Eclipse Science Results: Past and Present

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Abstract. We review the significant advances that have been achieved by eclipse experiments. First we note the anomaly that the corona was not even seen until relatively modern times. Beginning in 1860 white-light (W-L) photographs suggested structures that must have been dominated by magnetic fields. This led to the discovery of surface magnetism in sunspots by Hale in 1908; the first detection of cosmic magnetism. Delicate direct photographic observations confirmed the bending of starlight near the eclipsed Sun as predicted by Einstein’s General Theory of Relativity. Chromospheric flash spectra indicated that the outer layer of the Sun was much hotter than the underlying photosphere, leading to non-local thermodynamic equilibrium concepts and the idea of various mechanical and wave processes to maintain it. Decades have been devoted to understanding the corona. Discovery of its million degree plus temperature and figuring how to heat it, how cool prominences can co-exist within it, all are topics to which eclipse observations have contributed.

1. Totality without a Corona?

Eclipses have been chronicled for over 4000 years but the corona escaped being noticed until modern times. The single exception: Leonis Deaconis in AD 968 mentions “...a certain dull and feeble glow, like a narrow headband, shining round the extreme parts of the disc” (Stephenson 1997). Kepler made clear mention of it during the eclipse of 1609 (Zirker 1984), but the first real description came from Halley in 1715 who noted its structure and saw red prominences. Kepler and Halley both thought it was lunar in origin. Later, it was thought that coronal rays are produced by diffraction effects at the edge of the Moon and many false drawings were made on this basis.

Why has the world population been blind to what today we consider one of the spectacular displays of nature? Education for one thing; we see what we have been told is there. It was also unlikely any single person would see more than one eclipse in a lifetime. No one paid any attention to the corona since fear of the darkness and a concern about what the event portended probably dominated the experience. The question arises: what else are we missing?
2. Corona and Cosmic Magnetism

In 1860 photography was introduced as a way to record the corona. Sites 250 miles apart produced similar corona pictures. This meant it was not a terrestrial phenomenon. Schwabe discovered the sunspot cycle in 1843. Subsequent eclipses from 1874 to 1882 revealed that the coronal structures varied with the activity cycle. The corona was therefore solar in origin. There was the strong suggestion that coronal structures mimicked the iron filing patterns of bar magnets. About this time Peter Zeeman discovered that spectrum lines split when formed in a magnetic field. George Ellery Hale (1908), inspired by eclipse photographs and Zeeman's finding, looked for and found magnetic fields in sunspots. This was the first concrete detection of cosmic magnetism. However, eclipse pictures also indicated a complex of surface magnetism outside sunspots. The Mount Wilson observers struggled for 4 decades in vain to detect these weak non-sunspot fields. Finally, Babcock (1953), making use of a variety of new tools (photomultipliers, electro-optic polarization modulators, narrow-band amplifiers) developed the solar magnetograph. Extrapolated surface fields now could map out and to a extent explain coronal structure.

The corona on 11 August 1999, Figure 1, certainly is dominated by magnetic structures. We see helmets, rays, and a very nice loop at about 1 o'clock. This is a typical 'solar max' corona in its complexity and its brightness. Figure 2 shows a low-lying prominence which was pinkish in the original color recording. We can presume this color arises from the contribution of both Hα (red) and Hβ (blue) emission.

3. Einstein Light Bending

It is a valuable theory that predicts fundamentally new phenomena. Einstein developed his General Theory of Relativity; one consequence was that a light ray would deviate 1.75 arcsec toward the Sun at 1 R⊙. Recall that the theory was not widely accepted around 1920. W.W. Campell, Director of Lick Observatory, for example said he '...hoped it would not be true'. Two eclipse expeditions in 1919 carried out light deflection experiments. Star fields around the eclipsed Sun were photographed and the process repeated six months later with the same instrument and due attention to thermal and emulsion stability. The results were announced with great fanfare by the President of the Royal Society: 1.98 ± 0.16 and 1.61 ± 0.40 arcsec, a confirmation! Light deviation measurements were repeated at 6 eclipses from 1922 to 1973, all with positive results. Radio astronomers had the final word when Fomalont and Sramek (1977) used the 35 km baseline interferometer at Greenbank to obtain a deviation of 1.761 ± 0.016 arcsec.

4. Chromosphere and non-LTE

Donald Menzel invented the 'jumping film' spectrograph to observe the flash-spectra of the chromosphere/corona interface. At the Khartoum eclipse of 25 February 1952 definitive observations were obtained by Bernard Lyot and by Jack Evans (the former died in Egypt after the expedition and the latter broke
a leg). The Lyot spectra were finally brought to France with great difficulties; their processing revealed several new coronal lines. The behavior of the emission lines without a continuum indicated to later analysts (Pecker, Michard, Athay, Jefferies, Thomas, for example) that there was an increase of electron temperature outward, which required the development of non-Local Thermodynamic Equilibrium methods. Hiei and Hirayama (1966) obtained spectra to the heights of 50,000 km. See the new book *Total Eclipses* by Guillermier and Koutchmy (1999) for something of the history of this exciting era.

Besides the ground based eclipse experiments a new breed of observers took to high flying aircraft. Not only did they get above much of the water absorption but they could extend the time of totality by chasing the shadow. A Concorde flight on 30 June 1973 yielded 74 minutes of totality! The movie made from the numerous W-L coronal images did not show any dramatic changes and pressure
waves as expected. However, some polar plumes did show some subtle variations suggesting waves are propagating inside. Probably the shock waves surrounding the supersonic aircraft was a source of image distortion and bad seeing. Other results concerned IR spectra of the outer corona but these measurements were rather noisy. A 1981 NASA Kuiper Airborne Observatory flight allowed Lindsey and team (1986) to explore 30, 50, 100 and 200 μ radiation at the Sun’s limb and discover \textit{limb brightening.}

5. The Corona

Once the corona was historically identified as a part of the Sun new puzzles arose. Why didn’t the corona scatter the Fraunhofer lines of the photosphere? What was the identification of the strong green and red emission lines found there? Actually Grottrian (1939) did find the strongest Fraunhofer line Ca K in the corona. This line was noticeably broader than in the photosphere and, assuming it was a thermal effect, he deduced a kinetic temperature of about $10^6$ K.

The eventual identification by Edlen (1942) of Fe XIV 5303Å and Fe X 6374Å as forbidden lines that require an ionization temperature of $10^6$ K for their population is a triumph of eclipse science. The width of these lines is also compatible with this order of temperature (Kim 2000). The widths of Lyman$\alpha$, as observed from space show a run of temperature from 2.6 ($10^6$) at 1.5 R$_\odot$ to 1.2 ($10^6$) at 4 R$_\odot$. 

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Combine the above information with the fact that the white-light or K corona is polarized and we have that the corona is a primarily a tenuous cloud of million degree electrons. The light we see is due to Thompson scattering of light from the photosphere. The corona being electrically conducting, magnetic fields, with their footpoints on the solar surface, are the source of its varied forms (helmet streamers, rays, brushlike tufts near the poles, at solar maximum a sort of giant dahlia).

6. What Heats the Corona?

The $10^6$ degree corona cannot be heated by conduction from the photosphere or chromosphere as this violates the 2nd law of thermodynamics. Only 0.01% of the Sun’s radiative output energy is required, however. Biermann (1940) proposed acoustic heating from granular convection. This promising idea had to be abandoned because acoustic waves are reflected by the low chromosphere and do not propagate further out in the chromosphere and so are ineffective (they are standing waves). The consensus now points to the role of magnetic fields, say by the dissipation of propagating MHD waves via ohmic heating (Narain and Ulmschneider, 1990; Golub & Pasachoff, 1997). Recently the Ultraviolet Coronal Spectrometer aboard SOHO has detected such vibrating waves accelerating particles by a process analogous to ‘surfing’ (Crammer et al 1999). Another concept, possibly more controversial but easily understood, is an idea by Scudder (1994) wherein the high velocity tail of particle velocity distribution gives rise to shocks in the tenuous corona.

7. Infrared Spectral Diagnostics

Magnetic fields in the corona can be inferred by several means but direct measurements would be desirable. Because the effective Zeeman splitting is proportional to wavelength there is a large advantage to making measurements in the infrared. An airborne IR spectrometer was flown by Olsen et al. (1971) at the eclipse of 7 March 1970. They observed the outer chromosphere and inner corona from 1 to 3 $\mu$m and found 13 emission lines. Their spectra were re-examined by Kaster (1993) who updated assignments based on improved data. Judge (1999) has predicted a number of forbidden transitions including that of Si IX at 3.94 $\mu$m. Oliva et al. (1994) have observed Si IX at 3.934 $\mu$m in a Seyfert galaxy. Kuhn et al. (1998), using a narrow-band filter and imaging the corona at the 26 February 1998 eclipse, may have detected emission from the Si IX line. Lynch et al. (1999) propose to search for IR lines in the eclipse of 21 June 2001 using spectrographs designed to cover large areas of the corona. The results could be important for the design of the proposed Advanced Solar Telescope, an instrument of perhaps 3-4 meters aperture.

8. Fine Structure in the Corona

High resolution W-L images permit us to visualize what is believed to be current sheets well inside the corona. They are seen as tangential discontinuities (TDs)
Figure 3. Details in the inner corona from an observation at the 3.6 m CFHT on 11 July 1991. This may be the highest resolution W-L coronal picture ever obtained.

with a corresponding jump in gas pressure. Signatures of extended TDs have been seen as a sharp edge to streamers imaged using a neutral radial filter (Koutchmy, 1971). These TDs are seen over many radial scale heights which means that a radial and rather laminar flow is responsible for the existence and the stability of these structures. They are also good candidates to be the source of the slow solar wind. Additionally, reconnections could occur inside the sheet, starting at a certain distance from the Sun, as a result of instabilities and/or the influence of the outer more global field, producing plasmoids or fragments or detachments (Koutchmy et al. 1973) and releasing some energy. Recent SoHO observations made using the Lasco-C2 W-L coronagraph produced movies showing the more external parts of the corona with very convincing evidence of flows seen over the structures; they were called “blobs” by the Lasco Observers and their origin is certainly related to the discontinuities appearing in the low corona and seen during eclipses.
In the inner corona the brightness is such that images can be taken with very short exposure times during eclipses. This was done in 1991 at the focus of the CFH telescope in Hawaii (Mauna Kea) and the best resolution W-L images were obtained, see Figure 3. Many overlapping loops and multiple sharp threads are seen confirming that the magnetic field is shaping all structures but that dynamical effects are also important. This last point is certainly better studied based on spectroscopic diagnostics which are also used at eclipses.

9. Time

Historic records of eclipses, which extend back 4 millenia, can be used to investigate the rotation of the Earth (Stephenson 1997; Crump 1999). Many ancient records are questionable; the exact date and even the place having been ‘adjusted’ to fit important events like battles or the death of kings. Stephenson discusses this and concludes that the Babylonian eclipse of 15 April 136 BC is probably reported correctly because it is clearly described on cuneiform tablets in the British Museum without reference to any particular occasion. Assuming the Earth’s rotation to be constant and the same as today, a computer simulation places the 136 BC eclipse about 5000 km west of Babylon, Figure 4. Taking into account tidal forces, which slow the rotation, the prediction is for 2000 km east of Babylon. Geophysicists propose a number of factors to account for this error. Like changes in the polar ice-cap from post-glacial melting, or sea level changes associated likewise with the evolution of glaciers.
10. Conclusions

It has been suggested that the Golden Age of eclipse science is over. We have presented some of the principle results from that era: the concept of cosmic magnetism, the verification of the Einstein bending of light, a knowledge of the physical state of the chromosphere and corona including the development of non-LTE diagnostics that are now commonplace for stellar and galactic science. We foresee eclipse science continuing to prosper, however, with increased observations in the IR and the use of the new CCD detectors to perform high resolution images and sophisticated spectroscopic diagnostics.

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