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Early results from the solar-minimum 2019 total solar eclipse

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Abstract. We observed the 2 July 2019 total solar eclipse with a variety of imaging and spectroscopic instruments recording from three sites in mainland Chile: on the centerline at La Higuera, from the Cerro Tololo Inter-American Observatory, and from La Serena, as well as from a chartered flight at peak totality in mid-Pacific. Our spectroscopy monitored Fe X, Fe XIV, and Ar X lines, and we imaged Ar X with a Lyot filter adjusted from its original H-alpha bandpass. Our composite imaging has been compared with predictions based on modeling using magnetic-field measurements from the pre-eclipse month. Our time-differenced sites will be used to measure motions in coronal streamers.

Keywords. Sun: corona, eclipses, instrumentation: spectrographs

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1. Introduction

We tackled the observations of the 2 July 2019 total solar eclipse, which occurred at extreme solar minimum, with a variety of imaging and spectroscopy tools, following surveys of recent coronal research (Pasachoff 2017a; Pasachoff & Fraknoi 2017).

General background for eclipse studies has been available over a span of years (Pasachoff 1973, 2017b; Golub & Pasachoff 2014; Golub & Pasachoff 2017), with a more technical treatment in Golub & Pasachoff (2009). Observational techniques were discussed in Pasachoff (2019).

Maps showing the path of totality across the Earth's surface have been computed since the work of Edmond Halley for the eclipse of 1715 (Olson & Pasachoff 2019). In spite of worries about the prospective cloudiness or the marine layer†, especially given that

† http://eclipsophile.com

Figure 1. Totality in clear sky from our site above La Higuera on totality's centerline.

Figure 2. Orientation map showing details for our centerline site (Courtesy of Xavier Jubier and Google maps).

totality occurred with the Sun only 13° above the western horizon†, we have observations in clear skies from our three ground-based observing sites: (1) The Cerro Tololo Inter-American Observatory, 7,240-foot altitude, 2 min 6 sec; (2) La Higuera, centerline, 2,500-foot altitude, 2 min 35 sec totality (Figures 1 and 2); (3) La Serena, sea level, 2 min 15 sec totality. Prominences on the limb provided orientation and coordination with spacecraft observations from NOAA's GOES-16 Solar Ultraviolet Imager (SUVI) and the Atmospheric Imaging Assembly (AIA) on NASA's Solar Dynamics Observatory (SDO). We also have imaging and spectroscopy from a chartered Boeing 787 along the centerline, with nearly 8 min 30 sec of totality!

From our sites for the 2019 eclipse, we planned to enlarge on our observations of the 2017 American eclipse, though without the coronal-oscillation observations in the Fe XIV and Fe X coronal lines (the "green line" and the "red line," respectively), because we

† http://xjubier.free.fr/en/site_pages/solar_eclipses/xSE_GoogleMap3.php?Ecl=+20190702

Figure 3. Sunset view on 1 July 2019 from the La Higuera site (courtesy Ian Kezsbom).

Figure 4. Drone views of the La Higuera site.

worried that oscillations in the terrestrial atmosphere would overwhelm the slight effect in coronal intensity that we are monitoring. For our 2017 observations, see Pasachoff (2018); Pasachoff *et al.* (2018).

2. Observations from the centerline at La Higuera

For about two years prior to totality, we had planned our observations from the centerline, and our travel agent, Mark Sood, reconnoitered at La Higuera and chose a site on a high ridge overlooking the town.

Our scientific team consisted of JMP and three Williams College students, using equipment sent to La Serena with the assistance of the Kitt Peak National Observatory and the Cerro Tololo Inter-American Observatory. With the clear weather and absent marine layer the day before the eclipse (Figure 3), we had confidence that we would be able to observe totality (Figure 4).

Geosynchronous weather satellite GOES-16 showed that the umbra reached a cloud-free region of Chile (Figure 5). The new series of Geostationary Operational Environmental Satellites, including GOES-16, includes a Solar Ultraviolet Imager (SUVI) on each, carrying a sun-pointing set of telescopes that take ultraviolet images of continuum and corona (Figure 6). We also continue our interest in the effect of the

Figure 5. A view of the Earth showing the umbra approaching the Chilean Pacific coast, from NOAA GOES-16 satellite.

Figure 6. A 2 July 2019 eclipse-day view of 50,000-kelvin chromospheric gas (He II, 304 Å) from SUVI on GOES-16, eclipsed with prominences showing, centered in an early composite of our white-light eclipse images (courtesy Daniel B. Seaton and NOAA/U Colorado CIRES).

extreme eclipse darkening and cooling on the terrestrial atmosphere, continuing our joint work with Marcos Peñaloza-Murillo of Universidad de Los Andes, Mérida, Venezuela (Peñaloza-Murillo & Pasachoff 2018).

The solar cycle was in extreme minimum phase, with 111 days (61%) of 2019 prior to the eclipse showing no sunspots (Figure 7).

Our imaging includes series with an Astro-Physics 630 mm refracting telephoto, courtesy of Dan Schechter, Long Beach, CA, with a Nikon D850, courtesy of Nikon Professional Services (Figure 8).

On our site, we also had a team from Yunnan Observatory, China, headed by Zhongquan Qu, and Alphonse Sterling of NASA's Marshall Space Flight Center, Huntsville, AL, in addition to a tour group of about 100 people, arrangements for whom helped in the logistics. The morning drive from La Serena took about 1 hour, while the

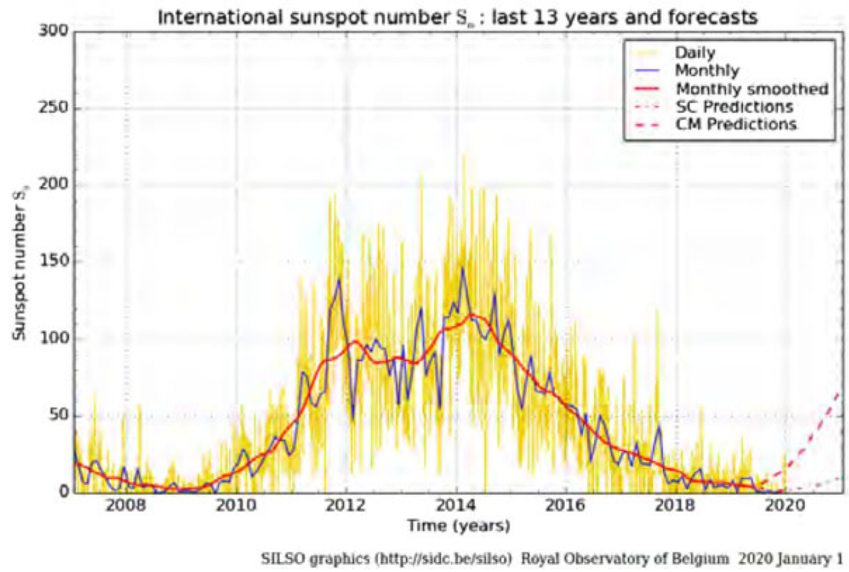

Figure 7. The recent sunspot cycle, from the Solar Indices Data Center (http://sidc.oma.be/silso) at the Royal Observatory, Belgium, 2020.

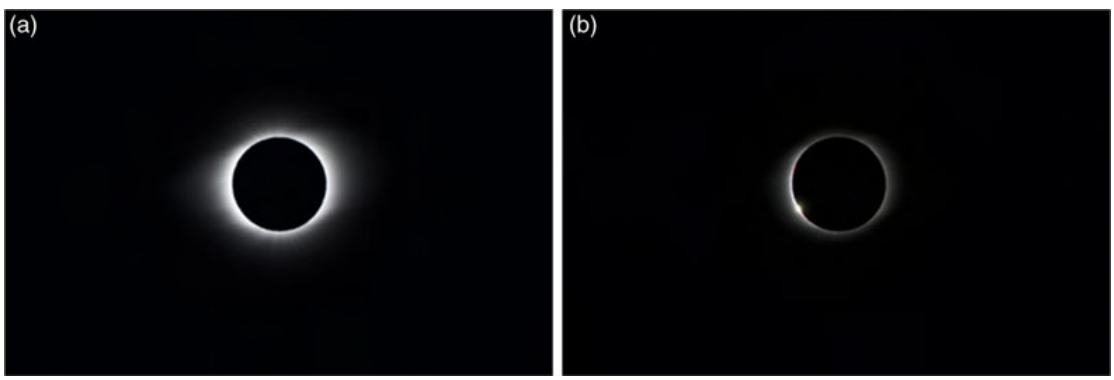

Figure 8. The eclipse seen from La Higuera during (a) totality; (b) the second diamond ring.

evening return to La Serena, because of the large number of tourists who had come from many parts of Chile, took over 5 hours.

3. Observations from the Cerro Tololo Inter-American Observatory

Some months before totality, five teams of up to four scientists each were awarded the opportunity to observe the eclipse from the Cerro Tololo Inter-American Observatory†. Four of the teams carried out coronal experiments, while a fifth was studying the effect of the eclipse on the Earth's atmosphere and ionosphere. Our team was headed by Williams College alumnus Kevin Reardon from the National Solar Observatory, and also included instrumentation specialist Aristeidis Voulgaris from Greece and father-and-son instrumentationalists Alan Sliski from Lincoln, MA, USA, and David Sliski from U. Pennsylvania. The site (2,207 m = 7,241 ft) sacrificed a half minute of totality (duration there was 2 min 6 sec, see Figure 9) in a trade-off for facilities and altitude (Figure 10). In the event, the sky was exceptionally clear for totality (Figure 11). With a view out over the ocean, the shadow could be seen to move over the city of La Serena, over 50 km away, several tens of seconds before it arrived at Cerro Tololo.

† http://www.ctio.noao.edu/noao/node/14748

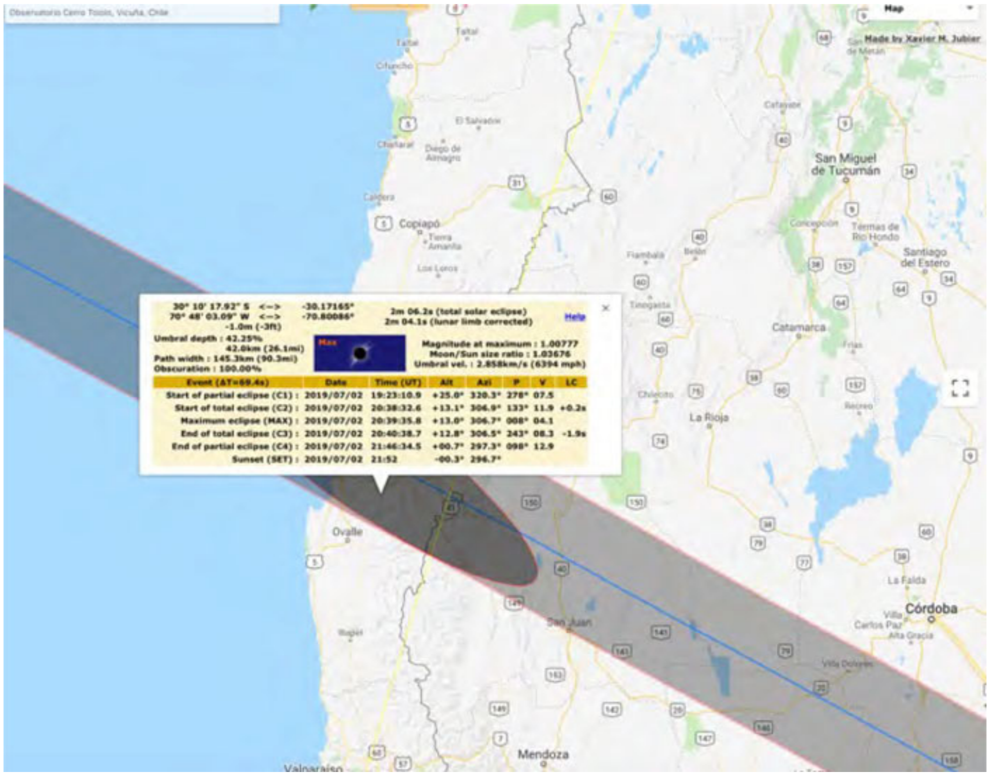

Figure 9. Map showing details for our Cerro Tololo site (courtesy of Xavier Jubier and Google maps).

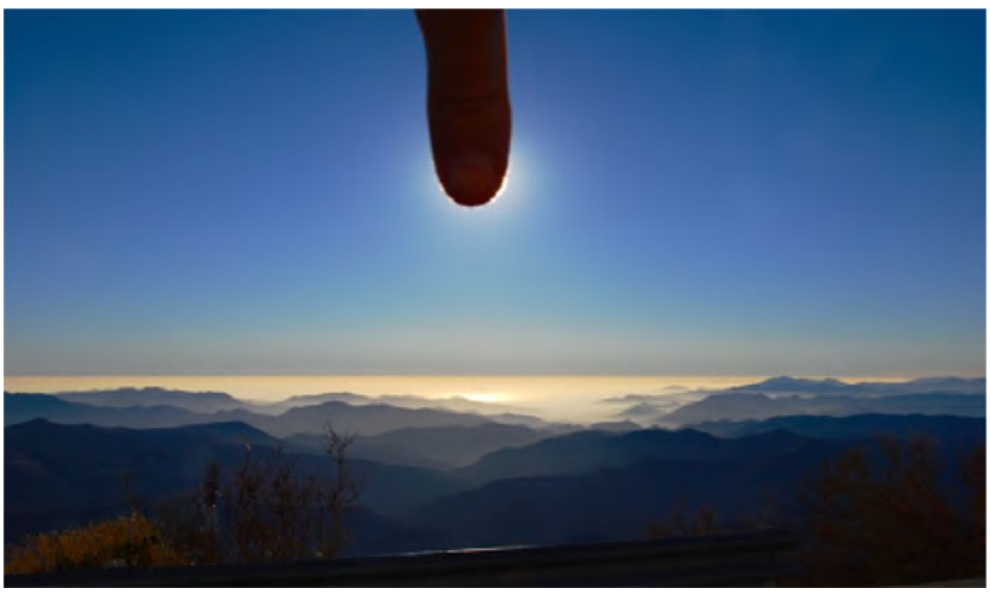

Figure 10. The sky with finger-tip occulting of the Sun at eclipse time one day before totality. Conditions on the day of the eclipse were very similar.

The double-diamond ring that appeared at second contact (Figure 12) will extend our determination at the 2017 American total solar eclipse of a new IAU-recommended value of the solar diameter through comparison with simulations (Pasachoff *et al.* 2017). The details of the lunar limb used for the simulations are now available from observations by the Japanese Kaguya spacecraft and the American Lunar Reconnaissance Orbiter.

Figure 11. Totality from Cerro Tololo was observed in an extremely dark and clear sky.

Figure 12. Second contact showed a double diamond ring.

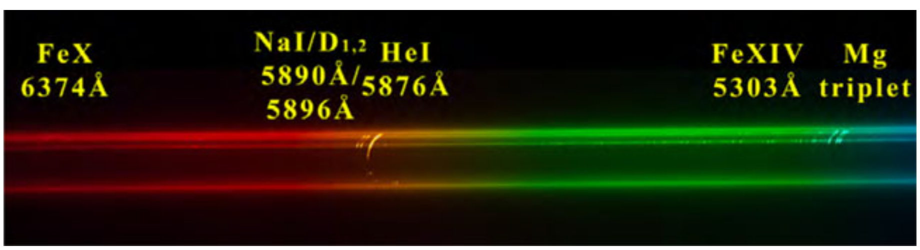

Figure 13. A slitless spectrum from the Cerro Tololo Inter-American Observatory.

Our coronal spectra from slitless spectrographs (Figure 13), from CTIO, showed the Fe XIV 530.3 nm green line substantially weaker than the Fe X 637.4 nm red line, corresponding to the relatively low coronal temperature at this phase of the solar-activity cycle.

On the spectra we also detected the weak coronal emission line of Ar X at 553.3 nm, as we also detected at the previous total solar eclipse of August 21, 2017, in the USA. We have on-band and off-band images of the corona in the Ar X line (Figure 14), using a Lyot filter transformed by Voulgaris from an H-alpha filter borrowed from the New Jersey Institute of Technology's Big Bear Solar Observatory.

We again worked with a theoretical team from Predictive Science Inc. (PSI) in San Diego to compare our observations with their prediction released days before totality, as we published for the 2017 American eclipse (Mikić *et al.*. 2018). The 2019 prediction of the structure of the corona from an MHD model (Figure 15) carried out by PSI compares well with a composite of our images. This was presented within two days after

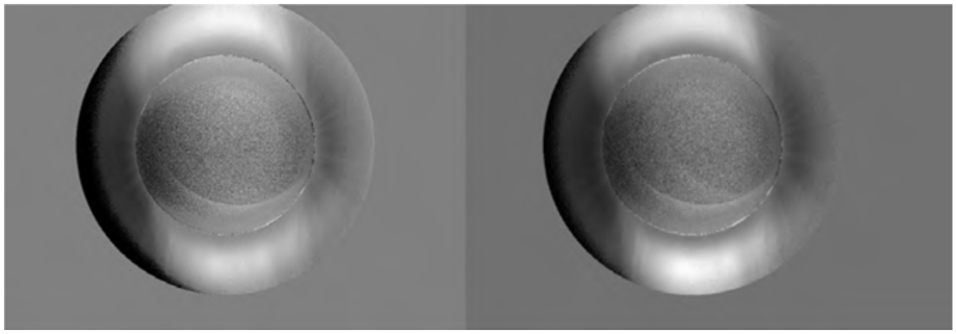

Figure 14. On-band and off-band images in Ar X, data still to be reduced.

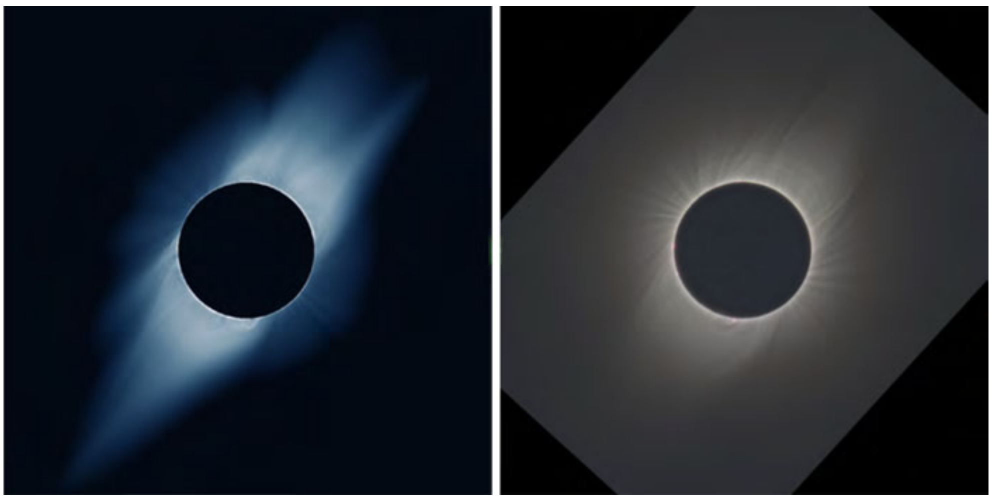

Figure 15. A comparison of our ground-based observations with data taken at Cerro Tololo (*right*), with pre-eclipse prediction produced by Predictive Sciences (*left*).

the eclipse in a NASA on-line display that allowed users to move a sliding vertical bar to transition between the prediction and the observed image to aid in the comparison†. We also reported the comparison to an American Astronomical Society meeting (Pasachoff *et al.* 2020; Lockwood *et al.* 2020).

4. Observations from La Serena

The city of La Serena, headquarters for several international observatories, was well within the path of totality (Figure 16).

In spite of months of worrying about the potential marine layer, the sky was clear (Figure 17). The corona and diamond rings were perfectly visible (Figure 18).

5. Observations from the e-flight on a Boeing 787-9

In a collaboration with Glenn Schneider, Voulgaris sent a spectrograph and Pasachoff sent a telephoto aloft for 8 minutes and 27 seconds of totality from mid-Pacific (Figure 19). The over 4 minutes of totality available at the intercept point were extended beyond 8 minutes by the aircraft keeping partial pace with the lunar umbral shadow‡.

† https://www.nasa.gov/feature/how-scientists-used-nasa-data-to-predict-appearance-of-july-2-eclipse

‡ Glenn Schneider, http://nicmosis.as.arizona.edu:8000/ECLIPSE_WEB/TSE2019/TSE2019_EFLIGHTMAX.html

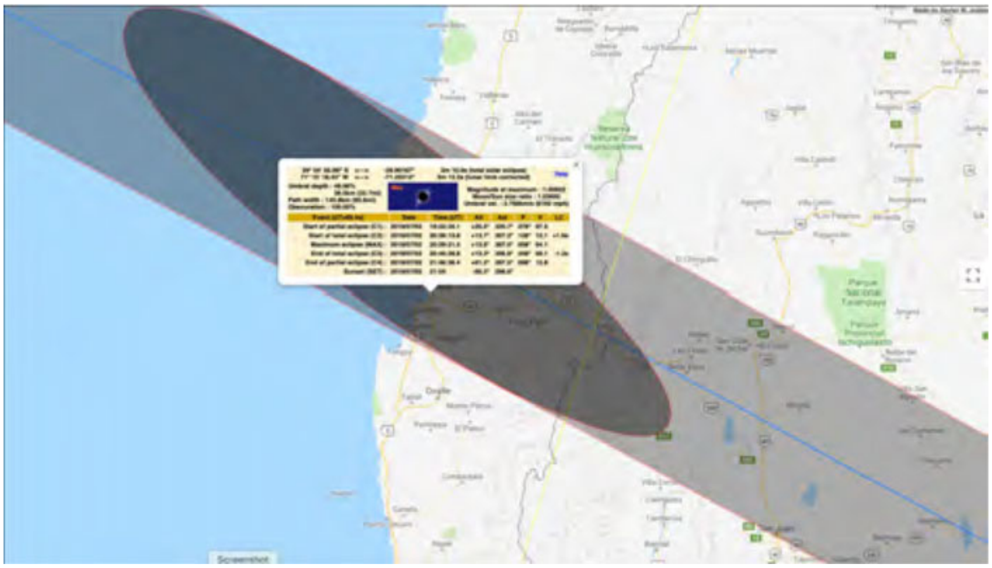

Figure 16. Orientation map showing details for La Serena (courtesy of Xavier Jubier and Google maps).

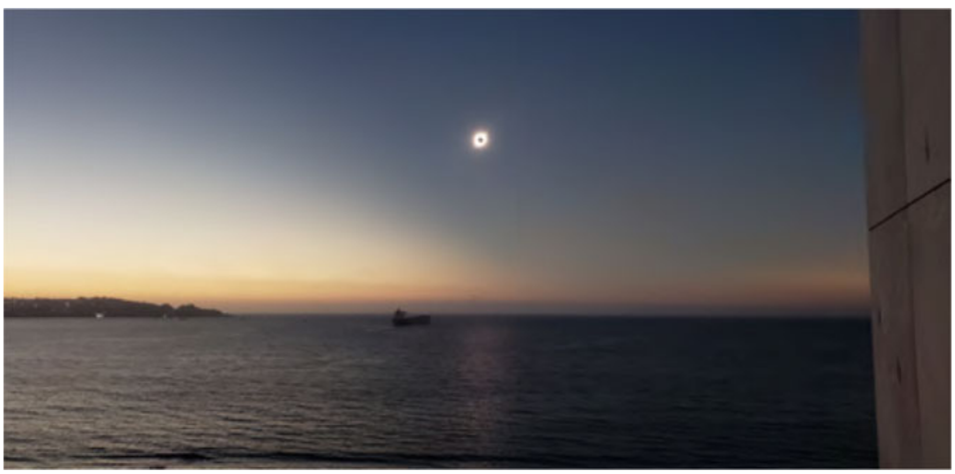

Figure 17. Westward totality view from La Serena. Credit: Ian Kezsbom

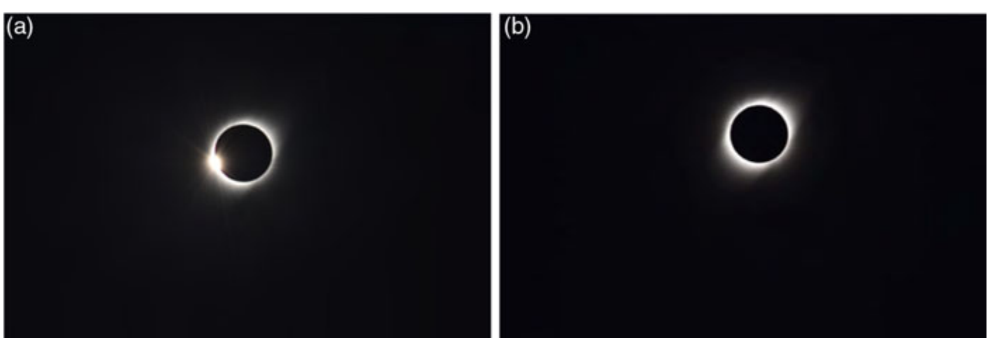

Figure 18. (a) The first diamond ring. (b) A still image of the corona. Credit: Ian Kezsbom and Sam Glaisyer.

Figure 19. Collaborative equipment sent aloft on the chartered 787-9 airplane. The NIR spectrograph and the telephoto lens are on a motorized azimuth mount. The image to the left was taken during a pre-eclipse test flight.

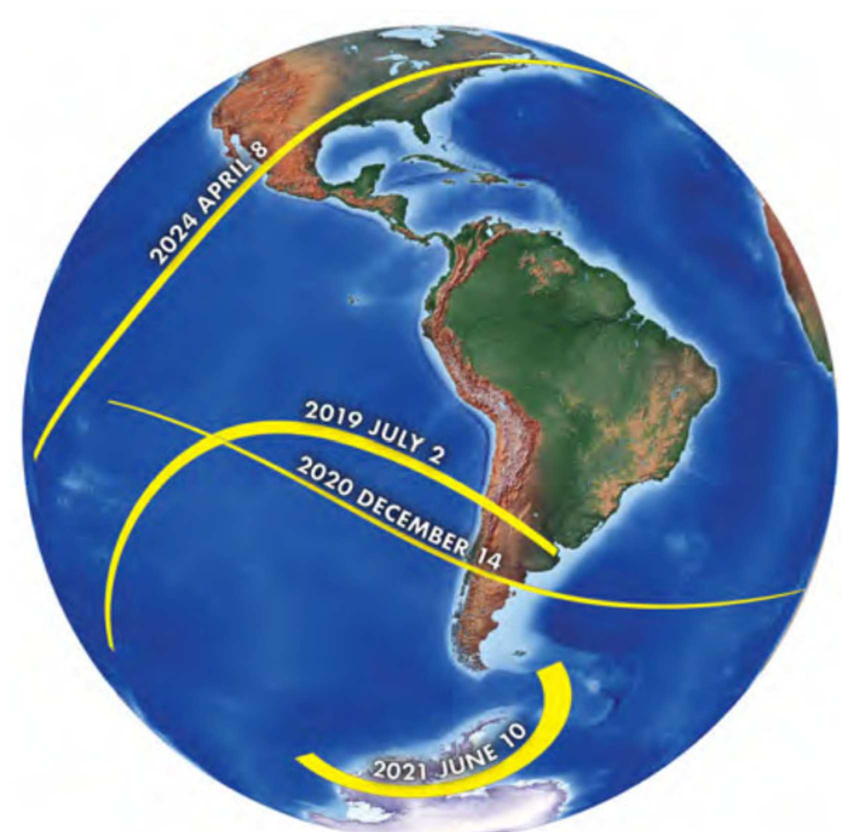

Figure 20. Totality paths in the western hemisphere of Earth through the American eclipse of 2024. Credit: Michael Zeiler, https://www.GreatAmericanEclipse.com.

6. Future eclipse observations

Totality in both 2019 and 2020 hits land in Chile and Argentina. Attempts to observe the 2019 total solar eclipse from Oeno Island in the Pitcairn group failed because of clouds. One cruise ship out of Tahiti did succeed in observing totality.

The peak of the 2020 totality will be over Argentina. The 2021 eclipse will be visible on ocean or land only in regions with poor cloudiness statistics†. The 2023 totality, not shown on this hemispherical map, will clip the westernmost protrusion of Australia and go over East Timor. The 2024 totality will hit land at Mazatlán, Mexico, and proceed over Mexico, the central and northeastern United States, and eastern Canada (Figure 20).

Our IAU Working Group on Solar Eclipses has colleagues from all over the world, and includes colleagues who make maps and predictions, as well as consult on safe observing. Our website at http://eclipses.info, an easy-to-remember URL, has useful links. Members are: scientists: Jay Pasachoff (USA, Chair), Iraida Kim (Russia), Hiroki Kurokawa (Japan), Jagdev Singh (India), Vojtech Rusin (Slovakia), Yoichiro Hanaoka (Japan), Zhongquan Qu (China), Beatriz Garcia (Argentina), Patricio Rojo (Chile); technical contributors to eclipse efforts: Xavier Jubier (France), web mapping; Fred Espenak (US), mapping and http://EclipseWise.com website, updated from "NASA website"; Jay Anderson (Canada), eclipse meteorology; Glenn Schneider (US), airborne planning; Michael Gill (UK), Solar Eclipse Mailing List, now SEML@groups.io; Michael Zeiler (USA), eclipse maps; Bill Kramer (USA), eclipse statistics; Michael Kentrianakis (USA), USA 2017 American Astronomical Society Project Manager; and Ralph Chou (Canada), eye safety.

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† Jay Anderson, 2019: http://eclipsophile.com

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