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SCIENCE

Total Eclipses of the Sun

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Summary. Total eclipses of the sun offer research opportunities in a variety of sciences. Some of the advances in solar physics resulting from eclipse observations are discussed. Experiments at the total eclipse of 16 February 1980 in India are also described. These included a test of general relativity, studies in coronal physics, investigations of solar prominences, diameter measurements, a search for interplanetary dust, a study of the gravity waves in the earth's atmosphere, and experiments on the biological effects on animals and humans.

By one of the strangest coincidences in nature, the angular sizes of the sun and moon, as seen from the earth, are nearly equal. As a result the moon eclipses the sun, at least twice a year and sometimes five times a year. A partial solar eclipse can be seen from large areas of the earth, but a total or annular eclipse is visible only along a narrow track, the path of the moon's umbral shadow over the earth (see Fig. 1).

Thus at any fixed location on the earth, a total eclipse of the sun is a rare phenomenon. One has to wait, on the average, 360 years between total eclipses if one is unwilling to travel. However, astronomers have been increasingly willing to travel, even to such uncomfortable places as Sumatra, New Guinea, Siberia, or Mauritania, in order to observe total solar eclipses. The main reason, briefly put, is that a total eclipse gives them a superb view of the outer atmosphere of the sun (the chromosphere and the corona), a region that is difficult or expensive to see any other way. Geophysicists, aeronomists, meteorologists, and, lately, biologists also have good reasons to observe solar eclipses. The total solar eclipse of 16 February 1980 in the south of India attracted experimenters in several of these fields. In this article, I will describe some of their ingenious experiments, although in many cases their final results are not yet available. As historical background (*1*), I will first sketch some of the more important scientific advances made at earlier eclipses.

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Historical Background

Because total solar eclipses are rare and spectacular, they make a deep impression when they occur. History is studded with accounts of such events. Modern reconstructions of the exact time of solar eclipses have helped to fix precise dates throughout antiquity. For example, the reign of Ashurbanipal was marked by a total solar eclipse in 661 B.C.

During the last three centuries before Christ, the Chaldeans noticed that eclipses recur at intervals of 18 years, $11^1/_3$ days, with paths displaced 120° westward in longitude. This period, later given the name saros, nearly equals 223 synodic lunar months (the interval between successive new moons). By another remarkable coincidence, it also approximately equals 19 revolutions of the sun in its apparent path around the sky with respect to a node. The apparent paths of the sun (the ecliptic) and the moon on the sky intersect at two points, the nodes. Imagine that at new moon, the sun is close enough to a node for a solar eclipse to take place (see Fig. 2). After 19 revolutions with respect to the node, the sun will be at the same distance from the node, and it will be new moon again because 223 synodic months will have passed. Therefore another solar eclipse will occur under nearly the same circumstances. Although it is not known how early the saros was used to predict eclipses from past records, Herodotus records that Thales of Miletus used the saros to predict the eclipse of 585 B.C.

Until the middle of the 19th century, scientists virtually ignored the spectacular crown of light (the corona) that surrounds the sun during its total solar eclipse. According to Mitchell (*1*), Kepler in 1605, Cassini in 1706, and Halley in 1715 each commented on the existence of the corona. Halley could not decide whether it was solar or lunar in origin, however. It remained for Francis Bailey, a stockbroker and an enthusiastic amateur astronomer, to describe the solar corona and "protuberances" at the eclipse of 1842 in such glowing terms as to interest professional astronomers in studying these phenomena. Here is Bailey's reaction to the eclipse (*1a*):

> I was astounded by a tremendous burst of applause from the streets below and at the *same moment* was electrified at the sight of one of the most brilliant and splendid phenomena that can be imagined. For at that instant the dark body of the moon was *suddenly* surrounded with a *corona*, a kind of *bright glory*. I had anticipated a luminous circle around the moon during the time of the total obscurity but I did not expect from any of the accounts of previous eclipses that I had read, to witness so magnificent an exhibition as that which took place. Splendid and astonishing, however, this remarkable phenomena really was, and though it could not fail to call forth the admiration and applause of every beholder, yet I must confess there was at the same time something in its singular and wonderful appearance that was appalling. But the most remarkable circumstance attending this phenomenon was the appearance of three large *protuberances* apparently emanating from the circumference of the moon but evidently forming a portion of the corona.

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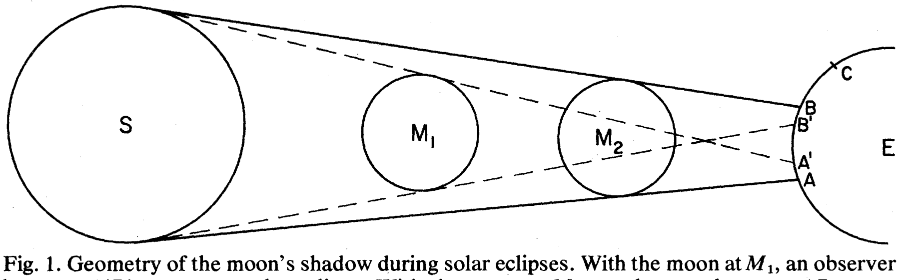


Fig. 1. Geometry of the moon's shadow during solar eclipses. With the moon at M_1, an observer between $A'B'$ sees an annular eclipse. With the moon at M_2, an observer between AB sees a total eclipse; at C, a partial eclipse is seen.

Fifty years of intensive investigation of total solar eclipses followed Bailey's announcement. In 1860, P. A. Secchi and W. de la Rue photographed the corona from sites 250 miles apart in Spain. When they compared their photographs, they concluded that the corona and the protuberances (now called prominences) were real physical structures attached to the sun and not some optical illusion produced by the earth's atmosphere.

The new science of spectroscopy led rapidly to new discoveries. During the eclipse of 1868, P. J. C. Janssen identified three emission lines of atomic hydrogen in the spectrum of prominences, thus establishing their composition. He also discovered a new line in the yellow region of the prominence spectrum. J. N. Lockyer confirmed its wavelength after the eclipse and proposed that it belonged to a hitherto unidentified element, helium, from the Greek *helios*, the sun.

Eclipse observations during the 1880's established that the overall shape of the corona changes systematically in phase with the 11-year sunspot cycle discovered by S. H. Schwabe in 1843. The decade beginning in 1860 also saw the evolution and confirmation of G. R. Kirchhoff's explanation of the solar absorption spectrum, which was discovered in 1817 by J. Fraunhofer. According to Kirchhoff, these absorption lines form in a gaseous surface layer. When observed tangentially against the dark sky, the gas should glow in a pattern of emission lines that is a reversal of the absorption pattern. At the eclipse of 1870, C. A. Young confirmed Kirchhoff's hypothesis when he observed the reverse pattern of emission lines in the "flash spectrum" of the solar chromosphere.

At the eclipse of 1883, Janssen showed that the pearly light of the corona has the same absorption spectrum as the solar surface and thus consists at least in part of light scattered from cool particles. Scientists were then led to believe that the corona is cool and were puzzled by its enormous extent. How were the cool particles supported against gravity?

C. A. Young and W. Harkness discovered a green emission line in the spectrum of the corona at the solar eclipse of 1869. Since no known terrestrial material emitted this line, they postulated a new substance, "coronium." By 1898, more than ten unidentified coronal lines attributed to coronium had been discovered. It was not until 1941 that B. Edlen, working on a suggestion by W. Grotrian, demonstrated that the coronal emission line spectrum arises from ions of several familiar elements. The green emission line of coronium, for example, arises from iron atoms that have lost 13 of their 26 electrons (Fe XIV). The presence of such highly ionized atoms implies that the corona is a tenuous incandescent gas, with a temperature of more than 2 million degrees. We now know, following a long chain of eclipse observations and atomic theoretical interpretation, that the coronal spectrum consists of three parts: an emission line spectrum radiated by hot ions, a polarized continuum scattered by free coronal electrons, and, at sufficiently great distances from the sun, a Fraunhofer spectrum scattered from cool interplanetary dust particles.

Until the 1930's, M. Saha's theory of atomic ionization sufficed to explain the variety of stellar spectra in terms of a continuous temperature scale. The eclipse spectrum of the chromosphere, however, gave evidence for different chromospheric temperatures. E. A. Milne and later D. H. Menzel developed a theory of atomic ionization under conditions that depart from thermodynamic equilibrium. The eclipses of 1932, 1936, and 1952 provided chromospheric spectra that enabled Menzel and his associates to develop this theory.

Although solar physics developed vigorously as a result of the interaction of total eclipse observations, laboratory spectroscopy, and atomic physics, each advance required a tremendous effort in mounting eclipse experiments. This hurdle was partially bypassed when B. Lyot enabled astronomers to view the corona in broad daylight by his invention, in 1930, of the coronagraph, a telescope that produces an artificial eclipse of the sun. This instrument has accelerated the study of the outer atmosphere of the sun but has not entirely supplanted natural eclipses. The solar disk is approximately 1 million times brighter than the corona, and although the coronagraph suppresses most of the glare, the scattering of residual stray light within the instrument masks all but the brightest inner portions of the corona. Thus, to record the fainter outer portions, astronomers still value natural eclipses. Figure 3 is an example of the Fe XIV corona photographed with a coronagraph. A new version of a coronagraph, with an occulting disk mounted in front of the instrument on a long arm, was invented by J. W. Evans. Such an instrument was flown aboard Skylab for 9 months and gave an unprecedented record of the evolution and dynamics of the inner corona (see Fig. 4).

The moon's umbral shadow sweeps the earth at a speed of 1600 kilometers per hour near the equator and faster at higher latitudes. As a result, the longest total eclipse lasts only 7 minutes, 40 seconds at a fixed position on the ground. A jet aircraft flying eastward can nearly keep pace with the shadow, however, and so prolong totality considerably. During the eclipse of 1973, for example, a group of experiments was flown aboard the Concorde and enjoyed a totality period of 74 minutes (*2*).

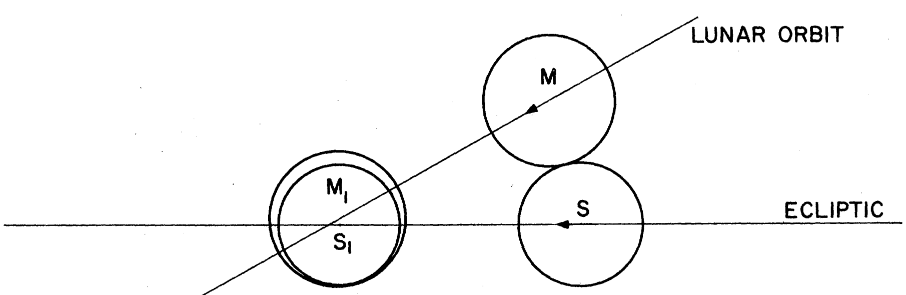


Fig. 2. Geometry of the solar and lunar apparent disks near a node in the lunar orbit. If the moon in its eastward motion overtakes the sun at S (the eclipse limit), it eclipses only the tangent point. If the moon overtakes the sun closer to the node (for instance, at S_1), a total or annular eclipse can occur.

The Recent Indian Eclipse

The eclipse of 16 February 1980 was the first to cross India in 82 years. The moon's shadow first touched the earth at sunrise in the south Atlantic, swept across the waist of Africa, the Indian Ocean, and the Indian subcontinent, and left the earth's surface in south China at sunset. The Japal-Rangapur Astrophysical Observatory, situated some 50 km south of Hyderabad, had the good fortune to lie in the path of totality. The duration of the eclipse there was predicted to be 2 minutes, 9 seconds and, although this is rather short, the weather prospects were good and the sun was near its phase of maximum activity. Therefore, about 50 astronomers from the United States, sponsored by the National Science Foundation, traveled to Rangapur to set up their experiments (*3*).

Indian astronomers and geophysicists deployed a large number of experiments along the eclipse track. The Indian Institute of Astrophysics at Bangalore, for example, established two camps with seven separate experiments. Hundreds of amateur astronomers, particularly from Japan, were attracted to India for the event. The eclipse excited tremendous interest and some apprehension among the Indian population. Several hundred thousand Hindu pilgrims traveled to Kurukshetra in the west of India to gain merit by bathing in two sacred lakes during the eclipse.

Shortly before the eclipse, the sky was partly cloudy at Rangapur, but fortunately the sun was visible between clouds during the critical moments of totality. All the equipment at Rangapur operated satisfactorily. The U.S. and Indian astronomers were jubilant after the glorious event. In Hyderabad, however, the streets were deserted, as the population remained indoors in fear of physical contamination or eye damage.

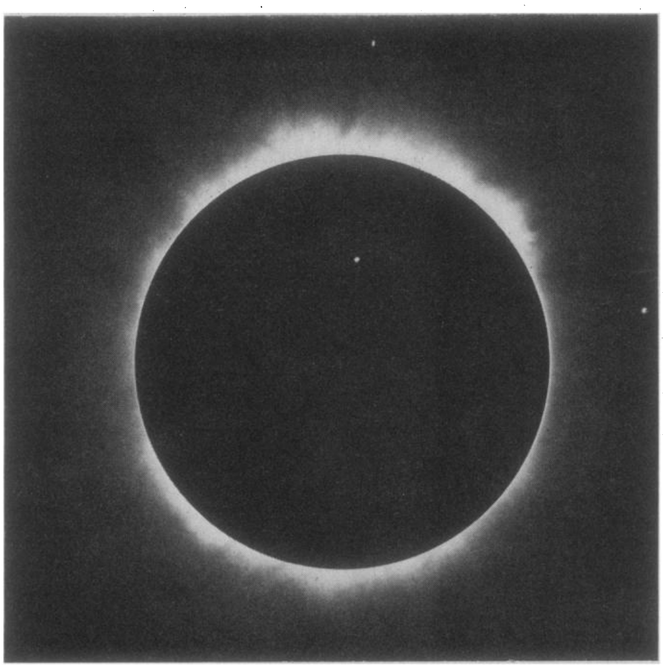
Relativity

The Rangapur Observatory contains a 48-inch telescope, the largest in India, and the observatory staff, under the direction of K. D. Abhyankar, decided to use it to measure the deflection of starlight in the gravitational field of the sun. This classical test of general relativity was first performed at the eclipse of 1919 (*4*) by the Greenwich Royal Observatory and Cambridge University. Although the technique is simple, execution is difficult. One photographs the field of stars around the sun during the eclipse and then 6 months later, when the sun has moved to the opposite part of the sky. The two sets of photographs must be taken under identical conditions to eliminate instrumental and atmospheric systematic errors. Einstein's theory of general relativity predicts a displacement by $\theta = 1.75$ arc seconds of the apparent position of stars near the solar limb. This experiment has been repeated several times since 1919, with a typical precision of 0.2 arc second or 10 percent.

A team from the University of Texas took elaborate precautions to improve the precision of this experiment at the 1973 eclipse in Mauritania. However, their measurements gave a final value of $0.95 \pm 0.11\,\theta$ (*5*). Formalont and Sramek (*6*) reported a formal error of only 1 percent in their measurement of the deflection of a microwave source in the vicinity of the sun. Their result, which virtually excludes alternative theories of general relativity, holds the present record for precision. The Indian team at Rangapur attempted to improve on previous optical experiments and hoped to match the microwave result. Unfortunately, the sky and the solar corona were brighter than expected during the eclipse and their photographic plates were overexposed. They are unlikely to extract a useful result from their data.

Corona and Prominences

A variety of experiments was carried out on the physics of the corona. The detailed results in most cases await further detailed analysis, and all I can report now are the objectives, methods, and degree of success attained. A two-man team from the High Altitude Observatory (HAO) in Boulder, Colorado, successfully recorded the brightness and the



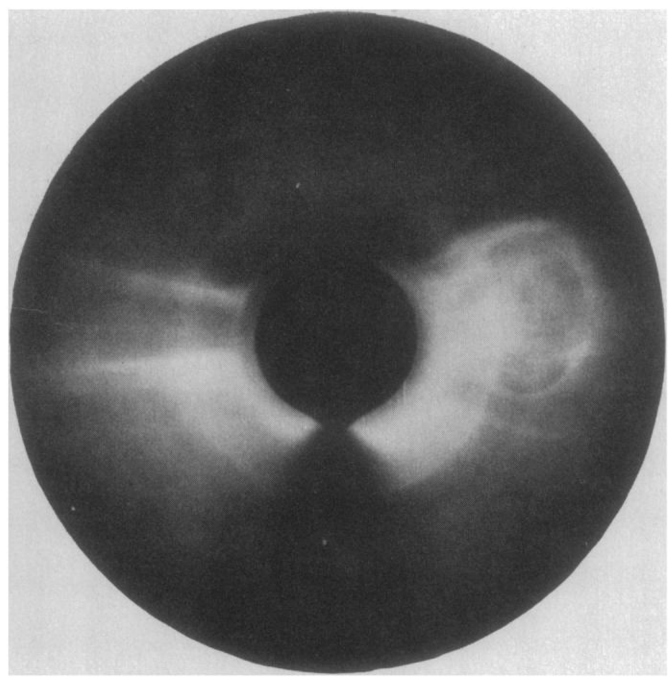


Fig. 3 (left). Coronal structures, photographed with a coronagraph in the emission line 5303 Å. [Association of Universities for Research in Astronomy, Inc., Sacramento Peak Observatory] Fig. 4 (right). A mass ejection in the corona observed with the High Altitude Observatory white light coronagraph on Skylab on 10 August 1973. The field of view is 6 solar diameters; the central dark spot is caused by the instrument's occulting disk. The coronal loop emerged at a speed of 250 km/sec. [Printed with permission of the High Altitude Observatory] linear polarization of the white light corona (Fig. 5). Similar photographs, taken by the HAO at the eclipses of 1966, 1970, and 1973, serve several purposes. First, they reveal the fine structural details that are generally thought to outline coronal magnetic fields. Second, they show the large-scale coronal structure and how it varies throughout the sunspot cycle. Finally, the polarimetric data can be used to derive the spatial distribution of free electrons following a method outlined by Van de Hulst (*7*) and developed by K. Saito. C. F. Keller, of the Los Alamos Scientific Laboratory, obtained similar photographs during the 1980 eclipse from a jet aircraft flying at an altitude of 37,000 feet down the eclipse path. Because the sky is darker at this altitude than at the ground, and because the eastward flight of the aircraft prolongs the eclipse, Keller was able to photograph the coronal streamers extending out to 20 solar radii, far more than is possible from the ground. By sheer luck, he also photographed a huge eruption taking place in the corona that extended from the solar limb to 6 solar radii (Fig. 6). Such coronal "transients" were first observed in quantity during 1973 and 1974 with the externally occulted coronagraph mounted aboard Skylab (*8*). A similar coronagraph is now operating aboard the Solar Maximum Mission to record such transients.

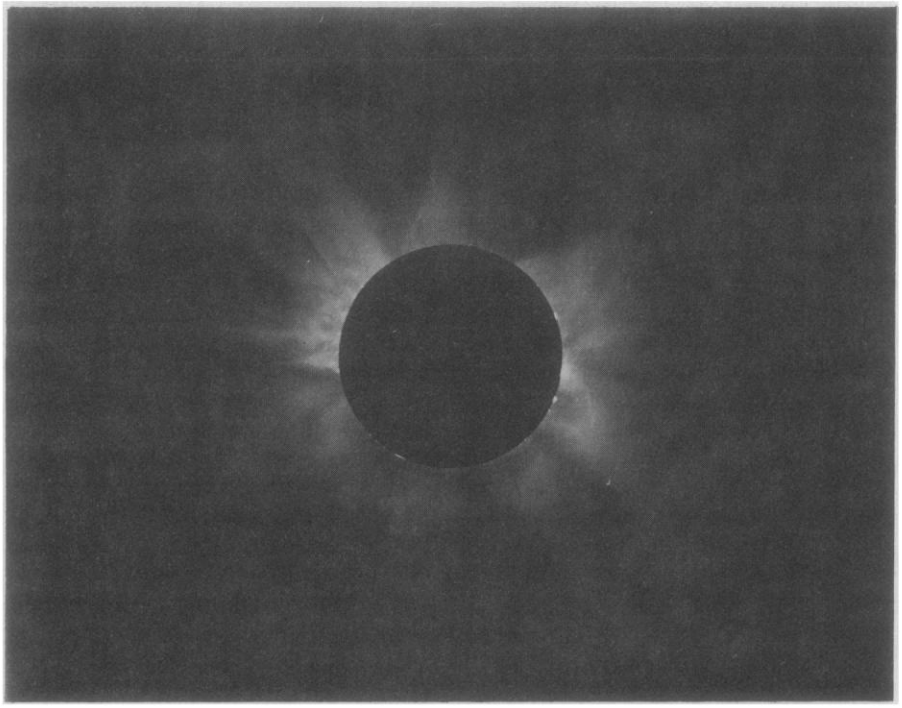


Fig. 5. The corona, photographed in visible light by the High Altitude Observatory team during the total eclipse of 16 February 1980. The circularly symmetric pattern of streamers is typical of the sun at the maximum phase of the sunspot cycle. [Printed with permission of the High Altitude Observatory]

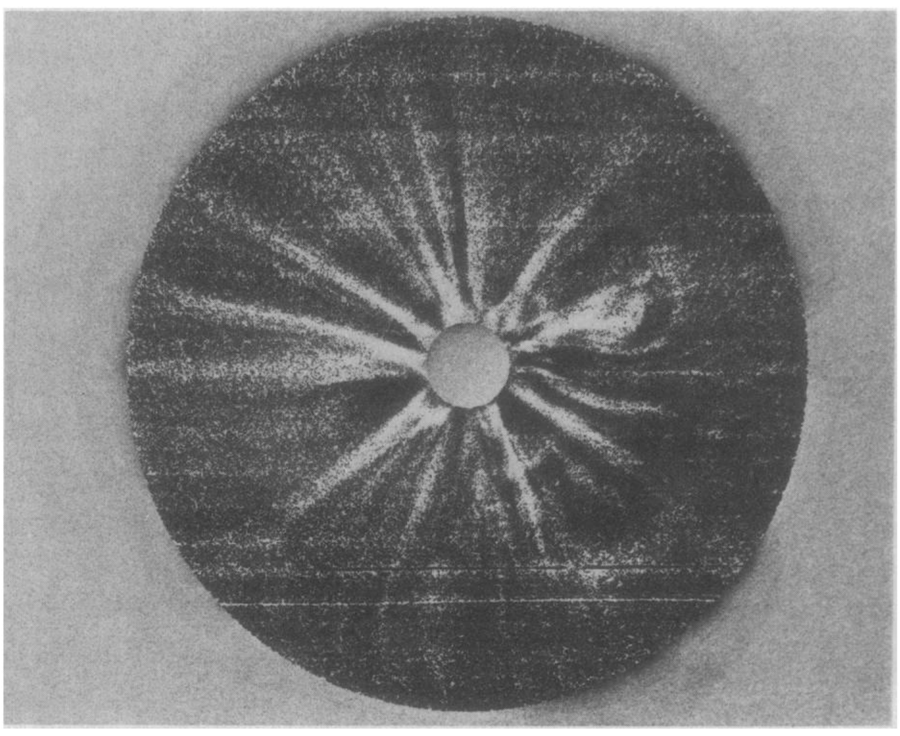


Fig. 6. Coronal streamers and a coronal transient (right side) at the 16 February 1980 eclipse. Several digital images have been added, and the image contrast has been improved. [Printed with permission of Los Alamos Scientific Laboratory]

The electron density distribution in the corona has been derived at different phases of the sunspot cycle from polarimetric experiments similar to the ones just described. In contrast, relatively little information is available on the temperature profile through the corona. To fill this need, scientists from Los Alamos performed two experiments to measure coronal temperatures. Two identical instruments were carried by a pair of rockets launched from Kenya down the eclipse path. The instruments measure the profile of the Lyman alpha line of hydrogen at wavelength 1216 angstroms. Spectra obtained during the total eclipse of 1970 (*9*) showed for the first time that the corona contains a sufficient number of neutral hydrogen atoms, even at its 2-million-degree temperature, to scatter the strong Lyman alpha radiation from the solar chromosphere. Following this eclipse, Beckers and Chipman (*10*) showed how the profile of Lyman alpha would be broadened by the high thermal speed of these neutral coronal hydrogen atoms and how the kinetic temperature of the corona might be derived from Lyman alpha spectra. In collaboration with H. Argo, Beckers designed and launched a Lyman alpha spectrograph at the 1974 eclipse in Western Australia. Of two payloads launched, one failed to point properly at the sun and the other could not be retrieved from the sea. Incredibly, Beckers and Argo encountered similar misfortunes at the 1980 eclipse. This is a beautiful experiment that can be done very well during an eclipse and should be tried again.

The second Los Alamos temperature experiment consisted of a Fabry-Perot interferometer that flew on a jet aircraft. It recorded the profiles of two coronal emission lines: 5303 Å, due to Fe XIV, and 5694 Å, due to Ca XV. D. H. Liebenberg, who conceived the experiment, reports that it was successful and that the profiles will yield useful ion temperatures and ion densities.

Several teams set out to measure streaming motions in the inner corona. Two types of motion are expected. Material is known to fall inward toward the sun within closed magnetic arches, but the speed and mass flux are uncertain. Material is also expected to flow outward and to escape the sun as the solar wind within 2 or 3 radii of the solar surface. This outward streaming has yet to be observed so close to the sun. The location, mass flux, and speed of the outward streaming are all interesting parameters for modeling the corona. Two kinds of instruments were used. Multiple slit spectrographs designed to measure the Doppler shift and width of the coronal green line at 5303 Å at several positions in the corona were set up at Rangapur by a team from Kitt Peak National Observatory and one from Udaipur Observatory. The Kitt Peak instrument had already detected downflowing material at the eclipses of 1970 and 1973 (*11*). The second type of instrument, consisting of a telescope and Fabry-Perot interferometer, was set up by a team from Sacramento Peak Observatory (Fig. 7) and one from Osmania University in Hyderabad. All four teams obtained useful data, but it will be several months still before their conclusions are known.

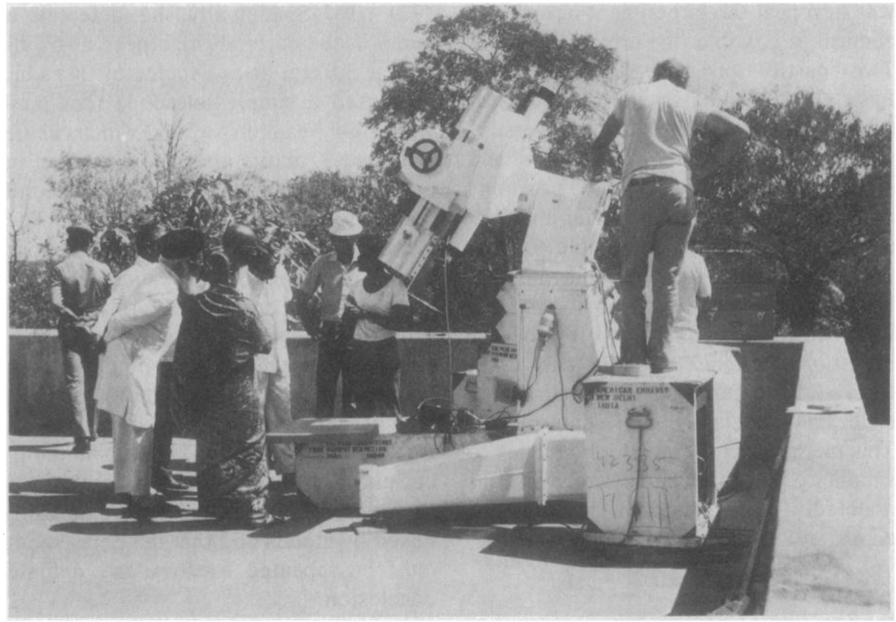


Fig. 7. Visitors to the Japal-Rangapur Observatory inspect the eclipse experiment of the team from Sacramento Peak Observatory.

For many years, astronomers have wondered how the corona is heated to 1 to 2 million degrees. According to the most popular hypothesis, sound waves or magnetohydrodynamic waves are generated by random motions near the solar surface and dissipate their energy in the corona. All attempts to detect such waves have been unsuccessful so far. J. Pasachoff, a veteran eclipse observer from Williams College, set up a new instrument at Rangapur to try to detect waves with higher frequency than any sought before. The critical part of this instrument consists of an array of optical fibers and fast photomultipliers, designed to detect small, rapid fluctuations in brightness of the coronal green line at 5303 Å within small, bright coronal structures. Pasachoff reports that his equipment worked, that there is sufficient signal to analyze, but that as yet no discrete periods have been discovered.

Solar prominences consist of a relatively cool plasma (10^4 K) embedded in the 2-million-degree corona. Energy radiated from a prominence is supplied from the corona through a boundary layer that has a steep temperature gradient. Numerical models of the transfer of radiant energy and the temperature profile in a prominence have improved markedly during the past 5 years, but still do not account fully for the prominence spectrum. To better constrain such models, D. Landman and his associates at the University of Hawaii photographed the complete visible spectrum of prominences during the 1980 eclipse. They used a venerable spectrograph, which has seen service at six previous eclipses, to record many faint emission lines. Landman reports that the spectra recorded will be useful, although the prominences were not especially bright.

Solar Diameter

Most of the experiments described so far involve high technology. In contrast, one of the most ingenious experiments relied on nothing more than naked eyeballs and stopwatches. A. Fiala, an astronomer from the U.S. Naval Observatory, came to Rangapur to measure the solar diameter with a precision of 1 part in 100,000. In 1979, Eddy and Boornazian (*12*) analyzed a long series of visual observations of the sun's transit made at the Royal Greenwich Observatory and the U.S. Naval Observatory. They concluded that the solar diameter has been decreasing by about 2 arc seconds per century. Such a large rate of decrease, if confirmed, would have exciting astrophysical and climatological implications.

Fiala and his collaborators used a new technique, first proposed by Dunham and Dunham (*13*), to derive a measurement of the solar radius from accurate locations of the northern and southern edges of the total eclipse path. The location of the edges depends sensitively on the relative positions and apparent radii of the sun and moon. Since the relative position and apparent radius of the moon can be predicted with high precision, a measurement of the position of an edge effectively determines the solar radius. An uncertainty of 750 feet of the position of the path's edge corresponds to an uncertainty of only 60 milliarc seconds in the solar radius. The position of the path can be determined by accurately timing the duration of totality at several positions perpendicular to its north and south edges. In principle, an observer standing precisely on the edge would see zero duration, whereas an observer a few hundred feet into the shadow would time a duration of some tens of seconds. The method was first applied to the solar eclipses of 1976 and 1979 and the historical records of the solar eclipse of 1715 (*14*). Fiala and his associates found that the solar radius had contracted by 0.34 ± 0.2 arc second in 264 years. Observations of 23 transits of Mercury, analyzed by Shapiro (*15*), showed no indication of a decrease in the solar diameter greater than 0.3 arc second per century. Thus, the sun seems to have shrunk, although by a much smaller amount than reported by Eddy and Boornazian.

At the 1980 eclipse Fiala's objective

was to repeat the experiment in order to confirm, if possible, the previous results. Two parties of observers, including Fiala, the Dunhams, and several students from East Carolina University, were provided with stopwatches and strung out across the predicted positions of the northern and southern limits of the eclipse. Both groups were able to time the duration of the eclipse and to establish their own geographic positions from large-scale maps. By comparing the observations obtained in 1979 and 1980, Fiala and the Dunhams detected a possible small change in the solar radius. This method has the great advantages of simplicity and precision and will undoubtedly be repeated in the years to come.

Dust Corona

The solar system is filled with particles of dust that are thought to be cometary and asteroidal debris. The familiar zodiacal light arises from sunlight scattered by such dust particles in the ecliptic plane. A number of drag forces, principally the Poynting-Robertson effect, decelerate the particles and allow them to fall into the sun. The particles should vaporize at some distance from the sun that depends on their size distribution and composition. Inside this critical distance, a dust-free shell should exist around the sun. In the vicinity of the vaporization zone the particles should radiate at infrared wavelengths. In 1963, Peterson (*16*) predicted detectable infrared thermal emission of hot dust particles near the vaporization limit. Since the dust composition was unknown, he assumed a range of possible albedos. Peterson searched for and found an emission bump in the coronal brightness at a wavelength of 2.23 micrometers during the eclipse of 12 November 1966 (*17*). The location of the feature near 4 solar radii suggested a vaporization temperature near 2000 K.

More recently, E. P. Ney and his associates detected the formation of dust particles in the ejecta of novae such as NQ Vulpeculae, carbon stars such as R Coronae Borealis, and several Wolf-Rayet stars. Lewis and Ney (*18*) proposed that the dust in these objects consists of the iron carbide Fe_3C, which forms at a temperature of about 1000 K. Ney was therefore motivated to search for the presence of a dust-free shell around the sun with an edge near 20 radii, corresponding to a radiation temperature of 1000 K. He found evidence for such a shell at the total eclipse of 26 February 1979 (*19*). Specifically, he detected a bump in the coronal brightness distribution at 3.5 μm at a distance of 24 radii. Ney used a simple telescope that projects a 1/4° beam on the sky, which can be switched 3° above and below the sun in order to subtract the sky background contribution to the infrared signal. The presence of cirrus during the 1979 eclipse casts some doubt on the reality of his discovery. To confirm the result, Ney brought the same equipment to Rangapur in 1980. Once again, he detected a feature around 20 solar radii, but this time it was almost certainly due to a small cloud that showed up in simultaneous photographs. Ney concludes that observations at both eclipses were contaminated by clouds and that the experiment must be repeated to draw any definite conclusion.

Ionosphere

Scientists who are concerned with the physics of the earth's ionosphere and upper atmosphere have found total eclipses useful for many years. During a total eclipse, the sun's ionizing radiation is cut off in a regular and predictable manner. It is then possible to study such phenomena as the recombination of electrons and ions in the ionosphere, the change in the heat balance of the upper atmosphere, and the generation of waves and wind. During the 1980 eclipse, a variety of ionospheric and atmospheric experiments were carried out, particularly by Indian scientists. Some examples were measurements of the atmospheric space charge and electric field by A. K. Kamra and J. K. S. Teotia from the Indian Institute of Tropical Meteorology, measurements of the charge of ozone by a group from the India Meteorological Department, and a search for gravity waves in the ionosphere by J. H. Sastry from the Indian Institute of Astrophysics.

The experiment on gravity waves is only the latest of a series that began in 1970. For many years, ionospheric physicists were aware of "traveling ionospheric disturbances." These are wavelike events with periods of 30 minutes or longer, horizontal wavelengths of a few thousand kilometers, and horizontal phase velocities between 400 and 700 meters per second. In general, they have no connection to solar eclipses and are thought to arise from auroral or geomagnetic activity. In 1961, Hines (*20*) explained them as the ionospheric manifestation of internal gravity waves in the neutral atmosphere. It occurred to Chimonas and Hines (*21*) that a solar eclipse, with its rapid cooling of the upper atmosphere, would generate such internal gravity waves and would allow a clear-cut experiment and interpretation. They predicted a pressure perturbation of 10^{-5} at ground level and 10^{-1} at 200 km.

Davis and Da Rosa (*22*) detected a wave in the ionosphere shortly after the eclipse of 7 March 1970 that arrived after the predicted delay and from the correct direction. Anderson *et al.* (*23*) measured air pressure and temperature fluctuations at ground level on the center line of this eclipse. They also detected a wavelike phenomenon with a primary period of 89 minutes but with a pressure amplitude two to three orders of magnitude larger than predicted by Chimonas and Hines. Chimonas subsequently revised his theory (*24*) and suggested that Lamb waves, triggered by the eclipse, caused the large-amplitude pressure fluctuations at ground level. Anderson and Keefer repeated their experiment at the eclipse of 30 June 1973 (*25*), but were prevented from obtaining results by a sandstorm. However, Broche and Crochet (*26*) observed the ionosphere during the 1973 eclipse from a station 450 km south of the eclipse path. They measured the time variations of the frequency shift of a high-frequency radio wave reflected from the F layer at an altitude of 300 km. Using the theory of Chimonas (*27*), they obtained a satisfactory prediction for the delay and the period of the traveling disturbance, but observed a neutral pressure amplitude 100 times larger than Chimonas's theory predicts, even at 300 km. Broche and Crochet suggested that clouds at "meteorological altitude" participate in the cooling of the atmosphere near the ground and that it is this low-level atmospheric cooling that excites atmospheric gravity waves, rather than the cooling of the upper atmosphere. Further development of the theory and better observations will be needed to understand what at first sight appears a relatively simple phenomenon. Sastry's measurements of waves in the ionosphere during the 1980 eclipse may contribute to this development.

Biological Effects

Indian scientists at several locations conducted an experiment on the biological effects of the eclipse on humans and animals. It is well known that birds tend to roost, as though preparing for night, as totality approaches. The behavior of such simple animals as freshwater crabs during previous partial eclipses suggested to some Indian zoologists that crabs, as well as other types of animals, may be sensitive to temperature, pressure, or geomagnetic changes that arise from the eclipse. J. V. R. Rao, from the Department of Zoology of Osmania University, organized experiments on the behavior of deer, fish, bats, crabs, and rabbits at ten locations on and near the eclipse path in order to further investigate this idea. Three eminent Indian neurosurgeons were interested in the possible effects of geomagnetic disturbances on the human brain. They measured electrical brain activity, cardiac response, skin resistance, and biochemical changes in a number of human subjects throughout the eclipse; one of the subjects was in a meditative state throughout totality. Inmates of the mental hospital of Hyderabad, including schizophrenics, epileptics, and retarded children, were the subjects of further electrical and biochemical tests. According to newspaper accounts, none of the human subjects in the experiments showed any marked reaction to the eclipse. Rao reported that a control group of rabbits at Rangapur, isolated in a lighted but windowless room, became quiescent or even inert during the totality phase.

Conclusion

As this survey indicates, scientific interest in total solar eclipses continues unabated. The next eclipses with reasonable chances for good weather and accessible sites will occur in July 1981 (in the Soviet Union and China), June 1983 (in Sumatra), and November 1984 (in New Guinea). I have no doubt that they will be well attended and that interesting experiments in a variety of disciplines will be performed.

References and Notes

1. S. A. Mitchell, *Eclipses of the Sun* (Columbia Univ. Press, New York, 1951).
1a. F. Bailey, *Memoirs of the Royal Astronomical Society* (1846), vol. 15, p. 4.
2. D. H. Liebenberg and M. M. Hoffmann, in *Coronal Disturbances*, G. Newkirk, Jr., Ed. (Reidel, Dordrecht, 1974), p. 485.
3. The U.S. scientists were from Brookhaven National Laboratory, East Carolina University, the University of Hawaii, the High Altitude Observatory, Iowa State University, Johns Hopkins University, Kitt Peak National Observatory, the University of Maryland, the University of Minnesota, Sacramento Peak Observatory, the U.S. Naval Observatory, and Williams College.
4. A. C. D. Crommelin, *Nature (London)* **104**, 280 (1919); Joint Eclipse Meeting of the Royal Society and the Royal Astronomical Society, *Observatory* **42**, 389 (1919).
5. B. De Witt and the Texas Mauritanian Eclipse Team, *Astron. J.* **81**, 452 (1976).
6. E. B. Formalont and R. A. Sramek, *Comments Astrophys. Space Phys.* **7**, 19 (1977).
7. H. C. Van de Hulst, *Bull. Astron. Soc. Neth.* **11**, 135 (1950).
8. J. T. Gosling, E. Hildner, R. M. MacQueen, R. H. Munro, A. I. Poland, C. L. Ross, *J. Geophys. Res.* **79**, 4581 (1974).
9. A. H. Gabriel, W. R. S. Garton, L. Goldberg, T. J. L. Jones, C. Jordan, F. J. Morgan, R. W. Nicholls, W. J. Parkinson, H. J. B. Paxton, E. M. Reeves, C. B. Shenton, R. J. Speer, R. Wilson, *Astrophys. J.* **169**, 595 (1971).
10. J. M. Beckers and E. Chipman, *Sol. Phys.* **34**, 151 (1974).
11. W. Livingston, J. Harvey, L. A. Doe, B. Gillespie, G. Ladd, *Bull. Astron. Soc. India*, in press.
12. J. A. Eddy and A. A. Boornazian, *Bull. Am. Astron. Soc.* **11**, 437 (1979).
13. D. W. Dunham and J. B. Dunham, *Moon* **8**, 546 (1973).
14. D. W. Dunham, S. Sofia, A. D. Fiala, D. Herald, P. M. Muller, *Science* **210**, 1243 (1980).
→ I. I. Shapiro, *ibid.* **208**, 51 (1980).
16. A. W. Peterson, *Astrophys. J.* **138**, 1218 (1963).
17. _____, *ibid.* **155**, 1009 (1969).
18. J. S. Lewis and E. P. Ney, *ibid.* **234**, 154 (1979).
19. E. P. Ney, *Bull. Am. Astron. Soc.* **12**, 257 (1980).
20. C. O. Hines, *Can. J. Phys.* **38**, 1441 (1960).
21. G. Chimonas and C. O. Hines, *J. Geophys. Res.* **75**, 875 (1970).
22. M. J. Davis and A. V. Da Rosa, *Nature (London)* **226**, 1123 (1970).
23. R. C. Anderson, D. R. Keefer, O. E. Myers, *J. Atmos. Sci.* **29**, 583 (1972).
24. G. Chimonas, *Planet. Space Sci.* **21**, 1843 (1973).
25. R. C. Anderson and D. R. Keefer, *J. Atmos. Sci.* **32**, 228 (1975).
26. P. Broche and M. Crochet, *J. Atmos. Terr. Phys.* **37**, 1371 (1975).
27. G. Chimonas, *J. Geophys. Res.* **75**, 5545 (1970).

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Toward a Unified Theory: Threads in a Tapestry

Sheldon Lee Glashow

In 1956, when I began doing theoretical physics, the study of elementary particles was like a patchwork quilt. Electrodynamics, weak interactions, and strong interactions were clearly separate disciplines, separately taught and separately studied. There was no coherent theory that described them all. Developments such as the observation of parity violation, the successes of quantum electrodynamics, the discovery of hadron resonances, and the appearance of strangeness were well-defined parts of the picture, but they could not be easily fitted together.

Things have changed. Today we have what has been called a standard theory of elementary particle physics in which strong, weak, and electromagnetic interactions all arise from a local symmetry principle. It is, in a sense, a complete and apparently correct theory, offering a qualitative description of all particle phenomena and precise quantitative predictions in many instances. There are no experimental data that contradict the theory. In principle, if not yet in practice, all experimental data can be expressed in terms of a small number of "fundamental" masses and coupling constants. The theory we now have is an integral work of art: the patchwork quilt has become a tapestry.

Tapestries are made by many artisans working together. The contributions of separate workers cannot be discerned in the completed work, and the loose and false threads have been covered over. So it is in our picture of particle physics. Part of the picture is the unification of weak and electromagnetic interactions and the prediction of neutral currents, now being celebrated by the award of the Nobel Prize. Another part concerns the reasoned evolution of the quark hypothesis from mere whimsy to established dogma. Yet another is the development of quantum chromodynamics into a plausible, powerful, and predictive theory of strong interactions. All are woven together in the tapestry; one part makes

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