home, a virtual MKO-wide outreach initiative, led by Mary Beth. MKO@Home consists of a series of short videos created by MKO staff and posted on a newly created MKO YouTube Channel (bit.ly/mkoathome). The short videos focus on science and staff with an emphasis on activities that families can do at home.

Figure 30 – Screenshot from Lisa Wells' MKO@Home video.

As of the end of November, the MKO@Home team created 49 videos and hosted five live events. The MKO YouTube channel now has 231 subscribers, over 9,300 views and over 64,000 impressions. Callie Crowder took the lead on technical support of the MKO@Home series while Mary Beth organizes the efforts.

Mary Beth serves on the School and Community Council for three local schools and offers support to the new STEM building at Waimea Middle School. These connections give CFHT a prominent role in the local educational community.

COVID created challenging times for Maunakea Scholars (MKS). All summit tours were cancelled in Spring 2020, allowing only one cohort of students to visit in February. The move to fully distance learning in the spring and the challenges that ensued within local schools caused several schools to not complete the program. Doug and Mary Beth successfully piloted a virtual MKS award ceremony with students from Kealakehe high school. Hawaiʻi schools faced confusion during the start of the 2020-2021 school year when the State Department of Education switched from blended learning to fully distance learning a week before the start of school. Each school runs a slightly different schedule resulting in several perennial MKS teachers not seeing their students until Spring 2021. To date, students at the majority of high schools hosting MKS have not returned to their classrooms or have gone back to distance learning after outbreaks. Despite the challenges, MKS is moving forward with several classes and will start in several more schools in January. We continue to work with students who already have received telescope time. We have twelve mentors, primarily graduate students from the University of Hawaiʻi's Institute for Astronomy.

In July, we awarded the third Hōkūala Scholarship to Shanen Arellano and Nathan Weir at a Zoom event. The scholarship is awarded to a senior who participated in the MKS program and plans on majoring in astronomy in college. Both students worked with CFHT astronomers on their projects—Shanen with Laurie Rousseau-Nepton on SITELLE data and Nathan with Nadine on ESPaDOnS data. The recipients split the $10,000 scholarship, each receiving $5,000 towards their education.

Figure 31 – Grand prize costume contest winner. His costume converted from a truck to a robot, just like a transformer.

MKS received one grant this year - a $100,000 grant from the Hawaiʻi Community Foundation. The HCF grant continued the MKS online astronomy class in partnership with UH Manoa for students at our participating Big Island MKS schools. The bulk of the increased funding is allocated to design a new cultural astronomy course for high school students in conjunction with ʻImiloa Astronomy Center. The course will be held in Summer 2021. We expect to receive the remainder of the two year First Hawaiian Bank grant in early 2020. Mary Beth is organizing Maunakea Scholar's participation in "Giving Tuesday" a national day of fundraising for nonprofit organizations.

With COVID cancelling in-person events, CFHT's two signature Waimea programs, the Solar System Walk and Winter Star Party moved to the virtual space. The Solar System Walk Costume Contest was held virtually in October in collaboration with the W. M. Keck Observatory and UH Institute for Astronomy. Participants submitted photos of their costumes on social media or via email. Judging was held via Zoom and the results revealed during an MKO@Home live event on October 30th. The footage of the event and interview with the winning parent was aired on all three statewide news outlets.

Planning continues on the Waimea Solar System Walk. Working with the W. M. Keck Observatory and UH IfA, Mary Beth is organizing a self-guided version of the event. Sidewalk decals are being designed that contain the solar system body's name, distance from the sun, and include a QR code. The QR code takes the participant to a short Solar System Walk video about the body recorded by staff across the MKOs. The videos are comprised of two parts—an English version which includes a discovery about the object made by one of the MKOs and an ʻolelo Hawaiʻi version which contains basic information about the object. The ʻōlelo Hawaiʻi versions were translated by Alyssa Leinani Lozi (Gemini) and Alexis Acohido (EAO) with the assistance of their kumu.

The decals will be placed along the Waimea Bypass Road at the appropriate scale. The final QR code leads participants to a Google form where they can register to receive an envelope of MKO stickers and other materials. The decals will remain in place for approximately one month. We anticipate launching this event in Spring 2021.

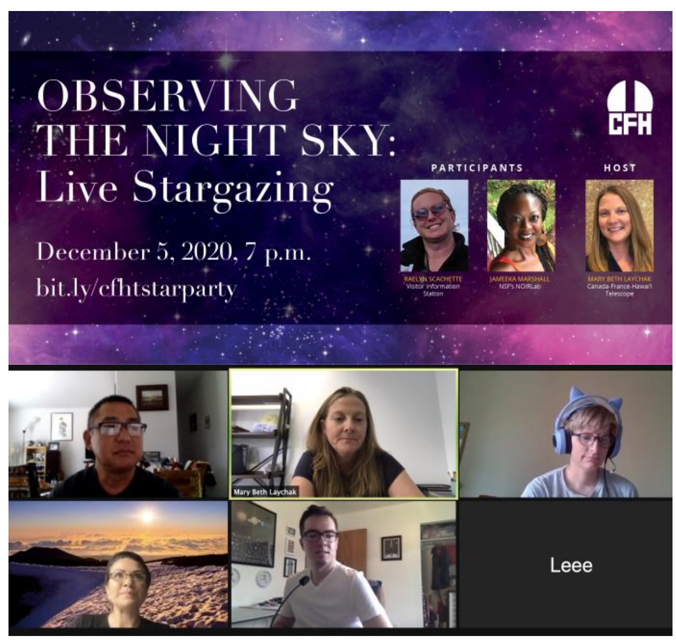


Figure 32 – Above, live stargazing was part of CFHT's annual (virtual) star party program. Below, a screenshot of CFHT staff talking to a student at the virtual career day "booth", i.e., Zoom room. Cam was explaining his position as a remote observer. The student is interested in potential internship opportunities.

The annual CFHT Winter Star party was held virtually November 30-December 5th. Each day featured a different video created by CFHT staff recreating a favorite activity of the star party: Marc Baril's binocular and telescope gift guide, RO room tour with Callie Crowder, Facebook and Instagram Live Ask an Astronomer with Laurie Rousseau-Nepton and Nadine Manset, Holiday Craft with Mary Beth, and fireside talk story with Doug. The culminating event is the virtual star-gazing, a live streamed event hosted in conjunction with the Maunakea Visitor Information Station. The VIS manager along with Gemini staffer Jameeka Marshall live streamed observations from the small VIS telescopes, airing on YouTube. Mary Beth hosted the event and members of the West Hawaiʻi Astronomy Club supported by answering questions in the chat. Mary Beth worked with North Hawaiʻi schools and nonprofit organizations to distribute star party craft kits to students so they can follow along with the star party crafts.

CFHT hosted a virtual high school social media intern during the summer of 2020. She worked with Mary Beth to develop the MKO social media architecture. She continues to work with Mary Beth alongside a college intern on assorted projects in the fall of 2020.

The Hawaiʻi Department of Education organized virtual career fairs in November. CFHT staff participated in two efforts, one for freshman statewide and the other for students in East Hawaiʻi. Both events were well attended and provide the opportunity to highlight the diversity of jobs at CFHT and local staff.

The following events were cancelled or significantly modified due to COVID: Astro Day Hilo (went virtual via MKO@Home), Astro Day Kona, Kamaʼāina Observatory Experience (KOE – on hiatus), and Akamai Internship (cancelled). The Akamai organizers are optimistic the program will resume in 2021 and started recruitment for that cohort in mid-November.

Social Media

The CFHT Facebook page grew from ~3,570 followers last year to 3,965 as of this report. Posts are made daily and focus on good news coming out of CFHT with emphasis on the staff, science, instrumentation, and outreach. During the early days of Hawaiʻi's work from home order, our social media focused on staff's adaptations to working from home. The accounts highlighted innovative experiments at home, staff home offices, landscape photos taken by staff, and very popular pet photos. Mary Beth and Callie Crowder met at the start of every month to review the previous month's metrics, evaluate successes, and plan the upcoming month. In the spirit of 2020 experimentation, we launched three video series—Summit Talk, a summit video tour series, Crafting with Science, and One Minute Science, which morphed into 2-5-minute videos explaining astronomical phenomenon, CFHT instruments, or general astronomy. All videos can be found on the CFHT Vimeo page as well.

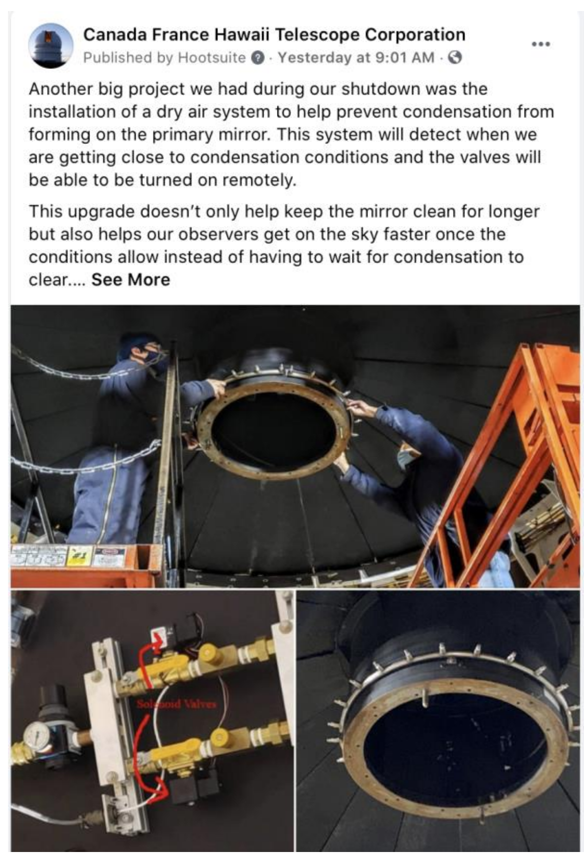


Figure 33 – Sample social media post.

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

Hawaiʻi State Department of Education. Our followers have increased from 1,450 in 2019 to 1,950 followers today. CFHT's Instagram account went from 380 followers in 2019 to 1,270 followers at the time of this report. After a slow start to Instagram, the account picked up steam throughout 2020 due in large part to Callie's analysis. Our Instagram followers tend to be less familiar with astronomy and our work, and are primarily drawn in by science images and pretty summit pictures. The content on all three accounts is complementary.

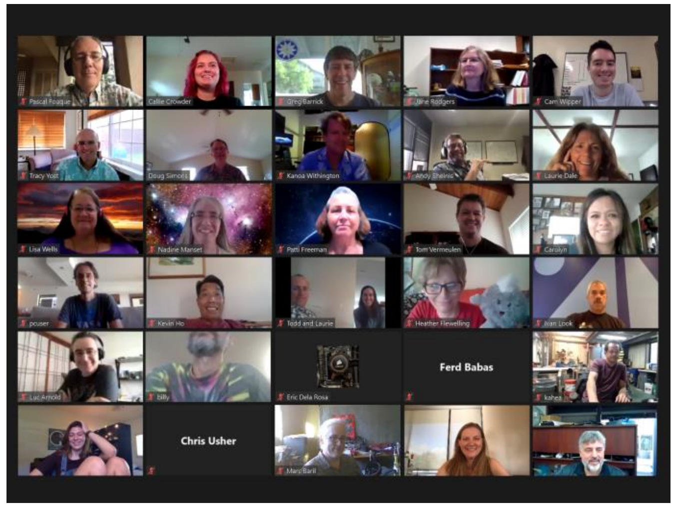


Figure 34 – Part of adapting our communications to COVID operations included the use of Zoom for nearly all staff events. Case in point, this photo from Pascal Fouqué's virtual going away party.

COVID Response

COVID-19 and the subsequent impact in Hawaiʻi provided new opportunities for community engagement. Doug Simons, Mary Beth Laychak, and Greg Green began working with Hawaiʻi STEM Community Care program. The group is a coalition of local organizations, students, and STEM supporters dedicated to creating innovative solutions to urgent needs on Hawaiʻi Island. Greg spearheaded the design and fabrication of stainless-steel hands-free door openers for local first responders. CFHT donated materials and staff support for the creation of 550 door openers.

Doug spearheaded a project to design and build UV light irradiators enabling first responders to sanitize N95 masks in ten minutes. With support from PISCES, UH Hilo Biology department, local doctor Craig Burger, and Greg Green, 24 units were built in the summer and fall of 2020. The units were donated to Hawaiʻi County Fire Department and Aliʻi Health Center.

Mary Beth began work on the Keiki Heroes (www.keikiheroes.org) project through the HI STEM Community Care program. The project continues to create and distribute child friendly and empowering COVID related messages designed for keiki grades pre-K-6. The program received $175,000 of funding from Hawaiʻi County and the nonprofit Vibrant Hawaiʻi to create and distribute materials across Hawaiʻi Island. Mary Beth hosts the monthly Keiki Heroes video segment that airs on the local TV show "Living in Paradise" and coordinates social media, news releases, distribution of materials in West Hawaiʻl, and educational connections.

Mary Beth's connections to local schools and West Hawaiʻi organizations have been instrumental to create an island wide program. She is building new connections in the community with organizations not traditionally reached by traditional astronomy outreach efforts. These newly created connections strengthen CFHT's reputation in the community and will aid in the upcoming MKO community engagement.

Mary Beth joined Connect Aloha, a North Hawaiʻi centric group aiming to identify and fill gaps in COVID-19 response in the community including food insecurity, PPE, and education. Among other projects, the organization designed and sewed children's face masks and distributed them via local elementary schools, organized a community wide celebration of Honokaʻa High School class of 2020 graduates, and a Halloween goodie bag distribution with the Food Basket. The group advised the Kō Educational Center on their development of virtual internships.

Figure 35 – CFHT and MSE virtual booth at the Summer 2020 AAS meeting.

Doug works with the Hawai'i Island Food basket, volunteering with their distributions and marshalling MKO staff when volunteers are needed. CFHT also funded several Thursday Community Meals in Waimea at St. James Episcopal church with CFHT staff members volunteering at that and other food distribution programs across the island.

CFHT supported a number of small, but impactful initiatives in North Hawai'i. We bought binders for all the Waimea Middle School students as part of a back to school drive the school was sponsoring, supported the Waimea Community Associations' Mahalo First Responders evening by purchasing four KTA gift cards for distribution. We provided candy to all the North Hawai'i public elementary schools for their Halloween drive through events. Events like these and others supported over the year reinforces CFHT's forty-year dedication to the Waimea community.

MSE

2020 proved a challenging year for the MSE EPO working group co-chaired by Mary Beth. The group's planned activities of creating personal connections in Indigenous communities sputtered as travel and conferences were cancelled. The group will reassess their efforts in early 2021 and evaluate how to move forward.

MSE and the MSE VR tour were heavily featured at the January AAS meeting. MSE actively participated in the CFHT virtual booth at the Summer AAS meeting, recruiting new members for the science team.

2020 Publications Including CFHT Data

More papers were published last year based upon CFHT data than any year in CFHT's 40+ year history. Overall, 227 unique papers were published including 80 based upon data that came directly from CFHT programs (facility papers), 62 from research using CFHT data present in the archives and 89 papers using data from catalogs incorporating CFHT data.

A historical analysis of publications is presented in the Figures to the right. This shows papers stemming from different instruments in 2020 and different categories of publications since 2013. 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.

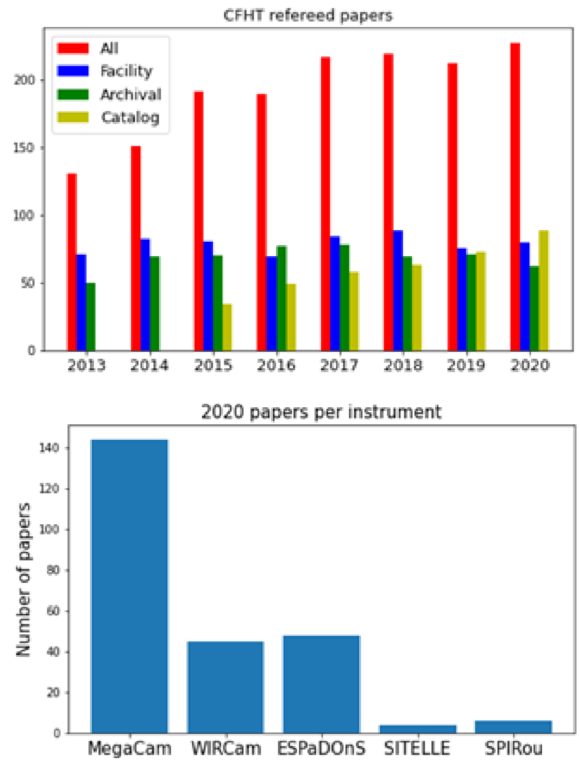


Figure 36 – (Top) CFHT papers by various categories since 2013 are listed and (bottom) papers by instrument during 2020.

Facility Papers (80)

Shultz, M. E., et al. The magnetic early B-type stars - IV. Breakout or leakage? Hα emission as a diagnostic of plasma transport in centrifugal magnetospheres, (2020), MNRAS, 499, 5379.

Järvinen, S. P., et al. The anomalous atmospheric structure of the strongly magnetic Ap star HD 166473, (2020), MNRAS, 499, 2734.

Fedorets, G., et al. Establishing Earth's Minimoon Population through Characterization of Asteroid 2020 CD_3, (2020), AJ, 160, 277.

Longobardi, A., et al. A Virgo Environmental Survey Tracing Ionised Gas Emission (VESTIGE). VII. Bridging the cluster-ICM-galaxy evolution at small scales, (2020), A&A, 644, A161.

Donati, J.-F., et al. SPIRou: NIR velocimetry and spectropolarimetry at the CFHT, (2020), MNRAS, 498, 5684.

Webb, K., et al. The GOGREEN survey: post-infall environmental quenching fails to predict the observed age difference between quiescent field and cluster galaxies at z > 1, (2020), MNRAS, 498, 5317.

Ko, Y., et al. Mysterious Globular Cluster System of the Peculiar Massive Galaxy M85, (2020), ApJ, 903, 110.

Wang, S., et al. The Sloan Digital Sky Survey Reverberation Mapping Project: How Broad Emission Line Widths Change When Luminosity Changes, (2020), ApJ, 903, 51.

Pan, H.-A., et al. SDSS-IV MaNGA: The Nature of an Off-galaxy Hα Blob—A Multiwavelength View of Offset Cooling in a Merging Galaxy Group, (2020), ApJ, 903, 16.

Bhardwaj, A., et al. Near-infrared Census of RR Lyrae Variables in the Messier 3 Globular Cluster and the Period-Luminosity Relations, (2020), AJ, 160, 220.

Bouvier, J., et al. Investigating the magnetospheric accretion process in the young pre-transitional disk system DoAr 44 (V2062 Oph). A multiwavelength interferometric, spectropolarimetric, and photometric observing campaign, (2020), A&A, 643, A99.

Cang, T.-Q., et al. Magnetic field and prominences of the young, solar-like, ultra-rapid rotator V530 Persei, (2020), A&A, 643, A39.

Sicilia-Aguilar, A., et al. Reading between the lines. Disk emission, wind, and accretion during the Z CMa NW outburst, (2020), A&A, 643, A29.

Allers, K. N., & Liu, M. C. A Novel Survey for Young Substellar Objects with the W-band Filter. I. Filter Design and New Discoveries in Ophiuchus and Perseus, (2020), PASP, 132, 104401.

Sikora, J., Wade, G. A., & Rowe, J. A spectroscopic test of the rotational modulation origin of periodic Kepler photometric variability of A-type stars, (2020), MNRAS, 498, 2456.

Bílek, M., et al. Census and classification of low-surface-brightness structures in nearby early-type galaxies from the MATLAS survey, (2020), MNRAS, 498, 2138.

Huang, T.-C., et al. CFHT MegaPrime/MegaCam u-band source catalogue of the AKARI North Ecliptic Pole Wide field, (2020), MNRAS, 498, 609.

Thomas, G. F., et al. The Hidden Past of M92: Detection and Characterization of a Newly Formed 17° Long Stellar Stream Using the Canada-France Imaging Survey, (2020), ApJ, 902, 89.

Gies, D. R., et al. Spectroscopic Detection of the Pre-White Dwarf Companion of Regulus, (2020), ApJ, 902, 25.

Rhea, C., et al. A Machine-learning Approach to Integral Field Unit Spectroscopy Observations. I. H II Region Kinematics, (2020), ApJ, 901, 152.

Ryu, Y.-H., et al. OGLE-2018-BLG-0532Lb: Cold Neptune with Possible Jovian Sibling, (2020), AJ, 160, 183.

Pouilly, K., et al. Magnetospheric accretion in the intermediate-mass T Tauri star HQ Tauri, (2020), A&A, 642, A99.

Moutou, C., et al. Early science with SPIRou: near-infrared radial velocity and spectropolarimetry of the planet-hosting star HD 189733, (2020), A&A, 642, A72.

Sestito, F., et al. The Pristine survey - X. A large population of low-metallicity stars permeates the Galactic disc, (2020), MNRAS, 497, L7.

Radica, M. C., Welch, D. L., & Rousseau-Nepton, L. A search for supernova light echoes in NGC 6946 with SITELLE, (2020), MNRAS, 497, 3297.

Monty, S., et al. Chemo-dynamics of outer halo dwarf stars, including Gaia-Sausage and Gaia-Sequoia candidates, (2020), MNRAS, 497, 1236.

Lavail, A., et al. The large-scale magnetic field of the eccentric pre-main-sequence binary system V1878 Ori, (2020), MNRAS, 497, 632.

Liu, C., et al. The Next Generation Virgo Cluster Survey. XXXIV. Ultracompact Dwarf Galaxies in the Virgo Cluster, (2020), ApJS, 250, 17.

Homayouni, Y., et al. The Sloan Digital Sky Survey Reverberation Mapping Project: Mg II Lag Results from Four Years of Monitoring, (2020), ApJ, 901, 55.

Takami, M., et al. Possible Time Correlation between Jet Ejection and Mass Accretion for RW Aur A, (2020), ApJ, 901, 24.

Jindal, A., et al. Characterization of the Atmosphere of Super-Earth 55 Cancri e Using High-resolution Ground-based Spectroscopy, (2020), AJ, 160, 101.

Martioli, E., et al. Spin-orbit alignment and magnetic activity in the young planetary system AU Mic, (2020), A&A, 641, L1.

Lima Neto, G. B., et al. NGC 4104: A shell galaxy in a forming fossil group, (2020), A&A, 641, A95.

Blagorodnova, N., et al. Progenitor, precursor, and evolution of the dusty remnant of the stellar merger M31-LRN-2015, (2020), MNRAS, 496, 5503.

Arentsen, A., et al. The Pristine Inner Galaxy Survey (PIGS) II: Uncovering the most metal-poor populations in the inner Milky Way, (2020), MNRAS, 496, 4964.

Tam, S.-I., et al. The distribution of dark matter and gas spanning 6 Mpc around the post-merger galaxy cluster MS 0451-03, (2020), MNRAS, 496, 4032.

Loubser, S. I., et al. Dynamical masses of brightest cluster galaxies I: stellar velocity anisotropy and mass-to-light ratios, (2020), MNRAS, 496, 1857.

Fonseca Alvarez, G., et al. The Sloan Digital Sky Survey Reverberation Mapping Project: The Hβ Radius-Luminosity Relation, (2020), ApJ, 899, 73.

Lim, S., et al. The Next Generation Virgo Cluster Survey (NGVS). XXX. Ultra-diffuse Galaxies and Their Globular Cluster Systems, (2020), ApJ, 899, 69.

Herman, M. K., et al. Search for TiO and Optical Nightside Emission from the Exoplanet WASP-33b, (2020), AJ, 160, 93.

Müller, O., et al. Spectroscopic study of MATLAS-2019 with MUSE: An ultra-diffuse galaxy with an excess of old globular clusters, (2020), A&A, 640, A106.

Sikora, J., et al. Spectropolarimetric follow-up of 8 rapidly rotating, X-ray bright FK Comae candidates, (2020), MNRAS, 496, 295.

Miroshnichenko, A. S., et al. Properties of Galactic B[e] Supergiants. V. 3 Pup-Constraining the Orbital Parameters and Modeling the Circumstellar Environments, (2020), ApJ, 897, 48.

Marsset, M., et al. Col-OSSOS: Compositional Homogeneity of Three Kuiper Belt Binaries, (2020), PSJ, 1, 16.

Seach, J. M., et al. A magnetic snapshot survey of F-type stars, (2020), MNRAS, 494, 5682.

Meštrić, U., et al. Outside the Lyman-break box: detecting Lyman continuum emitters at 3.5 < z < 5.1 with CLAUDS, (2020), MNRAS, 494, 4986.

Vieira, N., et al. A Deep CFHT Optical Search for a Counterpart to the Possible Neutron Star-Black Hole Merger GW190814, (2020), ApJ, 895, 96.

van der Burg, R. F. J., et al. The GOGREEN Survey: A deep stellar mass function of cluster galaxies at 1.0 < z < 1.4 and the complex nature of satellite quenching, (2020), A&A, 638, A112.

Moutard, T., et al. UV and U-band luminosity functions from CLAUDS and HSC-SSP - I. Using four million galaxies to simultaneously constrain the very faint and bright regimes to z ~ 3, (2020), MNRAS, 494, 1894.

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Zhang, W., et al. A Mysterious Ring in Dark Space?, (2020), ApJ, 893, 120.

Jose, J., et al. A Novel Survey for Young Substellar Objects with the W-band Filter. II. The Coolest and Lowest Mass Members of the Serpens-South Star-forming Region, (2020), ApJ, 892, 122.

Youakim, K., et al. The Pristine Survey - VIII. The metallicity distribution function of the Milky Way halo down to the extremely metal-poor regime, (2020), MNRAS, 492, 4986.

Antier, S., et al. The first six months of the Advanced LIGO's and Advanced Virgo's third observing run with GRANDMA, (2020), MNRAS, 492, 3904.

Venn, K. A., et al. The Pristine survey - IX. CFHT ESPaDOnS spectroscopic analysis of 115 bright metal-poor candidate stars, (2020), MNRAS, 492, 3241.

Ibata, R., et al. Detection of Strong Epicyclic Density Spikes in the GD-1 Stellar Stream: An Absence of Evidence for the Influence of Dark Matter Subhalos?, (2020), ApJ, 891, 161.

Ene, I., et al. The MASSIVE Survey XIV—Stellar Velocity Profiles and Kinematic Misalignments from 200 pc to 20 kpc in Massive Early-type Galaxies, (2020), ApJ, 891, 65.

Liepold, C. M., et al. The MASSIVE Survey. XV. A Stellar Dynamical Mass Measurement of the Supermassive Black Hole in Massive Elliptical Galaxy NGC 1453, (2020), ApJ, 891, 4.

Yang, H., et al. KMT-2016-BLG-1836Lb: A Super-Jovian Planet from a High-cadence Microlensing Field, (2020), AJ, 159, 98.

Lin, S.-J., et al. Physical and chemical modeling of the starless core L 1512, (2020), A&A, 635, A188.

Flagey, N., et al. Wide field-of-view study of the Eagle Nebula with the Fourier transform imaging spectrograph SITELLE at CFHT, (2020), A&A, 635, A111.

Wade, G. A., et al. No evidence of a sudden change of spectral appearance or magnetic field strength of the O9.7V star HD 54879, (2020), MNRAS, 492, L1.

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Carlos, M., et al. Li abundances for solar twins in the open cluster M67, (2020), MNRAS, 492, 245.

Bait, O., et al. Discovery of a large H I ring around the quiescent galaxy AGC 203001, (2020), MNRAS, 492, 1.

Donati, J.-F., et al. The magnetic field and accretion regime of CI Tau, (2020), MNRAS, 491, 5660.

Gould, A., et al. KMT-2018-BLG-0029Lb: A Very Low Mass-Ratio Spitzer Microlens Planet, (2020), JKAS, 53, 9.

Ferrarese, L., et al. The Next Generation Virgo Cluster Survey (NGVS). XIV. The Discovery of Low-mass Galaxies and a New Galaxy Catalog in the Core of the Virgo Cluster, (2020), ApJ, 890, 128.

Boselli, A., et al. A Virgo Environmental Survey Tracing Ionised Gas Emission (VESTIGE). VI. Environmental quenching on HII-region scales, (2020), A&A, 634, L1.

Jofré, E., et al. Gemini-GRACES high-quality spectra of Kepler evolved stars with transiting planets. I. Detailed characterization of multi-planet systems Kepler-278 and Kepler-391, (2020), A&A, 634, A29.

Cheng, X.-L. Search for strong galaxy-galaxy lensing in SDSS-III BOSS, (2020), RAA, 20, 002.

Pike, R. E., et al. A dearth of small members in the Haumea family revealed by OSSOS, (2020), NatAs, 4, 89.

Arentsen, A., et al. The Pristine Inner Galaxy Survey (PIGS) I: tracing the kinematics of metal-poor stars in the Galactic bulge, (2020), MNRAS, 491, L11.

Habas, R., et al. Newly discovered dwarf galaxies in the MATLAS low-density fields, (2020), MNRAS, 491, 1901.

Longeard, N., et al. The Pristine Dwarf-Galaxy survey - II. In-depth observational study of the faint Milky Way satellite Sagittarius II, (2020), MNRAS, 491, 356.

Hubrig, S., et al. The very slow rotation of the magnetic O9.7 V star HD 54879, (2020), MNRAS, 491, 281.

Gonçalves, R., et al. Venus' cloud top wind study: Coordinated Akatsuki/UVI with cloud tracking and TNG/HARPS-N with Doppler velocimetry observations, (2020), Icar, 335, 113418.

Li, Y., et al. Direct Detection of Black Hole-driven Turbulence in the Centers of Galaxy Clusters, (2020), ApJL, 889, L1.

Choi, B.-E., et al. Line Formation of Raman-scattered He II λ 4851 in an Expanding Spherical H I Shell in Young Planetary Nebulae, (2020), ApJ, 889, 2.

Schonhut-Stasik, J., et al. ROBO-AO Kepler Asteroseismic Survey. II. Do Stellar Companions Inhibit Stellar Oscillations?, (2020), ApJ, 888, 34.

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Marques-Chaves, R., et al. The discovery of the most UV-Lyα luminous star-forming galaxy: a young, dust- and metal-poor starburst with QSO-like luminosities, (2020), MNRAS, 499, L105.

Mashonkina, L., et al. Chemical diversity among A-B stars with low rotational velocities: non-LTE abundance analysis, (2020), MNRAS, 499, 3706.

Melbourne, K., et al. Estimating the Ultraviolet Emission of M Dwarfs with Exoplanets from Ca II and Hα, (2020), AJ, 160, 269.

Fensch, J., et al. Shedding light on the formation mechanism of shell galaxy NGC 474 with MUSE, (2020), A&A, 644, A164.

Larsen, S. S., et al. An extremely metal-deficient globular cluster in the Andromeda Galaxy, (2020), Sci, 370, 970.

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Mukae, S., et al. Cosmological 3D H I Gas Map with HETDEX Lyα Emitters and eBOSS QSOs at z = 2: IGM-Galaxy/QSO Connection and a ~40 Mpc Scale Giant H II Bubble Candidate, (2020), ApJ, 903, 24.

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Gruppioni, C., et al. The ALPINE-ALMA [CII] survey. The nature, luminosity function, and star formation history of dusty galaxies up to z ≃ 6, (2020), A&A, 643, A8.

Gonçalves, B. F. O., et al. Li-rich giant stars under scrutiny: binarity, magnetic activity, and the evolutionary status after Gaia DR2, (2020), MNRAS, 498, 2295.

Grossi, M., et al. Inverted metallicity gradients in two Virgo cluster star-forming dwarf galaxies: evidence of recent merging?, (2020), MNRAS, 498, 1939.

Tihhonova, O., et al. H0LiCOW - XI. A weak lensing measurement of the external convergence in the field of the lensed quasar B1608+656 using HST and Subaru deep imaging, (2020), MNRAS, 498, 1406.

Herbonnet, R., et al. CCCP and MENeaCS: (updated) weak-lensing masses for 100 galaxy clusters, (2020), MNRAS, 497, 4684.

Carlsten, S. G., et al. Radial Distributions of Dwarf Satellite Systems in the Local Volume, (2020), ApJ, 902, 124.

Kochukhov, O., & Reiners, A. The Magnetic Field of the Active Planet-hosting M Dwarf AU Mic, (2020), ApJ, 902, 43.

Vaduvescu, O., et al. Dozens of virtual impactor orbits eliminated by the EURONEAR VIMP DECam data mining project, (2020), A&A, 642, A35.

Ashton, E., Beaudoin, M., & Gladman, B. J. The Population of Kilometer-scale Retrograde Jovian Irregular Moons, (2020), PSJ, 1, 52.

Medvedev, P., et al. SRG/eROSITA uncovers the most X-ray luminous quasar at z > 6, (2020), MNRAS, 497, 1842.

Alabi, A. B., et al. NGC 474 as viewed with KCWI: diagnosing a shell galaxy, (2020), MNRAS, 497, 626.

Romanovskaya, A. M., Ryabchikova, T. A., & Shulyak, D. V. Fundamental parameters of Ap-star HD 108662, (2020), INASR, 5, 219.

Lunnan, R., et al. Four (Super)luminous Supernovae from the First Months of the ZTF Survey, (2020), ApJ, 901, 61.

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