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Science & Outreach at La Silla During the Total Solar Eclipse

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Figure 1. Some members of the ESA/CESAR team at their observing spot. From left to right: Manuel Castillo, Wouter van Reeven, Miguel Pérez-Ayúcar, Joe Zender and Darío Pérez de Carlos.

Total solar eclipses are rare phenomena, only occurring in a specific location once every 360 years on average. Historically, total solar eclipses have only been observed twice from large professional observatories, allowing specific science experiments to take place. On this occasion, ESO invited nearly 25 scientists, communicators and educators to observe and document the eclipse and benefit from La Silla's clear skies and its infrastructure and resources. This article presents an overview of these various activities.

Introduction

It is very rare that a total solar eclipse passes over an existing observatory with large telescopes — in fact, in the last fifty years there have only been two such opportunities: in 1961 over l'Observatoire de Haute-Provence in France, and in 1991 over Mauna Kea on the island of Hawai'i. A separate article in this issue of the Messenger (Ventura et al., p. 43) provides an overview of the total solar eclipse event at La Silla (also see ESO press release[1]).

Along with cameras and telescopes brought by 700 members of the public and more than 60 journalists, five different groups conducted outreach, education and science experiments on the day[2]. They were assigned a place on the side of the La Silla mountain just below the Visitor Centre (formerly called the Ritz building) as well as on the New Technology Telescope (NTT) platform. The two 4-metre-class telescopes at La Silla were also pointed near the Sun during the eclipse. The observations using the New Technology Telescope (NTT) are described in this issue of the Messenger (Dennefeld et al., p. 54). The eclipse was also captured with a small solar telescope called the HARPS Experiment for Light Integrated Over the Sun (HELIOS) which is installed on the catwalk of the ESO 3.6-metre telescope, and fed into the High Accuracy Radial velocity Planet Searcher (HARPS) instrument via a fibre. The high-precision spectroscopic data look promising and are currently under analysis. Two national telescopes, Exoplanets in Transits and their Atmospheres (ExTrA) and the Rapid Eye Mount telescope (REM), also attempted observations but encountered technical problems.

ESA/CESAR

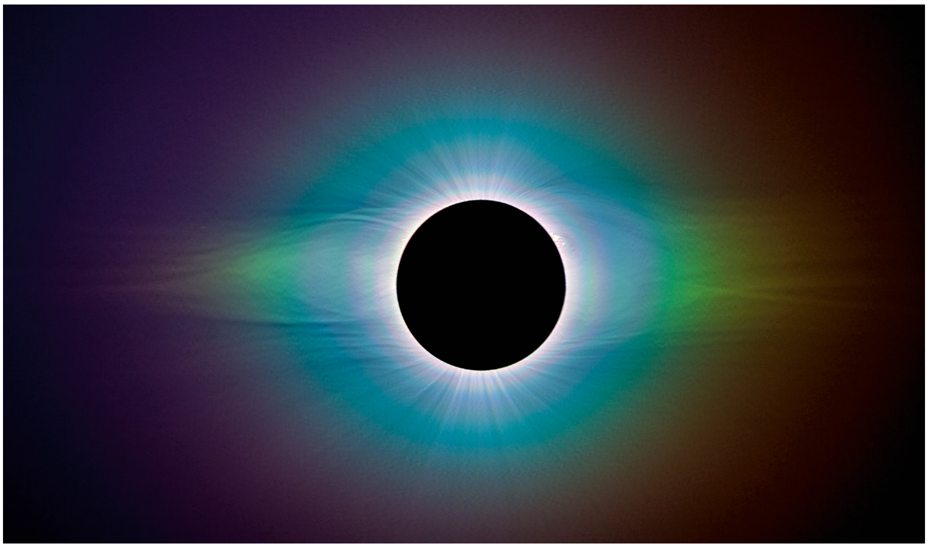


Figure 2. This image is a combination of polarised images obtained during totality to bring out the details of coronal structures.

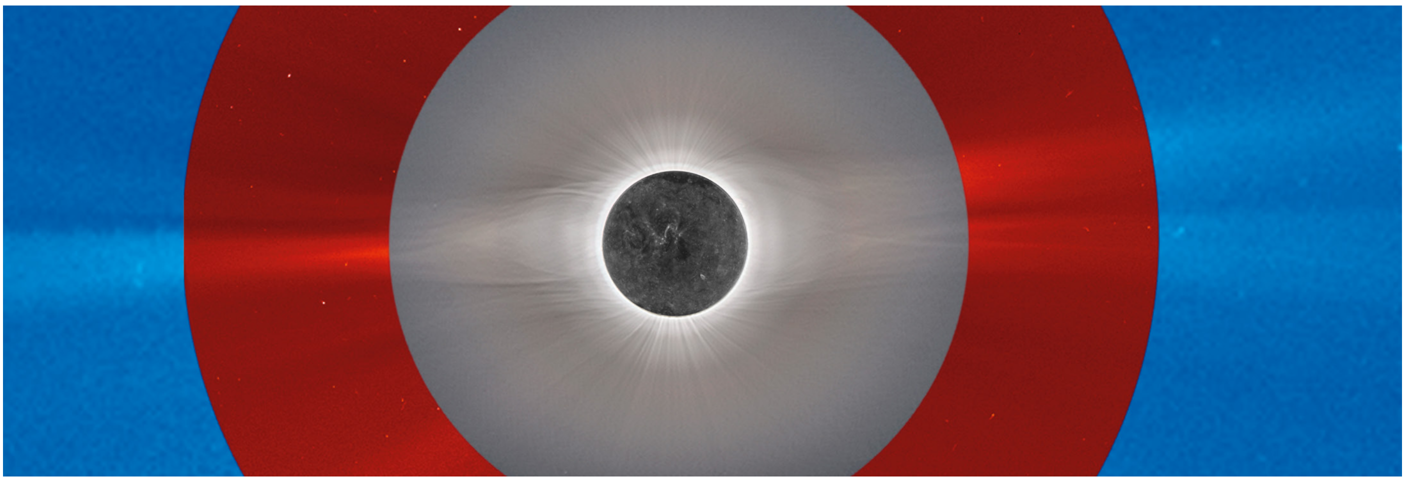
ESA/CESAR Activities

The primary goal of the European Space Agency (ESA) project Cooperation through Education in Science and Astronomy Research (CESAR) was to carry out scientific observations of the solar atmosphere and the Earth's ionosphere, as well as general observations for outreach and education. The results obtained to date are summarised below and online[3].

The CESAR team[a] (Figure 1) completed the following education and outreach objectives:
- Still images of the inner corona were obtained with a 1-metre focal length telescope. These were sent live (at a rate of two per minute) and posted online[4] as soon as they were processed through the servers at the European Space Astronomy Centre (ESAC) in Madrid.
- Live streaming on YouTube[5] was carried out with a 1-metre focal length telescope and a Sony Alpha 7 SII camera.
- A live Google hangout[6] included live connections to the La Silla team and talks and presentations related to solar projects and science. This was coordinated from the CESAR facilities at ESAC enabling a professional multimedia production (including mixing live video streams from different places, live images of the eclipse, presentation slides, etc.).
- In the days following the eclipse, ESA published images from the event on the main ESA webpages[7] (see Figures 2–5).

The team also completed most of its scientific objectives; at the time of writing this was the status of the (ongoing) analysis:
- Polarisation measurements were completed using the Eclipse K-corona POLarimeter (EKPOL) from the Turin—INAF Observatory using two different setups; first, the polarisation intensities of the corona were measured using observations at four different polarisation angles (0, 45, 90 and 135 degrees). From these measurements, the polarisation brightness is measured and the electron density in the corona derived. The second objective was to obtain the polarisation intensities at more polarisation angles to decrease the overall uncertainty in the computation of the polarisation brightness. EKPOL (see Zangrilli et al., 2009) is based on an optical telescope supplemented by an electronic controllable liquid-crystal variable retarder together with a specific CCD camera (funded by the ESA Faculty). EKPOL was developed as a technology demonstrator for the Metis coronagraph on Solar Orbiter (INAF) and the Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun (ASPIICS) on Proba-3 (ESA/Royal Observatory of Belgium).

Figure 3. A composite image of the solar eclipse made from ground and space observations: Proba-2 (SWAP) solar disc, CESAR corona in grey, SOHO/LASCO C2 outer corona in red, SOHO/LASCO C3 extended corona in blue.



ESA/CESAR; SOHO (ESA & NASA); Proba-2: ESA/Royal Observatory of Belgium

ESA/CESAR

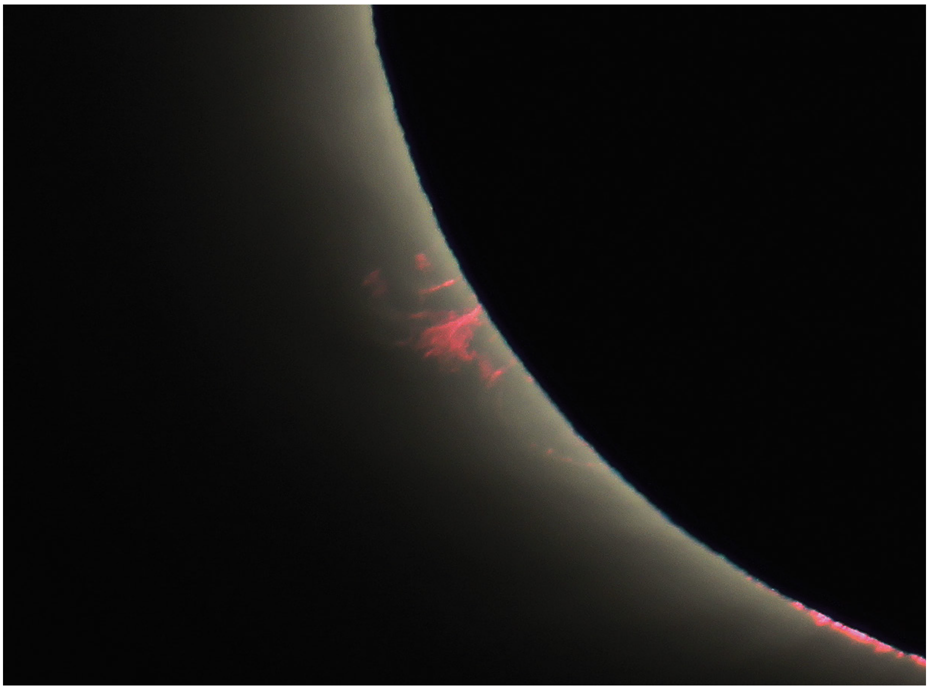


Figure 4. The Sun's chromosphere and prominence taken with a visible-light telescope (~ *f*/1000), with no filter and using a Canon 550D, during the Moon's exit (third contact).

- Independent polarisation measurements (Figure 2) were completed with simple polarisation filtering of white light (with improved equipment and procedures derived from experience gained during the total solar eclipse in the USA). A filter wheel with four polarisation angles (0, 45, 90 and 135 degrees) was used. A fifth filter position without a polariser allowed the capture of unpolarised images. The objective of this experiment was to calculate the different polarisation rates in the inner solar corona to obtain estimates of the electron content and the magnetic field. These estimates, together with physical models of the corona, can give information about the temperature and flow speed of coronal electrons.
- A flash spectrum of the chromosphere was attempted but was unsuccessful owing to the unfortunate failure of the camera two minutes before totality. It consisted of a telescope projecting an image of the Sun through a high-quality transmission diffraction grating onto a digital SLR camera without an infrared blocking filter. This configuration permits one to image the emission spectrum of the chromosphere covering wavelengths from 4000 to 10 000 Å, allowing the identification of features that are present in the photosphere but not in the chromosphere.
- The CESAR team also completed the first ever measurements of the Earth's ionosphere using a Galileo receiver to try to record changes caused by the transit of the Moon's shadow over the area of observation. The analysis is ongoing; by using multi-band and multi-constellation data from the Global Navigation Satellite System (GNSS), it is possible to analyse the total electron density perturbations with enough time resolution to reveal ionospheric irregularities during the eclipse. For this purpose, the team has a close collaboration with a GNSS research group at the Universitat Politècnica de Catalunya (UPC). The equipment provided by the Galileo Science Office at ESAC is the same as that used by the Galileo Experimentation & Scientific Tests in Antarctica project to study the effect of solar activity in the ionosphere at high latitudes.
- Surface ultraviolet irradiance measurements were also completed to observe Earth-atmospheric evidence of asymmetric ultraviolet opacity over the eclipse. This could have a bearing on how observations of the corona are interpreted. This was done in collaboration with Ralph Lorenz from Johns Hopkins University Applied Physics Lab (simple photodiode sensors equivalent to those flown on the Mars Science Laboratory Curiosity and the Beagle 2 lander). Additional low-cost ultraviolet and visible flux measurements were carried out, including measurements of a decline in all-sky brightness during totality — in a silicon solar cell, the brightness declined to < 0.02% of post-eclipse values.

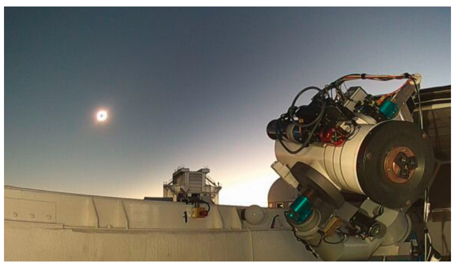
The TAROT observations

One century ago, on 29 May 1919, a seminal experiment led by Arthur Eddington confirmed Albert Einstein's prediction that light can be deflected by mass. Eddington used the Sun as a mass deflector and nearby stars as the targets with which to measure the light deflection. The experiment becomes feasible during a total solar eclipse because sky brightness drops to twilight levels and stars close to the Sun can be observed.

In 1915, Einstein predicted that the apparent position of a star is shifted radially away from the centre of the Sun. He predicted an angular displacement of 1.751 arcseconds when a star grazes the Sun's limb (twice the amount expected by Newtonian mechanics). This displacement decreases as the inverse of the distance to the centre of the solar disc.

Télescope à Action Rapide pour les Objets Transitoires (TAROT; see Figure 6) is a robotic telescope that was installed at ESO's La Silla Observatory in 2006 (Klotz et al., 2013). The primary goal of the TAROT team[b] observations was to repeat the Eddington Experiment. The telescope has an aperture of 25 cm, a

Figure 5. The TAROT telescope pointing north towards the Sun during totality. The enclosure of the NTT can also be seen. This frame is taken from TAROT's webcam sequence of the full eclipse[8].



The TAROT team

CESAR/ESA

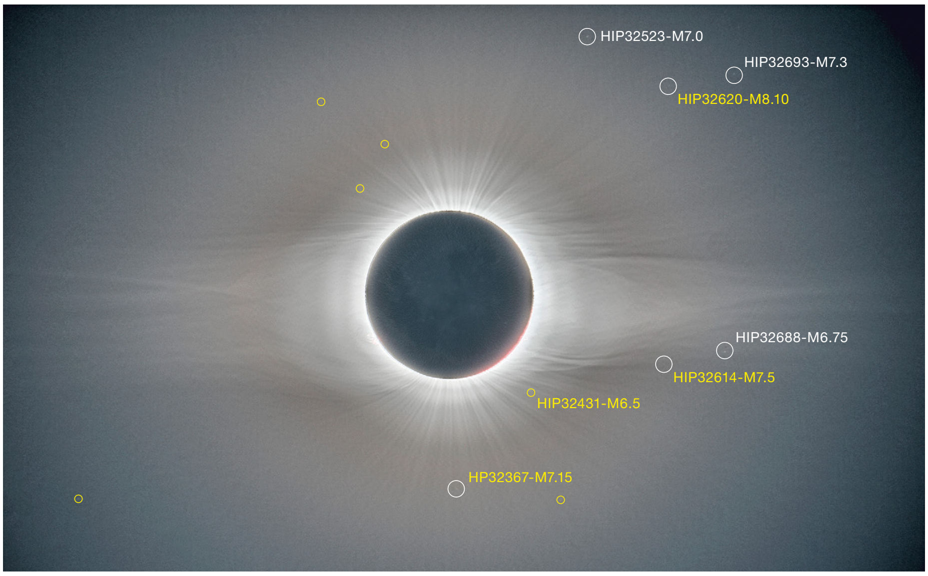


Figure 6. Stars during totality; 12 stars become visible through the extended corona, at separations less than six solar radii on sky.

focal length of 850 mm and a CCD camera that provides a field of view of 1.8 × 1.8 degrees with a spatial sampling of 3.29 arcseconds per pixel.

The stellar positions are measured experimentally on an image using Cartesian coordinates from the CCD sensor. The main difficulty is to link the Cartesian coordinates of the sensor to celestial coordinates on the sky, particularly as the light from stars recorded on the CCD is also affected by other physical effects unrelated to the Sun's gravitational field. Removing or accounting for these effects is crucial to allowing the accurate measurement of the gravitational deflection and confirming the general theory of relativity.

The most common way to calibrate these additional effects consists of recording images of field stars during a night with similar conditions to those during the eclipse: i.e., the same elevation of the stars, same optical setup, same temperature, etc. In the case of the TAROT observations, the advantage is that, as the telescope stays in the same place, the same stars that would be close to the Sun on sky during the eclipse can conveniently be observed at any period roughly six months before or after the eclipse.

The extended atmosphere of the Sun, the corona, poses another difficulty. The corona adds diffuse light which is not homogeneous because of its filamentary structure. Although very beautiful, coronal features can reduce the accuracy of the positional measurements of the stars.

Six months before the eclipse, a series of images of field stars were recorded at exactly the same elevation as during the eclipse. The analysis of these images demonstrated the ability to measure stellar positions with an accuracy on the order of ± 0.25 arcseconds, corresponding to an error of ± 15% in the value of the expected angular displacement that has been predicted by general relativity. Unfortunately, the TAROT CCD camera failed one month before the eclipse and had to be replaced two days before the eclipse. In order to have proper calibration images, the optical setup will be kept the same as during the eclipse, with the aim of recording new calibration images in January 2020.

The night before the eclipse, about 200 images were recorded in the same direction as the eclipse in order to compute the calibration coefficients between Cartesian coordinates and celestial coordinates. A second, more complex, calibration method is ongoing which involves computing the optical deformations for each image and merging all of the individual calibrations onto a master frame.

During the hour before totality, the partial eclipse was recorded with TAROT using an additional aperture solar filter. This filter was manually removed at the beginning of totality. A software script was specially written to record images during totality and to point the telescope away from the Sun when totality was over. Owing to the inherent dangers to the equipment, all of the steps were practised many times in the hours before the eclipse. In the end, image acquisition worked perfectly during the eclipse. A first analysis of the images shows that

PACA_SolPol19

Figure 7. Part of the PACA_SolPol19 setup on one side of the La Silla mountain.

stars are detected on images with exposure times of 5 and 10 seconds. The 1-second images do not saturate the corona but stars are almost undetectable. To illustrate the principles behind this experiment an image has been synthesised using one 1-second image and with stars visible from the 5- and 10-second images (see Figure 7). The next step will be the January 2020 observations needed for calibration.

The PACA_SolPol19 Activities

The Pro-Am Collaborative Astronomy project formed a a professional-amateur collaboration PACA_SolPol19[c] is to measure the linear polarisation of the K-corona during the total eclipse. The solar corona, extending far from the Sun, is hotter than the photosphere. The outer part of the corona becomes the solar wind that moves outward through the Solar System and interstellar space, interacting with planetary atmospheres and other Solar System objects, creating space weather. The corona exhibits radial filamentary structure — bright long streamers at all latitudes during periods of high solar activity.

During low solar activity, as during this eclipse, streamers are mostly limited to lower latitudes. The corona, being thin and tenuous, is only observable during total solar eclipses or with the use of a coronagraph to block the disc of the Sun.

ESO/C. Guirao/G. Ávila

Figure 9. The CAOS group comprised Carlos Guirao and Gerardo Ávila (both from ESO), seen here on their observing post on the NTT platform.

A major unanswered question in astrophysics is how the corona is heated. Current coronagraphs block much of the inner corona, making eclipses the simplest way this region can be investigated from the ground. Since the inner corona (K-corona) is dominated by electron scattering, which is linearly polarised, observations of polarised brightness during an eclipse provide information about the distribution of polarisation and the polarisation brightness, p_B, which is related to the local electron density.

PACA_SolPol19 consisted of four mini-teams, three of them located at the La Silla Observatory (Figure 8), using one imaging telescope and two polarimetric setups (one with a programmable polarisable sensor and the other with a polarised sensor), and one imaging setup at sea level at Punta de Choros, La Higuera. All setups used the same software to acquire imaging and polarimetric data, taking advantage of similar observing conditions and initial data reduction techniques. Detailed flat-fielding, calibration, and derivation of the polarisation follow procedures used to calibrate the data from the 2017 total solar eclipse in the USA. The end goal is to measure the polarisation brightness, degree of linear polarisation and angle of linear polarisation images (Elmore et al., 2000; Lites et al., 1999; van de Hulst, 1950; Quémerais & Lamy, 2002).

The team successfully imaged the K-corona, revealing equatorial streamers (as expected for a quiet Sun), and produced a map of the polarisation brightness (see Figure 9). The colours in the polarisation brightness map represent the angle of linear polarisation, with red being the maximum. The quiet Sun exhibited polarimetric minima at the solar poles and polarimetric maxima at the solar equator, with the solar prominence exhibiting low polarisation.

In addition, the solar prominence on the north-west limb of the Sun and two stars were imaged, one towards the north east and one to the south west (tentatively

PACA_SolPol19

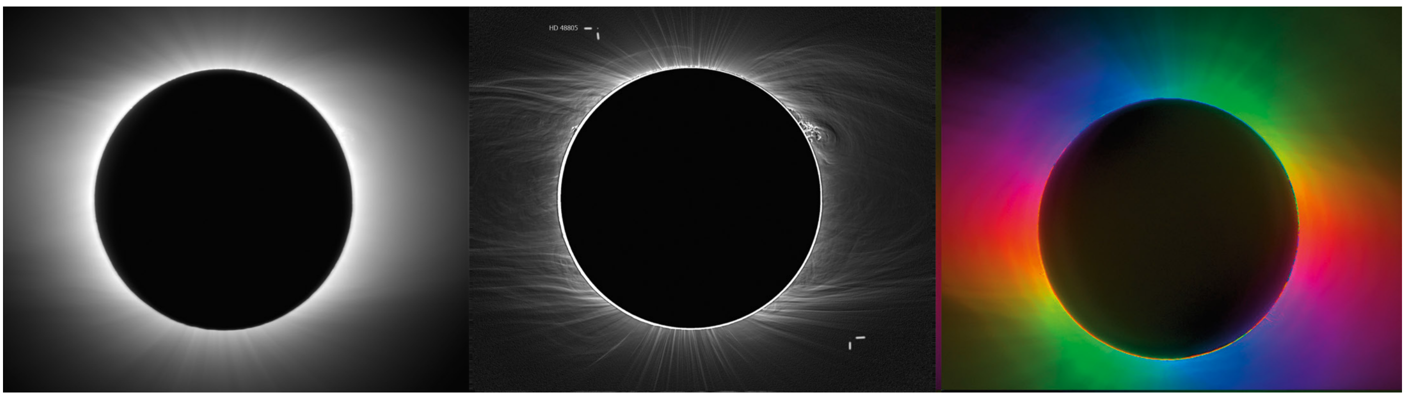


Figure 8. Left: The average total intensity of the corona. Middle: Sobel-filtered image of the solar corona. Right: The product of polarised brightness (pB) and the angle of linear polarisation, colour-coded with red indicating the maximum polarisation and green minimum polarisation.

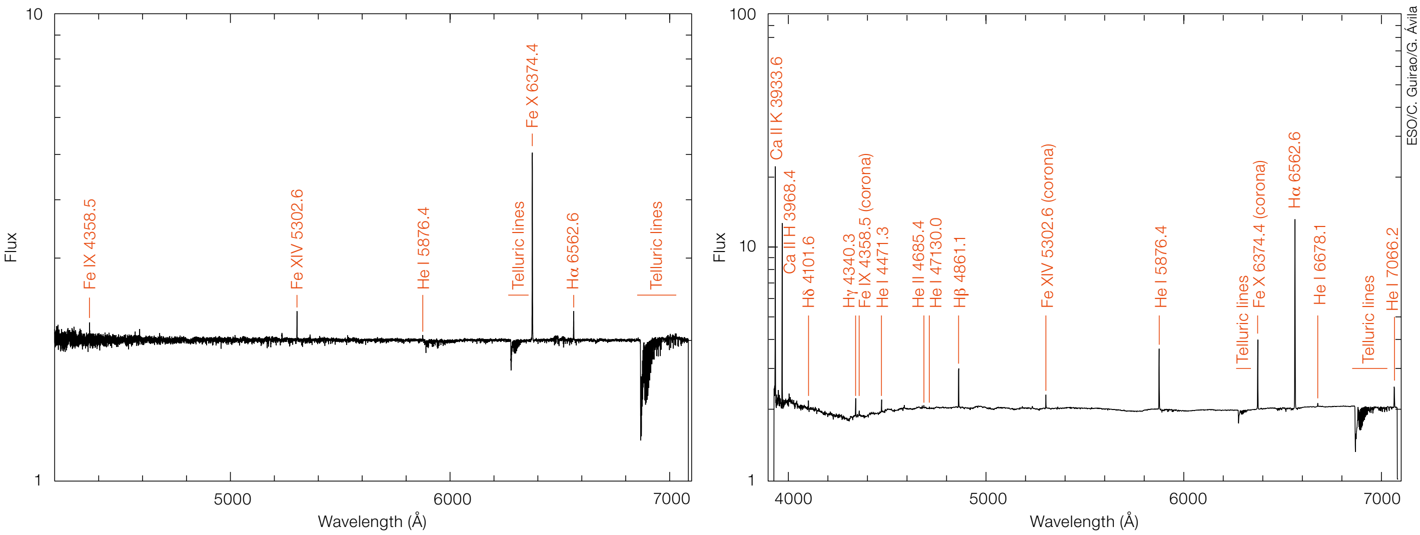


Figure 10. The two total solar eclipse spectra from the CAOS group: the spectrum of the corona (left, 10 exposures of 5 seconds) and the prominence (right, 3 exposures of 5 seconds).

identified as HD 48805 [SAO 78717] and HD 262616).

CAOS group

The group from the ESO Club of Amateurs in Optical Spectroscopy (CAOS)[d] (Figure 10) was observing from the NTT platform using a commercial 11-inch Schmidt-Cassegrain telescope and a spectrograph with a resolving power of 11 000 and spectral range of 3930–7070 Å. A commercial SBIG ST1603ME CCD camera recorded the spectra, which were calibrated with a thorium-argon hollow cathode and halogen lamps linked with a 300-μm optical fibre, for spectral calibration and order identification respectively.

Before totality, the telescope was covered with a Mylar sheet with an optical density of OD-5 to protect the instrument and our sight. In total, 13 exposures of five seconds were taken during totality. The slit of the spectrograph was placed close to the north pole of the Sun, and three of these 13 exposures showed partial illumination of the slit by a solar protuberance. The remaining 10 exposures recorded only the much weaker corona spectrum.

Both the protuberance and corona spectra (Figure 11) were reduced with the ESO–MIDAS software. The corona spectrum shows the "classical" iron (Fe XIV and Fe X) and Hα lines. The He line at 5876 Å is barely visible.

However, in the spectrum of the prominence, we found some interesting features: Ca II, five helium lines and the four hydrogen lines of the Balmer series.

ESO webcast

Starting at 19:56 CEST on 2 July 2019, a team[e] deployed by ESO provided a live webcast of the 2019 La Silla Total Solar Eclipse (see Figure 12). Organisations in the ESO Member States and beyond incorporated the webcast into public events set up for the occasion of the eclipse[9] and members of the public viewed it online in high definition on ESO's website and on ESO's YouTube channel[10]. The 4-hour live webcast was a "raw" feed without commentary regularly switching between sources, and featuring views of the Sun from three small telescopes and two cameras showing spectators at La Silla. The webcast finished

Figure 11. Part of the ESO webcast team in their working area in the shade under the Ritz (old control room building, now visitor centre). Left is engineer Lionel Gauze (APICAL), in the middle producer François Glasser (APICAL) and to the right ESO Photo Ambassador Alexandre Santerne (Aix-Marseille University/CNRS/CNES/LAM).

with a beautiful view of the Sun setting over the Pacific Ocean to conclude a day of amazing experiences at La Silla.

Considerable planning, including simulations, was carried out in the months before the eclipse. Different potential vantage points were analysed in detail using the online application The Photographer's Ephemeris[11]; this also revealed limitations in the tool's sunset times, which are most likely due to atmospheric refraction not being properly considered. The webcast was seen by tens of thousands of viewers on 2 July and has since accumulated more than 250 000 views (see Figure 13).

Acknowledgements

All authors are grateful to ESO's management for maximising the potential presented by this unique occasion.

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Notes

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[b] The TAROT team consists of Alain Klotz, Adrien Nicolas Klotz, Jean-François Le Borgne, Eric Denoux, Christian Buil, Valérie Desnoux, Yoann Richaud, Rico Sautile, Xavier Regal, Julien Lecubin, Loic Eymar, and Michel Boer.
[c] The PACA_SolPol19 team consists of Padma A. Yanamandra-Fisher, Robert F. Fisher, David Elmore, Wahab A. Baouchi, Kyle A. Motl, Roy Wellington, Theo Wellington and Andrei Ursache.
[d] The CAOS team consists of Carlos Guirao and Gerardo Ávila.
[e] The ESO webcasting team consists of François Glasser, Lionel Gauze, Alexandre Santerne and Lars Lindberg Christensen.

Links

1. Total Solar Eclipse: https://www.eso.org/public/news/eso1912/
2. Overview of experiments conducted at La Silla during the Total Solar Eclipse: https://www.eso.org/public/announcements/ann19031/
3. Results webpage from the CESAR team: http://cesar.esa.int/index.php?Section=Total%20Solar%20Eclipse%202019%20results
4. Archive of CESAR images: http://cesar.esa.int/sun_monitor/archive/ra/visible/2019/201907/20190702/
5. CESAR images broadcast live during eclipse: https://youtu.be/JKA2Vu_lyik
6. CESAR live-streaming webcast from the event: https://youtu.be/OTLbIPmvn4Q
7. ESA released images from the CESAR team: https://www.esa.int/spaceinimages/content/search?SearchText=%2Beclipse+%2Bcesar+%2Bjuly+-lunar&img=1&SearchButton=Go
8. Webcast from La Silla: https://www.youtube.com/watch?v=wEiyvX9GEDI&feature=youtu.be
9. Announcement of ESO webcast: https://www.eso.org/public/announcements/ann19027/
10. The ESO webcast page: https://www.eso.org/public/events/astro-evt/solareclipse2019/webcast/
11. The Photographer's Ephemeris: app.photoephemeris.com

Figure 12. Frame from the webcast at the time of totality.