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THE ECLIPSE EXPEDITIONS OF THE LICK OBSERVATORY AND THE DAWN OF ASTROPHYSICS

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ABSTRACT

Between the years 1898 to 1932, Lick Observatory organized a series of 17 solar eclipse expeditions, many to remote regions of the world. The science of these expeditions involved three issues of major significance in the development of astrophysics during the first three decades of the 20th century: (1) testing of General Relativity; (2) the physics of non-equilibrium stellar atmospheres; and (3) the role of magnetic fields in solar physics. The responses to these issues provide intriguing insights about the dynamics of paradigm change within astronomical culture, as well as culture in general.

KEYWORDS: solar eclipses, solar corona, magnetic fields, General Relativity, non-local thermodynamic equilibrium, cultural astronomy

1. INTRODUCTION

During the years 1898 to 1932, Lick Observatory organized 17 solar eclipse expeditions, which were all the more noteworthy because for most of this time few on the staff at Lick Observatory had a serious research interest in the physics of the solar corona. The science of these expeditions involved three issues of major significance during the development of astrophysics during the first three decades of the 20th century: (1) testing of General Relativity; (2) physics of non-equilibrium gas of the solar chromosphere; and (3) the role of magnetic fields in a hot corona. (Golub and Pasachoff 2010; Pearson 2009; Crelinsten 2006).

Figure 1 Lick Expedition to Jeur India 1898 (Mary Lea Shane Archives)

The responses to the issues raised by these eclipses among the astronomical community provide some fascinating insights into the culture of astronomy and about the processes of paradigm change within that culture. Although the shape of the corona suggests the presence of a magnetic field, the idea of a hot corona structured by magnetic fields was difficult for the astronomical community to accept during the first third of the 20th century. There was a delay of 30 years between Hale's measurement of magnetic fields in sunspots until the magnetic nature of the hot corona was accepted. In contrast, there was an extraordinarily quick acceptance of General Relativity by the community of European astronomers and physicists, following the report of a confirmation of Einstein's prediction of deflection of starlight results by Dyson and Eddington for the 1919 eclipse. The enthusiasm of the British press in response to this report played a large role in the rapid acceptance of General Relativity. Unfortunately, Eddington's results were flawed, since one-third of data had to be discarded to achieve the predicted deflection. The definite confirmation of Einstein's prediction was achieved by the Lick expedition to Australia in 1922, led by W. W. Campbell (Earman and Glymour 1984; Crelinsten 2006; Pearson 2009; Golub & Pasachoff 2010).

The importance of non-local thermodynamic equilibrium (non-LTE) in extended atmospheres of stars, nebular, and the upper atmosphere of the earth was difficult to accept by astronomers because it enormously increased the difficulty of analyzing the spectra of stars and nebulae. It took some 20 years after Donald Menzel demonstrated non-LTE in the solar chromosphere for it to be fully accepted by the astronomical community.

2. CULTURAL CHANGE

These paradigm changes that contributed to the emergence of astrophysics in the 20th century can be viewed from the perspective of what anthropologists describe as processualism, i.e., cultural evolution driven by cultural or environmental processes. These changes that happened in the astronomical community in the early 20th century may shed light on the broader anthropological issue of cultural change. The emergence of new paradigms among the astronomical community appears similar to changes when self-organized systems become metastable, reaching critical and unstable states (Bak and Sneppen 1993; Kaufman 1995; Malville 2009). Bak (1996) identifies this state as one of self-organized criticality. In this condition a system is open, such that energy and information can flow inward and outward. When the system becomes thusly metastable, it achieves self-coherence. Its parts are no longer independent but behave cooperatively. Small perturbations upon a metastable system can cause major and sudden transformations. For example, a supersaturated salt solution is metastable in that the addition of a small amount of salt may cause the solution suddenly to transform into a solid. Another example is a pile of sand that has reached the angle of repose (Bak 1996). The addition of each new grain of sand will induce cooperative behavior of the sand grains and will trigger avalanches. Sometimes these perturbations will transform the system into states of higher complexity, while on other occasions the system may be essentially destroyed.

Examples of self-organized criticality in other cultures include the Andean world, which gradually transformed over millennia, culminating in the large-scale organization of the Inca empire, and the pilgrimage center of Varanasi, which displays cooperative behavior of populations throughout much of northern India (Malville 2014a, b).

3. THE LICK EXPEDITIONS

Soon after the 36″ refractor saw first light in 1888, the first director of Lick Observatory, Edward Holden, convinced San Francisco banker Charles Crocker to fund solar eclipse expeditions. Holden was interested in testing his idea that coronal filaments were produced by streams of meteorites falling into the sun. The first Lick expedition, on January 1, 1889, was a relatively modest expedition to Bartlet Springs, California, to test Holden's hypothesis. Holden's drawing (Figure 2) of the eclipse, showing extensive polar streams, should have laid to rest his theory about meteor streams and, as seen with 20-20 hindsight, should have revealed the presence of a coronal magnetic field.

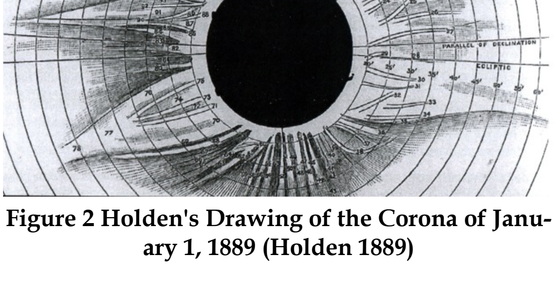

Figure 2 Holden's Drawing of the Corona of January 1, 1889 (Holden 1889)

The majority of the following expeditions were to foreign countries, many requiring extensive preparation and travel. W.W. Campbell, who became director in 1901, took over leadership of the expeditions. Campbell considered the radial velocity program made with the 36″ refractor, supplemented by southern hemisphere observations in Chile, to be the most important work of the observatory. Eclipses were also a high priority of Campbell's, and his approach to them was consistent with his belief in the importance of the collection of comprehensive archival data. As a skilled and careful spectroscopist, he initiated the program of spectroscopy of the chromosphere during eclipses, although any effort he put into analysis of the chromospheric spectra after the expeditions was minimal.

4. THE HOT CORONA

Beginning with the expedition to Chile in 1893, the Schaeberle 40-ft camera became the primary instrument for photographs of the corona (Pearson 2009; Pearson and Orchiston 2008). Schaeberle was interested in evaluating his own mechanical theory that coronal forms were produced by volcanic forces emanating from sunspots. Although he noted that the structure of the corona was similar to two opposite magnetic poles, Schaeberle never proposed that magnetic fields determined the structure of coronal filaments. Using multiple images from his 40' camera, Schaberle produced a diagram of coronal filaments, which look to modern eyes remarkably similar to maps of coronal magnetic fields (Figure 3). He traced filaments downward to prominences and active regions of the chromosphere revealed in spectroheliograms Hale had acquired at Yerkes Observatory. Consistent with Schaberle's diagram, Lockyer (1903) had shown a connection between sunspots and the number and type of coronal streamers. A fascinating insight into the difficulty of paradigm change is provided by the anomalous feature in the lower right-hand portion of the diagram that is labeled as "comet". Schaberle's mechanical model of the corona ignored any electrical and mechanical forces and could not explain this odd feature. It has now been identified as a disconnected coronal mass ejection propelled outward by magnetic forces (Cliver 1989).

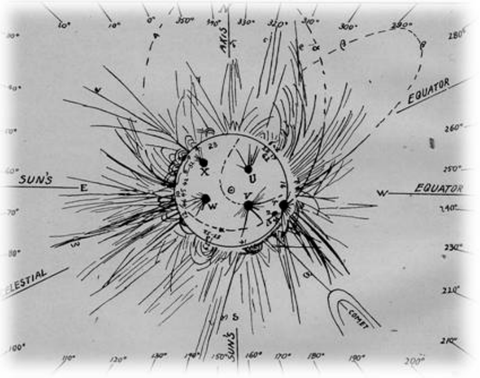

Figure 3 Drawing of coronal structures by Schaeberle: total eclipse 16 April 1893. A coronal mass ejection, labeled as a comet, appears in the lower right-hand side of the figure.

When Hale measured magnetic fields in sunspots in 1908, it should have been a small step to propose that prominences were supported by magnetic fields, which extended into the corona, and that the coronal streamers above active regions were aligned with magnetic fields. Hale had been encouraged to search for magnetic fields in sunspots by the apparent magnetic orientation of solar floculi near spots. Alignment of coronal streamers could have led to a similar insight, but alignment of material by magnetic fields would have been highly unlikely in a cool corona.

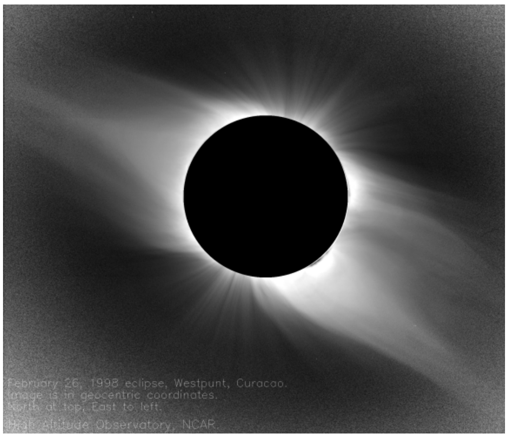

Figure 4 Eclipse of 1998 using the Newkirk camera, showing the fine details of coronal structure produced by magnetic fields (High Altitude Observatory)

Non-magnetic interpretation of the corona continued to dominate the thinking at Lick and elsewhere in the astronomical community. In 1918 Campbell still believed that coronal matter could be transported by volcanic force and radiation pressure.

In the following decade astronomers came tantalizingly close to appreciating the role of magnetic fields in the corona. A hot corona was certainly hinted at by its large-scale height. Likewise, the width of the green coronal line λ5303 Å indicated either turbulence or a high temperature. The magnetic character of prominences, which extend into the corona, should have been another clue. But the community of solar astronomers did not venture such serious speculation.

Figure 5 Prominence photographed at Principe during the eclipse of 1919, showing a helical magnetic structure (Royal Astronomical Society, London)

The nature of the corona was indeed recognized as a major problem in astrophysics. The sources of the green, yellow, and red coronal lines at λ5303 Å, λ5694 Å, and λ6374 Å were particularly vexing puzzles. The element "coronium" had been suggested as the source, which, it was speculated, had an atomic weight less than hydrogen because of the large-scale height of the corona gas. The source of the prominent yellow-green line λ5577 Å in the earth's aurora was a similar puzzle. In 1911 Alfred Wegner, of continental drift fame, developed a detailed thermodynamic model for the earth's atmosphere and suggested the auroral yellow-green line was produced by geocoronium, a terrestrial variant of coronium. Because the aurorae were produced high in the earth's atmosphere, Wegner also suggested an atomic weight less than that of hydrogen. The suggestions that these mysterious elements had masses less than hydrogen did not garner very much traction, because Bohr's 1913 model of the hydrogen atom and the lack of space in the Mendeleev table rendered the existence of such elements highly improbable.

Nebulium, which had been proposed for similar reasons, was explained in 1927 as the result of forbidden transitions of oxygen and nitrogen. In 1933 Walter Grotrian noted that the breadth of photospheric H and K lines scattered in the corona indicated a temperature above a million degrees, but he still could not bring himself to suggest such a high temperature for the corona.

Grotrian was one of the advisors of Karl Kiepenheuer, who prepared his thesis *On the Theory of the Solar Corona* at Potsdam Observatory and was awarded his Ph.D. in 1935. In his thesis Kiepenheuer investigated the role of the magnetic fields in the dynamics and structure of the corona. In particular, he proposed that coronal streamers were formed by streams of ionized particles moving along magnetic fields. Kiepenheuer's thesis broke new ground in coronal physics, in which he developed the concept of frozen-in magnetic fields independently of Hans Alfven. However, based upon the understanding of the corona in 1934-35, he could not propose a hot corona.

The breakthrough came from an unexpected direction, namely the suggestion that the red line of the corona was the result of two unlikely physical conditions: (1) a forbidden transition from (2) a highly ionized form of iron. The stage had been set by identification of Fe VI and Fe VIII emission lines in the recurrent novae RS Oph and Nova Pictorus. High temperatures in a violent and explosive nova were not surprising, but the solar corona was something else. Finally, in 1939 Grotrian (Golub and Pasachoff 2010) showed that the red coronal line could be identified with a forbidden transition of Fe X, based upon Edlen's laboratory measurements of far ultraviolet lines near λ95 Å produced in a spark discharge. The temperature of the spark discharge was about 500,000K. A direct observation of the red line was not possible because the density of the gas in the discharge was too high to allow forbidden transitions. With remarkable rapidity, the green and yellow coronal lines were identified with highly ionized Fe XIV and Ca XV. It is as if there had been a sigh of relief by solar astronomers to discover the true nature of the corona, and, especially after the war, there was a flood of new studies of the corona. Although its high temperature was well established, the mechanism for coronal heating remained elusive for several more decades.

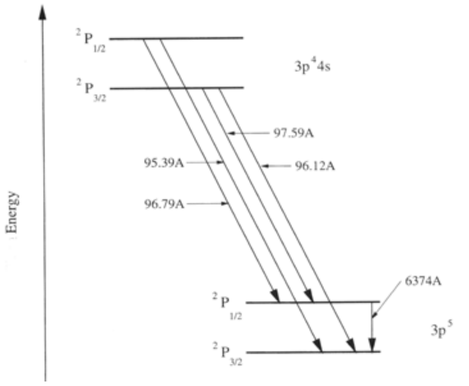

Figure 6 Portion of the term diagram for Fe X, showing Edlen's measured far UV lines and Grotrian's calculation for the red coronal line 6374 Å (Golub and Pasachoff 2010)

5. TESTING EINSTEIN

Once Campbell became director, photography of the corona became mainly an archival program of systematically documenting the shape and brightness of the corona. Part of his program was the unsuccessful search for the planet Vulcan, which, it was argued, would better explain the precession of the perihelion of Mercury than would General Relativity. With his Vulcan cameras (Figure 7) Campbell was well placed to test another feature of the theory, namely the deflection of starlight near the edge of the sun. He approached the challenge of measuring the Einstein deflection with considerable distrust of the theory and was thus an excellent person to subject the hypothesis to severe and unbiased testing.

Einstein had given two arguments for the deflection of light passing near a massive body such as the sun. One, provided in 1911, before the General Theory was fully developed, relied on the Principle of Equivalence and involved a deflection of 0.83 seconds of arc, while the other, provided in 1916, was based upon his own approximate solution to his gravitational field equations, amounted to 1.7 second of arc.

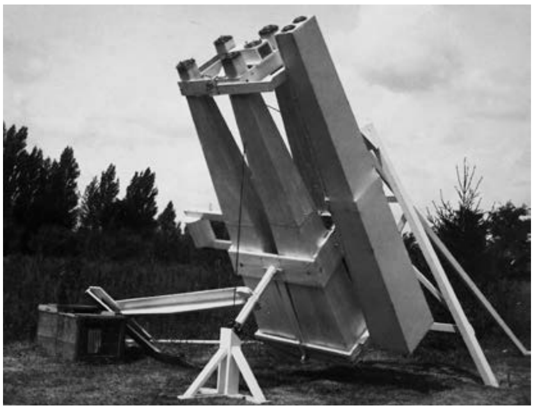

Figure 7 Einstein-Vulcan Cameras in Russia 1914 (Mary Lea Shane Archives)

Campbell first attempted to test for the predicted deflection in Russia in 1914, but that expedition was clouded out. He again attempted in 1918 at Goldendale, Washington, using less than satisfactory instruments, because the instruments he had designed for the 1914 eclipse had been impounded in Russia.

Frank Dyson, the astronomer royal and director of the Greenwich Observatory, was principally responsible for organizing the expeditions to Principe, which was led by Arthur Eddington, and to Sobral, Brazil in 1919. Campbell did not have time to organize an expedition to that eclipse because of the war.

It is possible to concludethat the real reason Eddington led the expedition to Principe was to keep him out of jail for being a pacifist during World War I (Teukolsky 1997; Earman and Glymour 1984). At the eclipse Eddington had difficulty with his equipment, partly due to clouds. Only six of his 16 plates showed stars, and those contained no more than five stars each. His plates gave a limb deflection of 1.61 seconds of arc**.** Dyson's team in Sobral was more successful and obtained measurements both larger and smaller than the predicted value of 1.75 seconds of arc.

The natural conclusion from these results is that gravity definitely affects light, and that the gravitational deflection at the limb of the sun is somewhere between a little below 0.87" and a little above 2.0". For a number of reasons Eddington and Dyson discarded the Sobral Astrograph result and thereby achieved an average close to the Einstein prediction. In retrospect, it was a shrewd decision for Eddington, the theorist who had been an outspoken advocate for the General Theory, but it would not have been the approach of an experienced experimentalist, especially if so doing would verify the desired result.

These results, without the Sobral astrograph results, were communicated to the world at a joint meeting of the Royal Society and royal Astronomical Society. The public reception to this announcement was extraordinarily enthusiastic, and Einstein was catapulted into the position of the world's most brilliant scientist. In contrast to the enthusiasm in Great Britain, American astronomers were cautious. When Campbell learned of the announced results, after refusing to publish his own results from the Goldendale eclipse, he commented: "Professor Eddington was inclined to assign considerable weight to the African determination, but, as the few images on his small number of astrographic plates were not so good as those on the astrographic plates secured in Brazil, and the results from the latter were given almost negligible weight, the logic of the situation does not seem entirely clear" (Crelinsten 2006:149).

Earlman and Glymour (1980) suggest that for Eddington, the pacifist, one of the chief benefits to be derived from the eclipse results was a rapprochement between German and British scientists and an end to talk of boycotting German science.

Campbell, however, was very loath to release or accept an experimental result if it might contain an error. After the initial flurry of excitement following the announcement by Eddington, skepticism developed among many astronomers and physicists, especially in the U.S. The Nobel committee, cognizant of the uncertainties associated with the General Theory, awarded Einstein the 1921 Nobel Prize for his work on the photoelectric effect rather than for either Special or General Relativity (Crelinsten 2006).

Instrument	Standard deviation	Deflection
Sobral Astrograph	0.48"	.86
Sobral 4"	0.178"	1.98
Principe astrograph	0.44	1.61

Recognizing the weakness of the Principe/Sobral measurements, Dyson organized a second expedition, led by Harold Spencer Jones, to observe the eclipse of 1922 from Christmas Island. Eddington did not join that expedition.

Campbell pulled out all the stops in organizing his expedition to the remote Ninety-Mile Beach at Wallal, Australia, wishing to perform the definitive experiment to settle the matter once and for all. He dispatched Robert Trumpler to Tahiti three months before the eclipse to obtain comparison plates. To Wallal he brought two pairs of newly designed cameras.

That British expedition was clouded out. It was clear in Australia, and the astronomical community waited upon Campbell for the final word on the test of General Relativity. Unlike Eddington, he was not interested in establishing a détente with Germans, whom he disliked, partly because his three sons fought in the war. Before he completed measuring the plates, Campbell replied to a question of what he would find: "I hoped it would not be true" (Douglas 1957:44).

The task of measuring and reducing the plates taken at the 1922 eclipse was shared with Robert Trumpler. Both Campbell and Trumpler independently measured the plates, which contained at least 128 stars ranging in distance above the limb from 33' to 170'. It is to Campbell's great credit that the results published jointly with Trumpler confirmed the predictions of Einstein with higher-quality data than what Dyson and Eddington had been able to achieve, obtaining a deflection at the limb of 1.72" ± .11". Personally, Campbell was converted into a staunch advocate of General Relativity.

It is remarkable that the results of Campbell's meticulously planned expedition have not been improved upon. Fifty years were to elapse before a comparable experiment was mounted by a team from the University of Texas and Princeton University (Texas Mauritanian Team, 1976) at the eclipse of 30 June 1973. The team measured 160 stars and obtained a shift of 1.66" ± 0.18". It is to be judged a successful experiment, but it failed to improve upon those of Campbell and Trumpler. The most precise measurements have been of quasars, using long base-line radio interferometry, achieving a precision of 0.02% (Will 2006).

Throughout the 1920s, predictions of the gravitational red shift of light in the sun and in Sirius B were confirmed by St. John and Adams, establishing further the credibility of the General Theory (Crelinsten 2006). In 1931 Einstein visited Pasadena and posed with Campbell under a portrait of George Ellery Hale (Figure 8). Also in the photograph are Milton Humason, Edwin Hubble, Charles St. John, A. A. Michelson, and Walter Adams. In Figure 8 Einstein is flanked by the ebullient Michelson and Campbell, the converted skeptic. The two have notably different demeanors.

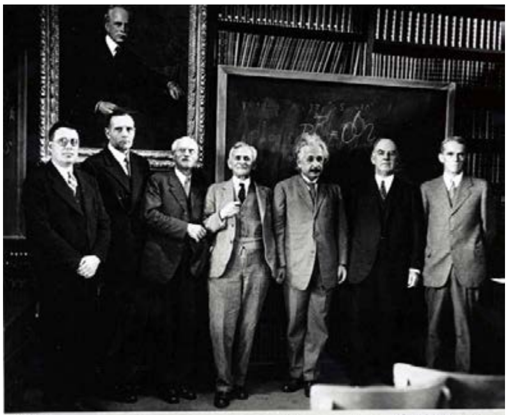

Figure 8. Einstein in Pasadena in January 1931 underneath a portrait of George Ellery Hale. (Carnegie Observatories)

6. NON-LOCAL THERMODYNAMIC EQUILIBRIUM IN THE CHROMOSPHERE

Donald Menzel joined the staff of Lick Observatory in August 1926 as their first astrophysicist. Osterbrock (2002:100) describes him as a "stranger in a strange land." He was assigned to the all-important radial velocity program, but most importantly, he was also given the analysis of the flash spectra taken by Campbell in the eclipses of 1898, 1900, 1905, and 1908. This project consumed most of his time for four years, and he finished it in June 1930. His work shows a truly extraordinary grasp of quantum mechanics and atomic physics in its earliest stages, especially for someone living in physical and relative intellectual isolation on Mt. Hamilton. He started on this project when quantum mechanics was truly in its infancy. Just eight months before Menzel arrived at Lick, Schrodinger had started publishing his four basic papers on wave mechanics. And later that year, in October 1926, Schroedinger and Bohr had their famous long and exhausting (for Schroedinger) debates about his wave mechanics and the matrix mechanics of Heisenberg. Somehow, without paying a visit to Europe, Menzel was able to master quantum mechanics. It wasn't until the fall of 1929, when J. Robert Oppenheimer began lecturing in Berkeley on quantum mechanics, that Menzel could learn from him and collaborate with him.

The beginning sentence of Menzel's major monograph (Menzel 1931) on the chromosphere conveys his sense of the revolutionary nature of the endeavor: "Physicists and astronomers are becoming 'atom-minded."

Campbell and Acting Director Robert Aitken approved of Menzel's project, as they were eager to get results from their many expensive expeditions, but Aitken didn't particularly approve of Menzel's occasional departures from the mountain to consult Oppenheimer and others.

As we now understand, in a thin gas, temperature can be defined by a number of atomic processes (Shklovskii 1965):

1) Excitation temperature based upon the Boltzmann formula;

2) Ionization temperature based upon the Saha equation;

3) Radiation temperature based upon the Planck equation;

4) Temperature based upon the Maxwellian velocity distribution.

In a gas that is in thermodynamic equilibrium all these temperatures are equal. In thin gasses such as the chromosphere and corona these four temperatures may have wildly different values. In that case all individual atomic processes need to be calculated, requiring knowledge of atomic parameters such as transition probabilities and collision cross sections.

Menzel concluded there were large departures from thermodynamic equilibrium in the chromosphere. Campbell and Aitken were taken aback by his results concerning large deviations from thermodynamic equilibrium. The differing radiation, ionization, and electron temperatures evidenced in the chromosphere were indeed worrisome, as they cast doubt upon standard approaches of analyzing stellar atmospheres and gaseous nebulae.

Menzel left Lick and started at Harvard on 1 September 1932, a day after observing the total eclipse from Fryeberg, Maine. At Harvard he began a series of influential papers on the analysis of the physical conditions in nebulae, which demonstrated major departures from local thermodynamic equilibrium (LTE). These papers laid the foundation for nebular astrophysics. His approach in analyzing extended stellar atmospheres, nebulae, and other dilute gasses was not fully implemented for at least two decades because of the difficulty of the calculations and the lack of the necessary atomic parameters. Menzel's work was carried to fruition by Richard Thomas, a student of Menzel, and Grant Athay, a student of Thomas, by their monograph on the physics of the chromospheres (Thomas and Athay 1961), published 30 years after Menzel's monograph at Lick. Thomas and Athay used data from the excellent chromospheric spectra obtained during the 1952 eclipse expedition of the High Altitude Observatory to Khartoum. By the 1950s it became clear that non-LTE were so dominant in extended atmospheres, gaseous nebulae, and aurorae that extensive knowledge of atomic parameters such as collision cross-sections and f-values were needed. The Joint Institute of Laboratory Astrophysics (JILA) was established in Boulder for the explicit purpose of obtaining the atomic measurements needed for analysis of stellar chromospheres and other non-equilibrium gasses.

7. FINAL REMARKS

During the 34 years of their eclipse expeditions, Lick Observatory was caught up in a number of paradigm shifts, as well as the transformation of astronomy into astrophysics. Acceptance of a hot corona threaded by magnetic fields was painfully and surprisingly slow. The acceptance of General Relativity following the flawed observations of Dyson and Eddington was swift in contrast, partly due to the enthusiasm of the popular press in Great Britain. Campbell did more than simply "confirm" the Dyson and Eddington measurements. He provided the first satisfactory test of Einstein's prediction and deserves more credit than he normally receives for his integrity, persistence, and skill in testing Einstein's prediction.

As viewed from the perspective of cultural change and transformation of self-organized systems, the large and robust culture of physicists interested in Einstein's General Theory of Relativity reached criticality much faster than the smaller culture of astronomers interested in the solar corona. Eddington's contribution was more modest than that of Campbell, but the 1919 eclipse data arrived at such a time that they were sufficient to transform an already critical system. The 50 years of observational and theoretical indications of a hot corona, starting with Holden's observations, failed to transform the understanding of the corona until the measurements of Edlen appeared on the scene. After that revelation, the physics of the solar corona was dramatically changed and the hot corona became an important aspect in the flourishing of astrophysics in the second half of the 20th century.

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