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REVIEWS

Solar eclipses as an astrophysical laboratory

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Observations of the Sun during total eclipses have led to major discoveries, such as the existence of helium (from its spectrum), the high temperature of the corona (though the reason for the high temperature remains controversial), and the role of magnetic fields in injecting energy into—and trapping ionized gases within—stellar atmospheres. A new generation of ground-based eclipse observations reaches spatial, temporal and spectral-resolution domains that are inaccessible from space and therefore complement satellite studies.

Solar eclipses occur when the Moon comes directly between the Earth and the Sun. By a happy coincidence, the Moon and Sun subtend the same angle in the sky to within 10%. As the lunar orbit is tilted by 5° with respect to the plane of the Earth's orbit around the Sun (the ecliptic plane), solar eclipses occur only when both Moon and Sun are sufficiently near the nodes, the crossing points of the Moon's apparent path in the sky and the ecliptic[1]. Such events occur at least yearly, though the region on Earth from which the totally eclipsed Sun (Fig. 1) is visible is sufficiently small that travel is usually necessary[2].

The original motivation for studying solar eclipses was to take advantage of rare opportunities, rather than any specific observational plan based on theory. The nature of the outer solar atmosphere was deduced during the roughly hundred years starting in 1860, when it was definitively associated with the Sun instead of being thought of as a lunar atmosphere. This 'solar corona' appears to people on Earth only during total eclipses (Fig. 2), forming a faint crown (Latin, *corona*) of light that Halley called pearly white. We now know it to be hot and ionized, that is, a plasma.

Because of their dramatic nature, bringing the darkness of twilight even at midday, total solar eclipses have been noted for thousands of years. A total eclipse results in a darkening by a factor of approximately a million, meaning that the coverage of the last 1% of the everyday solar surface produces a darkening by a remaining factor of about 10,000—so the onset of darkness comes only from a change even smaller than that last 1%. Therefore, it can be deduced, even from ancient chronicles, whether a writer was inside or outside the zone of totality. Such observations have therefore been searched for and found in tablets, parchment, and other writing from Asia, the mid-East, and Europe, and then used to determine variations in the Earth's rotation over thousands of years[3,4].

Advantages of contemporary eclipse research

Though many areas of coronal research are well covered from telescopes on satellites, there remain several aspects that are, and remain for the foreseeable future, uniquely able to be studied from Earth at total solar eclipses[5]. The low corona can also be monitored to some extent from mountain-top coronagraphs, such as the K-coronameter of the High Altitude Observatory on Mauna Loa, Hawaii, but even that instrument occults (hides) the lowest corona, and its images are relatively noisy and show little detail[6]. Other coronagraph stations include those at Lomnický štít, Slovakia, and at Sacramento Peak, New Mexico.

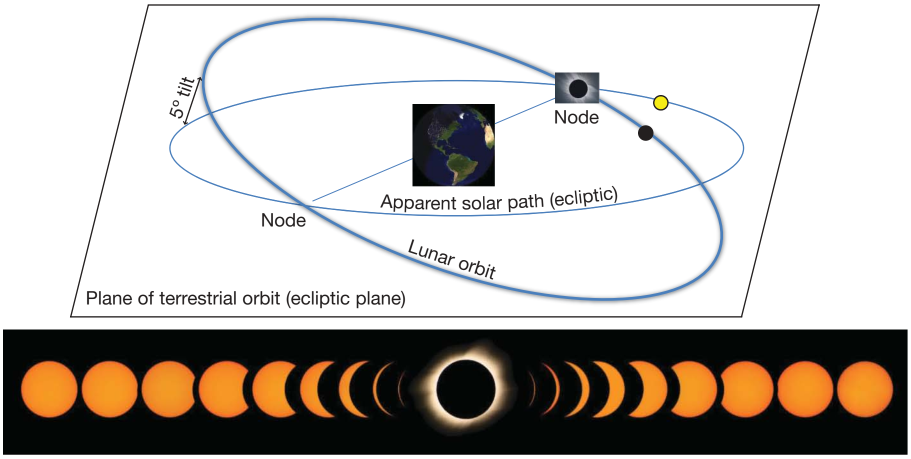

Figure 1 | The geometry of eclipses. Eclipses occur only when both Sun and Moon are sufficiently near to one of the nodes where the Moon's orbit around the Earth crosses the plane of the Earth's orbit around the Sun (the ecliptic plane). The node shifts around the orbit by 18.7° per year, making the eclipse year 5% shorter than a terrestrial year. Sufficiently near the node, a series of partial phases are seen, as shown over a 3-h interval, photographed through a filter of neutral density 4 or higher. For seconds or minutes, for observers in the umbra of the lunar shadow, the corona can be seen; it is photographed here with no filter, since its total brightness is only roughly that of the full Moon. (eclipse sequence copyright 2006 J.M.P. and R. Ressmeyer, Science Faction).

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Figure 2 | The corona at totality. A composite image of the sunspot-minimum 2008 eclipse corona and prominences, put together from 16 individual frames of a variety of exposure times made at Akademgorodok, Siberia. (Image processing by W. Carlos from exposures by J.M.P., W. G. Wagner and J. Guertin; copyright 2008 W. Carlos and J.M.P.)

Instruments on spacecraft are carefully made for specific purposes, and are locked into their configurations many years in advance of their use. In contrast, eclipse expeditions have the flexibility to use the latest equipment and to take advantage of new theoretical ideas to frame observations. Eclipse expeditions can also take larger solar telescopes than are in space. Further, an eclipse expedition is so much less expensive than any space instrument that, even allowing for equipment and weather failures, total eclipse expeditions are a relatively inexpensive way to obtain a variety of chromospheric and coronal information. Eclipse expeditions also provide a way to test equipment and methods destined for space launch.

A forthcoming eclipse, even the partial phases, can get the attention of local people through (at least) newspaper coverage, and instructions on safe eclipse observing should be widespread[7]. Unfortunately, there is often a public and even governmental misunderstanding of what an eclipse entails, and a widespread belief that some additional, harmful rays come out of the Sun during an eclipse. All too often, people in general and students of all ages in particular are prevented from seeing the eclipse, sometimes with misinformation about the chance of eye damage that could lead the public to ignore significant public-health warnings about other, more serious matters at later dates[8].

Eclipse predictions and the Saros

A modern era of eclipse observing may be said to have begun in 1715, with the first predictions in the form of a terrestrial map bearing a delineated path of totality, worked out by and published for Edmond Halley[9]. The observed path was displaced by some tens of kilometres from the prediction, and the revised, actual path was plotted along with predictions for the subsequent European eclipse, that of 1724.

Solar eclipses occur periodically, with eclipses similar in latitude and duration appearing with an 18 year $11^1/_3$-day interval[10], with the $^1/_3$ day allowing the Earth to rotate 120°. The period, known as the Saros, was discovered by the Babylonians but was named by Halley[11].

In a given calendar year, there can be as many as five solar eclipses or as few as two. At a given spot on Earth, an eclipse would be viewed only about every 350 years, though that average interval varies with a terrestrial observer's latitude[12]. Paths of some successive eclipses overlap, and fortunate viewers at those locations could see two total eclipses with only a one-year interval (Fig. 3)[13]. Now that travel is so convenient, ardent eclipse viewers travel to all total or even to all solar eclipses. An average interval between total eclipses is about 18 months (ref. 14). The next total solar eclipses to cross the United States occur in 2017 and 2024[15].

The shape of the corona, with the streamers and plumes governed by the coronal magnetic field, varies with the solar-activity cycle. The shape of the corona can be accurately predicted in advance with calculations based on the observed surface magnetic field[16]. The Ludendorff flattening coefficient measures the overall shape, with sunspot-maximum coronas appearing relatively round because of the large number of streamers at all latitudes, and the sunspot-minimum

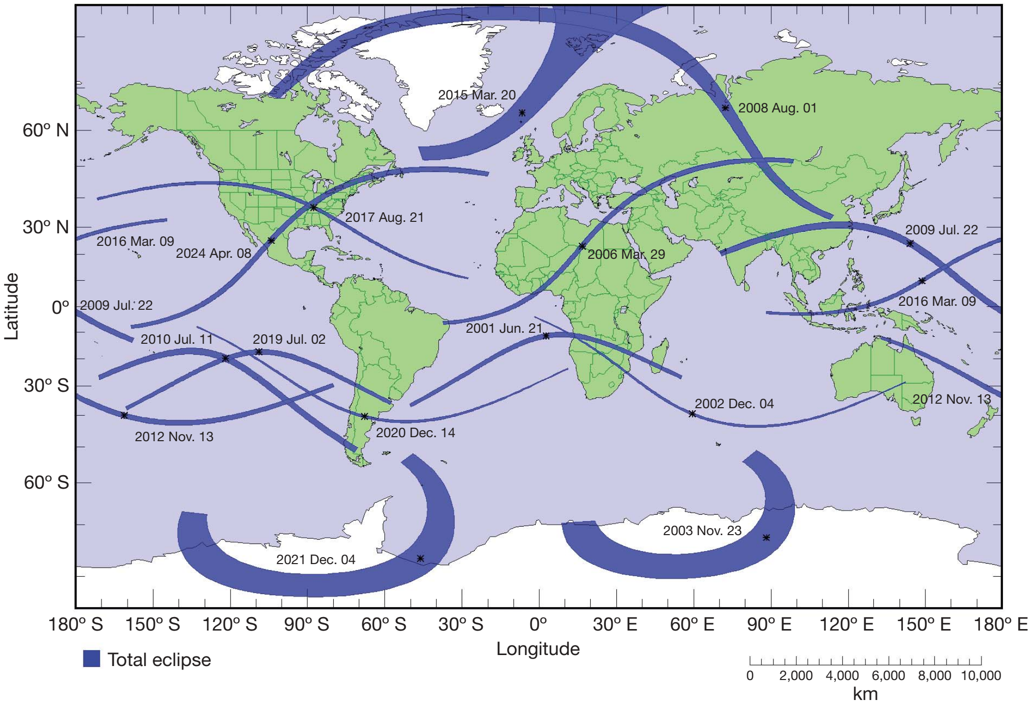

Figure 3 | The paths of total eclipses, 2001–25. Partial phases can be seen to distances of thousands of kilometres to the sides of the umbral paths. (F. Espenak, NASA's Goddard Space Flight Center.)

coronas appearing relatively elongated because mainly equatorial streamers remain (Fig. 3)[17,18].

Historical eclipses and corona parameters

Many solar physicists devote their attention to the question of how the solar corona is heated to millions of kelvins, almost 1,000 times hotter than the underlying solar photosphere[19–21]. The fact of this temperature inversion is a twentieth-century result based on nineteenth-century eclipse observations with the then newly invented spectroscope.

The light from the everyday Sun comes from a layer of semitransparent gas, the photosphere (named from the Greek *photos*, light), at a temperature of about 5,800 K (ref. 22). Observers in the path of totality at a solar eclipse see first a gradual covering of the Sun by the lunar silhouette for over an hour, and then a set of 'Baily's beads', the last bits of the bright photosphere shining through valleys aligned at the edge of the Moon[23]. As the Baily's beads disappear behind the advancing lunar edge (the phenomena occur in reverse at the end of totality), a thin reddish edge, called the chromosphere (named from the Greek *chromos*, colour), appears. Though the reddish hydrogen radiation is most visible to the unaided eye, the chromosphere also radiates thousands of additional spectral lines[24]. When the chromosphere is covered, as it is within seconds, the corona appears as a halo around the Sun. But what is this corona, what is it made of, and how hot and dense is it? Answering these questions became the goal of eclipse research in the late nineteenth and early twentieth centuries. And the question of how the corona is heated to, as we now know, millions of kelvins, far hotter than the underlying photosphere, remains a major astrophysical question for twenty-first-century astrophysicists.

In the mid-nineteenth century, the near-simultaneous development of spectroscopes that could be taken on expeditions[25] and, starting in about 1860, photography[26], led to a series of scientifically important eclipse expeditions. Though the motivation was purely observational, in the absence of a theoretical understanding of the Sun, which was thought to resemble the Earth in composition, the developments led decades later to the establishment of solar physics and, eventually, to the rise of astrophysics instead of the traditional astronomy of the time. This traditional nineteenth-century astronomy had a higher quotient of positional measurements—astrometry—and of measuring time-varying phenomena (such as variable-star brightnesses), rather than understanding the causes of stellar evolution and the structure and evolution of the Universe that are centres of today's astronomical studies.

In 1868, astronomers used their newly available types of instrument to make several expeditions to India to observe the total solar eclipse. P. J. C. Janssen observed the spectrum of the chromosphere that was briefly visible at the beginning and at the end of totality. He saw a bright yellow emission line, apparently at or close to the wavelengths of the known sodium D lines. The spectral lines he saw were so bright that he realized that by broadening his spectrograph's slit he could see them even without an eclipse, a realization also reached independently soon thereafter by a non-eclipse observer, N. Lockyer (founder of *Nature*) in England. Measured in detail, the position of the bright yellow line was not quite that of sodium D_1 or D_2, so it was called D_3 and was said to come from 'helium' (after the Greek Sun god, Helios), since it apparently came from a source only on the Sun. It was not until 1895 that helium was isolated on Earth.

At the eclipses of 1868 and 1869, observed from Siam (now Thailand) and from the United States, respectively, the first coronal emission line was detected[27]: about 25 years later, it was said to be from the element 'coronium', by analogy with the prior discovery of helium. This first 'coronium' line is in the green region of the solar spectrum. At subsequent eclipses, a red coronal line was observed, and also several fainter emission lines. At the eclipse of 1870, a more complete set of emission lines from the chromosphere was observed; it is still known as the 'flash spectrum' from the way it flashes into view as the Moon completely covers the solar photosphere.

In 1871, not only emission lines but also absorption lines were detected in the coronal spectrum. We now know that the corona we see has three main parts: emission from hot coronal gases, absorption from the solar photospheric spectrum reflected from dust particles in interplanetary space relatively near the Sun, and a continuum from scattering of photospheric light off coronal electrons. These are known as the E-, F-, and K-coronas, respectively. At the same eclipse, spectrographic observations found an emission line detectable almost a solar radius above the limb, a surprising height for the coronal ions that emit the spectral lines (as opposed to the coronal continuum that results from electron scattering).

The solution to the problem of identifying 'coronium' did not come until the 1930s. The smooth, absorption-line-free spectrum of the K-corona could indicate that photospheric absorption lines were blurred by exceedingly high electron velocities[28]. This effect is used to the present day in studying the coronal temperature. Also in the 1930s, with the artificial eclipse formed in the newly invented 'Lyot coronagraph', which could observe limited aspects of the corona under special conditions from certain high mountain sites, astronomers found that the coronal green line was 0.9 Å broad; this would have meant high temperature if the atomic mass of the element emitting the line had been known. The solution to identifying the source of the spectral lines came only in 1939, with the extrapolation along isoelectronic sequences from lower states of ionization to discover that the 'coronium' lines were actually emitted by highly ionized states of elements such as iron, calcium and nickel[29]. The coronal green line, for example, came from the 'forbidden line' of iron-14, written [Fe XIV], iron stripped of 13 of its 26 electrons (neutral iron is Fe I, so the Roman numerals exceed the ionization number by 1), which would require such a high temperature that the corona must be at millions of kelvins. (The transition probabilities are low for forbidden lines, which are indicated by square brackets, as they do not obey the normal selection rules of spectroscopy.) So all the spectral lines could be explained by extremely ionized states of known elements, and no new element was needed; in any case, the periodic table had been filled in during the decades since the first 'coronium' lines had been found. In the current era, spectroscopic observations of coronal lines are made with coronagraphs and at eclipses[30].

Though ground-based observations observe the forbidden lines, many of the corresponding coronal permitted lines were discovered on spectra taken by a rocket launched during the 7 March 1970 eclipse, in which totality was convenient for NASA's rocket-launching range on Wallops Island, Virginia[31]. These observations were taken with a slitless spectrograph, in which no narrow slit is used as the emitting solar crescent of radiation acts as a slit. (The intensity diminishes rapidly with height above the photosphere, so the approximation of a slit is useful but not perfect.) Surprisingly, strong Lyman-α radiation was discovered in the spectra; calculations show that even at coronal temperatures enough neutral hydrogen remains to provide the observed intensity by resonance scattering of Lyman-α radiated in the chromospheric–coronal transition region. The discovery has been exploited by subsequent measurements of coronal parameters such as temperatures, electron densities and ion densities from Lyman-α observations made from rockets, a space shuttle, and satellites[32]. An independent determination of the high temperature of the corona was made outside eclipse from radio observations[33].

Motivated by the opportunity to observe an eclipse for a time a factor of 10 longer than normally possible, and by the low-scattering background and high infrared atmospheric transmission available at high altitude, a unique eclipse flight was made in a supersonic Concorde in 1973, with 74 min in totality. For an equatorial eclipse near noon, the relative velocity of the lunar umbra on the Earth can dip to 1,730 km h^{-1} (ref. 34). Several scientific experiments had an unprecedented 74 min of totality[35,36]. The infrared has also been observed from high-altitude mountain sites, when the 1991 eclipse went over Mauna Kea[37]. The 2.5-m telescope on the Stratospheric Observatory for Infrared Astronomy (SOFIA), the instrumented aeroplane soon to begin its scientific work, should be valuable for eclipse studies, since its location above so much of the terrestrial atmosphere's water vapour, along with the extremely low scattering background at its altitude, will allow unprecedented surveying of the coronal infrared spectrum.

Merging eclipse and space observations

Because the intensity gradient of the inner corona is so great, with the intensity diminishing by a factor of ~1,000 in the first solar radius, space coronagraphs such as that on the Large Angle and Spectrometric Coronagraph (LASCO) on the NASA/ESA Solar and Hemispheric Observatory (SOHO), launched in 1995, are forced by internal scattering to over-occult, hiding not only the solar photosphere but at least 0.4 solar radii above it. Even the more recent coronagraphs on NASA's STEREO (Solar Terrestrial Relations Observatory) mission, launched in 2006, leave such a 'doughnut' of unobserved lower corona extending 0.4 solar radii above the solar limb. At the same time, the corona on the face of the Sun can be observed in the extreme ultraviolet with the Extreme-ultraviolet Imaging Telescope (EIT) on SOHO and a newer pair of similar instruments with the name Extreme Ultraviolet Imager (EUVI) on the two STEREO spacecraft; with NASA's Transition Region and Coronal Explorer (TRACE), to be superseded in late 2009 by NASA's Solar Dynamics Observatory; and in X-rays with the Smithsonian's X-Ray Telescope (XRT) on the Japanese Hinode (English translation, sunrise) spacecraft. The 'doughnut' inaccessible to spacecraft can be filled in on the days of eclipses with ground-based eclipse observations. The combination provides a full view of coronal features from their footpoints on the solar disk (except for the half of the features whose footpoints are on the Sun's far side) through the lower corona, where the solar wind is formed, and onto the streamers in the upper corona observed with LASCO on SOHO or the coronagraphs on STEREO (Fig. 4)[38].

The resolution available at eclipses observed from the ground exceeds that available from spacecraft coronagraphs, and spacecraft designers should be trained in part by viewing total solar eclipses. The designer of LASCO said immediately after the 1994 eclipse, and subsequently, that he would have designed his coronagraphs with higher resolution had he seen an eclipse earlier and so realized how much coronal detail is available.

Testing general relativity at eclipses

Total eclipses were in the popular mind in 1919, when the press publicized reports by Arthur Eddington (who was later knighted) that his two eclipse expeditions to Principe, an island off Africa's west equatorial coast, and Sobral, Brazil, confirmed an important prediction by Albert Einstein[39]. The report galvanized the public and made Einstein into a celebrity, in addition to providing the scientific backing to his general theory of relativity that I describe below, though W. W. Campbell's data reduction from a similar experiment at the 1918 eclipse had contradicted the 1919 result[40].

Einstein, in 1916, with his general theory of relativity had explained or predicted three astronomical phenomena. The first was the advance of the perihelion of Mercury, that is, the change in orientation of Mercury's elliptical orbit around the Sun by a small amount, only 43 arcsec per century, after the effects of known gravitational perturbations of the planets were subtracted from the observed rate of change. But since this effect was already known observationally, its explanation by Einstein was not a convincing proof of his theory. The second was the deflection of starlight that passes near the Sun, because of the way that the Sun's mass warps space-time. This effect could be tested only at a total solar eclipse, when the Sun would be up but without a blue sky masking the stars. Since this effect had not yet been measured, if Einstein's theory predicted the correct deflection, agreement of observations with theory would provide proof convincing to many, if not most. The third, a gravitational redshift of light leaving the Sun, was not tested until later.

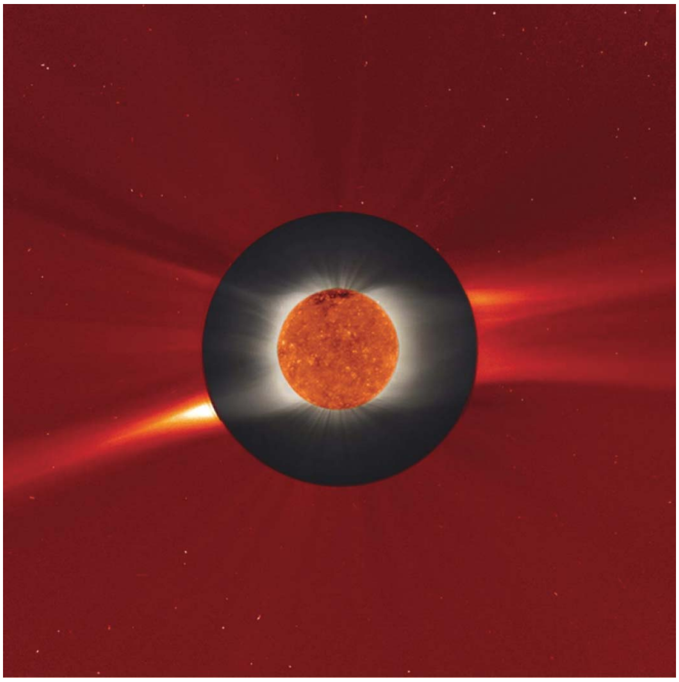

Figure 4 | The 1 August 2008 eclipse from the ground and from space. Shown is a composite image, consisting of a single eclipse image from 2008 in Siberia (black and white image) sandwiched between an on-disk image from SOHO/EIT in helium radiation at 304 Å in the ultraviolet (central image) and an outer-corona image from SOHO/LASCO. (Eclipse image from Williams College Expedition (J.M.P., B. A. Babcock, M. Baldwin, K. DuPré, M. Freeman, W. G. Wagner, M. Demianski, P. Rosenthal), with A. Nesterenko and I. Nesterenko, State University of Novosibirsk; compositing of eclipse image by W. Carlos. Inner image from the EIT Team, NASA's Goddard Space Flight Center; outer image from the LASCO Team, Naval Research Laboratory. Final composite of eclipse and space images by S. Hill, NASA's Goddard Space Flight Center).

Fortunately for the reputation of Einstein and for posterity, an attempt at the 1914 eclipse to verify an earlier version of Einstein's deflection prediction was ruined when the astronomer who was trying to test the effect by viewing during the totality that crossed Russia was interned there at the outbreak of the First World War; at that time, Einstein's prediction was a factor of 2 lower than his later prediction, and had the eclipse mission succeeded in making its measurement, Einstein's revised calculation might have been perceived as patching rather than pure deduction. In any case, Einstein was later asked what he would have thought if his prediction had not been verified. He famously replied, "Then I would have been sorry for the dear Lord; the theory is correct"[41].

No longer is this Einstein experiment repeated at eclipses, any more than eclipse astronomers search for Vulcan inside Mercury's orbit. The 1919 eclipse had the advantage of the Sun's being in the Hyades star cluster, providing many star images close to the Sun's disk to measure. The 1922 repeat of the experiment with improved equipment provided valuable confirmation that Einstein's prediction was correct[42]. But since that time, the gravitational deflection of starlight by the Sun has been more accurately measured by other methods[43–46]. The last professional expedition to attempt to verify Einstein's deflection prediction was at the 1973 total solar eclipse; it did not significantly improve prior results[47,48].

Heating the corona

There are at least four main types of proposals for coronal heating. (1) Acoustic waves were long thought to provide enough energy, but this class of theory was discarded when spacecraft observations in 1970s did not find enough energy in such waves passing through the chromosphere. Most of the current generation of theories involves waves on the coronal magnetic field, but whether the waves are (2) Alfvén waves or (3) kink or other magnetic wave types remains controversial[49]. (4) Another set of theories involve 'nanoflares', a set of small but frequent explosions on the solar surface[50]. The answer applies not only to the solar corona but also to the coronas of thousands of other stars that are observed with the Chandra X-ray Observatory and other X-ray telescopes. It is not clear what type of observations can distinguish among the theories, so the current state of the art is to make whatever observations are possible in improving time and spatial domains, in order to push the explanatory capabilities of the theories.

One type of eclipse observation that has the potential to distinguish among classes of coronal-heating theory obtains data at much higher cadences (repetition rate) than are available from any solar telescope in space. For example, images of coronal loops have been obtained at 10 Hz, a factor of about 100 faster than can be obtained with NASA's TRACE, albeit at a resolution of a few arcsec compared with TRACE's 1 arcsec (740 km) resolution. Recent observations are being studied with Fourier and wavelet techniques, with the aim of distinguishing among theories[51–53]. Such rapid oscillations are not possible for Alfvén waves on the full coronal loops that are observed with high resolution from spacecraft, but could correspond to, for example, Alfvén waves in surface sheaths on coronal loops. The lack of ability to search for such waves for more than the few minutes available at any given eclipse, not to mention impediments such as atmospheric variations, have prevented definitive measurements from having been made and call out for further eclipse observations in the absence of the ability to make suitable observations from the current or the next generation of solar spacecraft. Relevant observations will be carried out at the 2009 total solar eclipse by several groups.

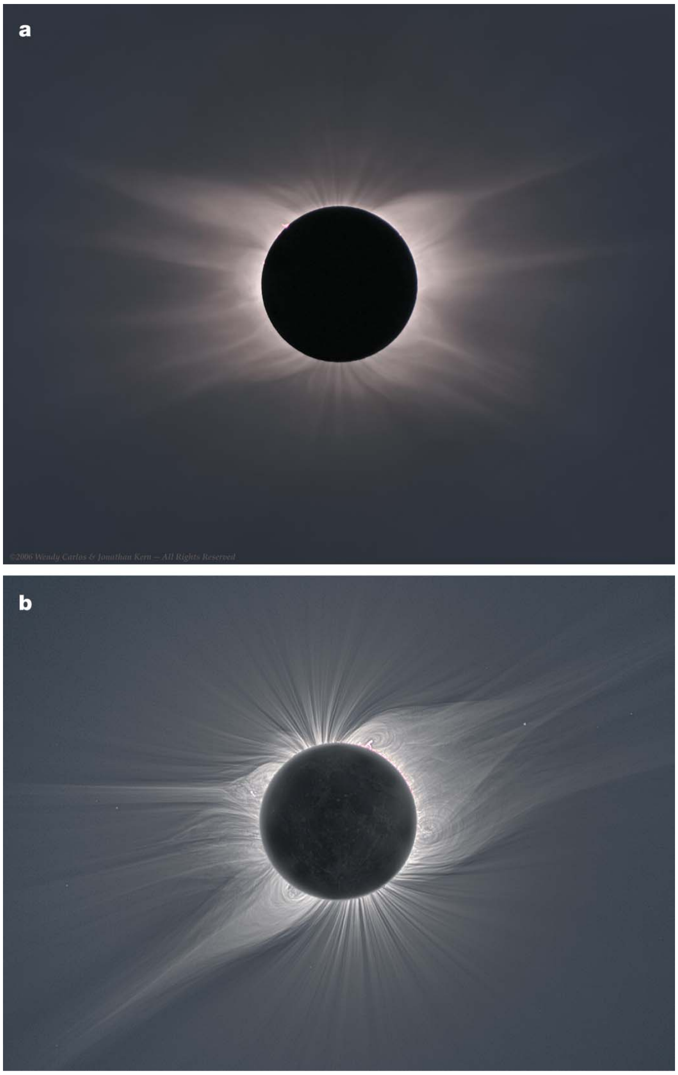

Figure 5 | Correcting for the large dynamic range in coronal intensities. **a**, A composite of several radial-filter images, each also originally showing the same resulting reduction of the wide dynamic range of the corona, taken on film at the 29 March 2006 eclipse from Kastellorizo, Greece. Not only must the radial filter match the average fall-off in intensity to avoid the result showing an obvious ring, but also the alignment of the filter and the solar image must be accurate during the eclipse itself to avoid the equivalent of a Moiré pattern. The radially graded, metal-deposited-on-glass filter declines from neutral density 2.9 at the limb, to 0.7 at 1 solar radius above the limb, to 0.33 at 2 solar radii, to 0.06 at 3 solar radii. The High Altitude Observatory group provided a notable series of radial-filter images at every major eclipse from 1966 to 1984 on film and in 1988 with a CCD. The set of images clearly shows how the shape of the corona varies over the solar-activity cycle. **b**, The total solar eclipse of 1 August 2008, observed from Siberia. Equatorial streamers and polar plumes clearly map the corona's magnetic field. Earthshine illuminates the silhouetted lunar disk. (Image processing of **a** by W. Carlos from radial-filter images by J. Kern, now of the Observatories of the Carnegie Institution of Washington, as part of the Williams College Expedition, copyright 2006 W. Carlos and J. Kern. Images in **b** from J.M.P., W. G. Wagner and H. Druckmüllerová, image processing by H. Druckmüllerová.)

Detecting fine-scale coronal dynamics

The first known coronal photograph was a daguerreotype taken in Königsberg, Germany, at the eclipse of 28 July 1851. Only the innermost corona showed, but its equatorial elongation is easily seen. A difficulty in photographing the corona is its extreme brightness range, diminishing in intensity by a factor of about 1,000 within one solar radius above the limb. Neither film nor electronic detector can handle such a range in intensities. Two main methods have been used to overcome the problem: (1) a radial filter (Fig. 5a), and (2) post-eclipse compositing (Fig. 5b).

(1) The use of a filter radially graded in intensity, with neutral density above four near the limb (that is, absorption by a factor of 10^4) and zero far out, was pioneered first for the eclipse of 1961 and exploited later by French[54] and American[55] astronomers. (2) The methods of post-eclipse compositing of multiple images have improved greatly in recent years[56]. High-contrast imaging reveals wave structure and coronal cavities around limb features like prominences[57,58]. The resolution is such that motions can be detected in the corona even during the interval that the lunar shadow takes to travel along the path of totality. The dynamics of the corona can be revealed only with such high-resolution observations[59,60].

Spectroscopic studies continue, including new observations at current phases of the solar-activity cycle in the visible region of the spectrum, and images in the various coronal emission lines[61]. New capabilities of infrared detectors will allow further spectroscopic studies to find additional infrared spectral lines, especially from the altitudes obtainable with the 2.5-m telescope aboard the SOFIA aircraft. High-resolution, Fabry-Perot spectrographs can be and have been taken to eclipses[62]. A spectral passband of 0.016 nm was obtained at the coronal red line at the 2006 eclipse[63].

The high-spatial-resolution imaging from post-processing has allowed motions to be measured over the 1 h 9 min period among separated stations along an eclipse path. For example, the motion of a polar plume was measured to be ~70 km s^{-1} during the 2006 eclipse as the umbra moved from Libya to Egypt to Greece to Turkey, setting a value for comparison with prior plume velocities and deduced lifetimes[64]. Similar measurements are being made from the 2008 eclipse observations by comparing images from Russia, from Mongolia, and, with lower resolution because of the aircraft window, at a latitude of 83° from an aircraft north of Svalbard (midway between Norway and the North Pole)[65].

Box | Eclipses: public safety and education

The Working Group on Eclipses of the International Astronomical Union (IAU) comprises active eclipse scientists from all over the world, and provides advice to people in countries with forthcoming eclipses. It also works to facilitate and coordinate such matters as duty-free entry of scientific equipment to the relevant countries through which totality passes[71]. Additionally, the IAU Commission on Education and Development has a Program Group on public education at the times of eclipses, which includes a professor of optometry in addition to astronomers.

A Solar Eclipse Mailing List (SEML) facilitates correspondence and coordination among amateur and professional eclipse observers. Postings fall into several classes, including plans for future eclipses, results of recent eclipses, calculations of sometimes obscure eclipse statistics, and sightings of eclipses in movies (SEML@yahoogroups.com).

NASA's Goddard Space Flight Center runs a solar eclipse homepage, which has links to maps, charts, and a variety of detailed eclipse publications[72]. Solar eclipse technical publications have recently been prepared for each major eclipse[73]. They may also be prepared for all the central (total and annular) eclipses in a given year[74].

The International Year of Astronomy will be marked on 22 July 2009—especially in India, China, and some smaller Japanese islands—by the longest totality in the 18 year $11^{1}/_{3}$-day Saros cycle, which will be observed by many teams of professionals as well as unprecedentedly large numbers of eclipse enthusiasts, providing an entrée not only for astrophysics but also for public education in all aspects of astronomy and other sciences[75]. It is to be the longest duration of totality that will occur until the year 2132.

Variation of coronal temperature and density

The corona we see during an eclipse is an overlap of the continuous, largely polarized, K-corona, the basically unpolarized F-corona, and in the inner corona an overlay of emission lines. The million-kelvin temperature means that the coronal electrons are moving so rapidly that they blur out the solar photospheric spectrum as scattered in the corona, and the F- and K- coronas can be separated from each other by the residual depth of the absorption lines[66]. At the eclipse of 2001 in Zambia, measurements of the coronal spectrum at several wavelengths were compared with a model to determine the coronal electron temperature and bulk flow speed of the solar wind[67]. The results were extended to test the effects of coronal streamers[68]. At the 2008 total solar eclipse in Siberia, polarization measurements were again obtained in order to separate the coronal components. After the separation of the components, the electron density can be determined[69]. Such determinations that can be made on the Sun only because of its proximity to Earth are extrapolated not only to sunlike stars but also to stars of all types, so our detailed studies at solar eclipses inform our understanding of trillions of stars throughout the Universe.

Few if any other phenomena are available for scientific study only at predictable intervals and then for periods of only seconds or minutes. It is not a surprise, then, that some solar astronomers choose to gather whatever information can be observed at total eclipses even in the absence of plans for definitive astrophysical tests.

Eclipse ecotourism

Seeing an eclipse is so dramatic, with daylight turning abruptly to twilight at midday and unique phenomena becoming briefly visible as totality begins and ends, that even non-scientists have long followed up on eclipse reports and travelled to the path of totality. Eclipse tourism may have begun with the eclipse of 1868, for which the King of Siam made his own, correct, predictions, and led a large team of notables and others to the path of totality. Unfortunately, he was bitten by a malarial mosquito on that expedition and died soon thereafter from that disease.

Major eclipse expeditions, with large quantities of equipment and large numbers of accompanying persons, were common in the Victorian era, to find out whatever could be found by such observations[70]. In the modern era, the single cruise ship carrying tourists and a few scientists as lecturers into the path of totality off the African coast of the 1973 eclipse has developed into an industry, with several cruise ships and dozens of land expeditions for each totality, as ecotourism grows and people who experienced one eclipse come back for others, bringing along friends to experience the remarkable phenomena.

Future eclipse research

The Moon is receding from the Sun sufficiently slowly that our descendants on Earth will be able to see total eclipses for over 600 million years. In the nearer term, it appears that for decades ground-based capabilities will still allow unique observations to be made from Earth rather than from space. Eventually, propinquity of spacecraft to the Sun plus improvements of space solar telescopes in spatial, temporal and frequency domains may allow such space solar telescopes to take over completely, perhaps adding to observations of distant stellar coronas to explain the coronal-heating problem. At present the paired science and beauty of solar eclipses remain uniquely available to scientists and others in the path of totality.

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