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From the ionosphere to high energy astronomy – a personal experience

In the first half of the 20th century, recognition of the existence of an electrified layer of the upper atmosphere that provided a mode for radio communication over great distances on the Earth grew with little sense of the role of invisible solar radiation in creating the electrical mirror. Solar radiation was thought to be black-body in spectral shape characterized by a temperature of 6000 K with a maximum in the yellow-green, trailing off rapidly in the infrared and ultraviolet. None of this spectrum could produce significant ionization of the major constituents of the atmosphere.

X-rays were discovered by Wilhelm Röntgen shortly before the turn of the century and Guglielmo Marconi, a few years later, demonstrated trans-Atlantic radio communication via a high altitude, natural electrical mirror. Several ingenious physicists and electrical engineers pursued the problems of radio reflection but had few clues to the nature of the solar radiation that keyed the phenomena of ionospheric production and variability. The true nature of solar ionizing radiation remained a baffling puzzle until after WW II when the availability of rockets to carry detectors directly into the ionosphere finally made the studies definitively diagnostic. Captured German V-2 (Vengeance) rockets while being studied by propulsion engineers were also turned from "weapons into plowshares", when they were adapted to ionospheric studies.

To preface the story of the modern era it is interesting to sketch the early ideas of radio propagation science. The perceptions of solar-terrestrial connections had developed slowly over most of the 19th century. Lord Kelvin, one of the most influential physicists of his time, was adamant in rejecting any notion (Kelvin 1892) "that terrestrial magnetic storms are due to the magnetic action of the Sun; or to any dynamic action within the Sun, or in connection with hurricanes in his atmosphere, or anywhere near the Sun outside." Furthermore he held strongly "that the connection between magnetic storms and sunspots is unreal and the seeming agreement between the periods has been mere coincidence." Kelvin's enormous prestige discouraged any dispute and set back solar-terrestrial research for decades.

Toward the end of the 19th century Colonel Sabine of the British army monitored a network of magnetic observatories throughout the empire and noted that by "a most curious coincidence" the magnitude and frequency of magnetic disturbances was synchronized with the appearance and disappearance of sunspots. The direction of the compass needle swung in regular fashion over the diurnal cycle, but at times the movements became more intense and rapid in the auroral zone, giving rise to the name "magnetic storms". It was commonly believed that interplanetary space was a vacuum and that auroras were excited by direct streams of particles from Sun to Earth unimpeded by any interplanetary medium. By timing the appearances of auroras and magnetic storms relative to the visible outbursts of flares on the Sun, the travel speed was calculated to be about 800 km per sec, slower than light, but consistent with concepts of particle streams.

Friedrich Gauss, the great German mathematician-physicist-astronomer, as early as 1839, related fluctuations in the compass needle to the passage of electric currents at high altitudes. In 1882, the Scotsman, Balfour Stewart, defined these currents as a great dynamo of tidal movements of ionized air above 100 km that were driven by solar heating. The vertical movement was only 2 or 3 km, but it was sufficient to generate a great horizontal current sheet of electricity. Observations near the geomagnetic equator indicated circulating systems of electric currents of opposite symmetries in the northern and southern hemispheres. At

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the equator the currents joined to form a strong flow from west to east at 1100 local time, that Sidney Chapman, in the early 20th century, named the Equatorial Electrojet.

The young Guglielmo Marconi at age 21, in 1895, built a demonstration wireless telegraph on his father's estate near Bologna, Italy. On December 12, 1901 he transmitted a simple Morse code signal from England to Newfoundland, a distance of 2900 km to the astonishment of most scientists who could not fathom how the waves, that were thought to travel in straight lines, could curve over the 160 km high bulge of the surface of the earth. In 1902, Arthur E. Kennelly proposed that the radio waves were ducted around the earth by an electrically conducting layer. Almost simultaneously, Oliver Heaviside reached the same conclusion and the layer came to be called the Heaviside layer. With the above background, the stage was now set for a more focused scientific attack on the nature of a reflecting layer, now called the ionosphere, that eventually came to be associated with solar X-rays. In England, ionospheric research was lead by Edward Appleton and his student Miles Barnett [1925]; in the United States studies were conducted by E.O. Hulburt and A. Hoyt Taylor at the Naval Research Laboratory [1926] and by Gregory Breit and Merle A. Tuve at the Carnegie Institution [1926]. Successful experiments and interpretations were achieved almost simultaneously in England and the United States, both groups working from the ground. When German V-2 rockets were captured by the Americans, they moved ionospheric research into space and outraced the ground-based competition.

Appleton set out to determine the height of reflection of a continuous wave with the cooperation of the British Broadcasting Co. whom he persuaded to provide him with a continuously varying signal from London at the end of the broadcast day so that he could detect the interference pattern of ground and sky waves at Oxford. He observed the elapsed time between emission and reception of the same frequency, as the broadcast frequency was oscillated back and forth. Starting with low frequencies, Appleton probed only the lower portion of the reflecting layer; working later with higher frequencies, he distinguished layered regions of reflection, that he labeled D, E, and F. For these experiments, Appleton later received the Nobel Prize.

Much of the early research by NRL scientists was characterized by an admirable simplicity and economy of means. Hulburt and Taylor cooped the partnership of radio amateurs around the world who used vacuum tubes with power outputs of less than 50 watts and very short radio waves, less than 200 meters, to communicate around the world. Transmissions skipped over a "zone of silence" encircling the transmitter to a distance of 30 to 50 km and at the same time were received out to distances of hundreds of kilometers. Hulburt and Taylor showed that the waves were reflected only when the angle of incidence exceeded a critical value. At smaller angles the waves penetrated the reflecting region and escaped into space. At night, skip distances were greater than during the day and greater in winter than in summer in temperate latitudes. From these simple observations Hulburt calculated the height of reflection and the electron density (about 500,000 electrons and ions per cm^3 at a reflection height of about 150 km). By 1926, Hulburt and Taylor were able to publish a remarkably accurate account of the diurnal variation of ionospheric electron density. The work was almost coincident with Appleton's and Barnett's 1924–25 studies.

In the early years of ionospheric research, theorists speculated about particle radiation as a possible source of ionization of the upper atmosphere. Confronted with an apparent 6000 K solar spectrum it was not possible to model interactions of electromagnetic radiation with atmospheric constituents that would lead to the required ionization. Within the space of a decade after the end of WW II, however, the solar spectrum was revealed from its X-ray limit throughout the ultraviolet with instruments carried on rockets to ionospheric height. Ionizing radiation was observed in X-rays and ultraviolet from the solar corona and chromosphere, where temperatures range from hundreds of thousands to millions of degrees K, and every spectral interval was matched with its absorption at a particular height range.

Throughout this early epoch, some theorists still favored solar particles as the source of ionizing radiation. Confronted with the apparent 6000 K temperature of the solar disk (Figure 1) it wasn't possible to model atmospheric interactions with solar radiation that would lead to the required ionization. At the higher chromospheric and coronal temperatures shorter-wavelength extreme ultraviolet and X-rays would be produced but the particle concentrations

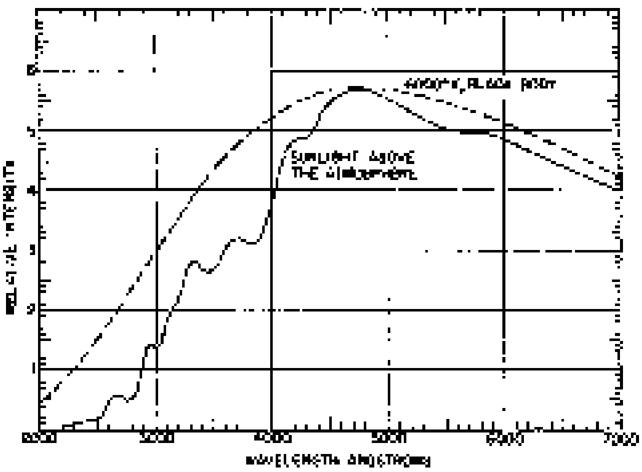

Figure 1 Solar spectral energy distribution from 2000 A to 7000 A compared with 6000 K black body sunlight above the atmosphere.

in the solar atmosphere were estimated to be too thin (emission measure too low) to provide high enough intensities to generate an E or F region. Appleton's early measurements of vertical reflections between midnight and sunrise showed that substantial concentrations of electrons or ions persisted throughout the night, contrary to the prevailing idea that charges would disappear rapidly by attachment once the source of ionization was removed. Radio scientists were thus led to believe that an important portion of the ionization might be produced by corpuscles arriving equally by both day and night. Because a charged particle stream could not readily penetrate the earth's magnetic field, serious thought was given to neutral particle streams.

In 1928, Hulburt proposed that ultraviolet radiation shortward of 1230 Å might be the source of the ionosphere. By 1930 he was intrigued by a possible connection between solar ultraviolet and sunspots and their link to magnetic storms and radio fadeout. In 1935, J.H. Dellinger at the U.S. National Bureau of Standards (NBS), summarized observations of a series of sudden ionospheric disturbances over a period of six months and stressed the importance of understanding the connection with solar activity. He proposed a joint effort of the NBS and the solar observatory on Mt. Wilson. During the same time frame, Robert H. Goddard was developing his rocket to carry instruments to high altitudes for atmospheric research. Correspondence between Hulburt and John Fleming reveals that Hulburt contemplated solar rocket astronomy to understand the basic physics of solar control of the ionization. He noted the theoretical match between atmospheric absorption of solar soft X-rays and the altitude of ionization and suggested that a good test would be to fly photographic film covered with thin aluminum foil or black paper in one of Goddard's rockets to detect X-rays.

Those early glimmerings of high altitude research with rockets were interrupted by the war but the new technologies of the war were soon transferred to peaceful research. In 1942, Ernst Krause in the radio division at NRL undertook to develop a program of guided missiles, specifically a new version of the German V-1 buzz bomb known as the JB-2 and the Lark, a rocket-propelled, guided ship-to-air missile. At the end of the war, Krause pursuaded NRL to commit to a substantial effort in rocket development for high altitude research which led to the resurrection of V-2 rockets late in the 1940s (see Figure 2). The first generation of successful studies of solar X-rays and extreme ultraviolet radiation began in 1949 when my NRL group flew a set of Geiger counters sensitive to a narrow band of X-rays centered at about 8 A, hydrogen Lyman-alpha (1216 A), and the Schumann region, 1425 to 1600 A. As the rocket climbed to an altitude of 150 km, the detectors pointing normal to the spin axis swept the sky repeatedly. X-rays were detected above 80 km with increasing intensity to

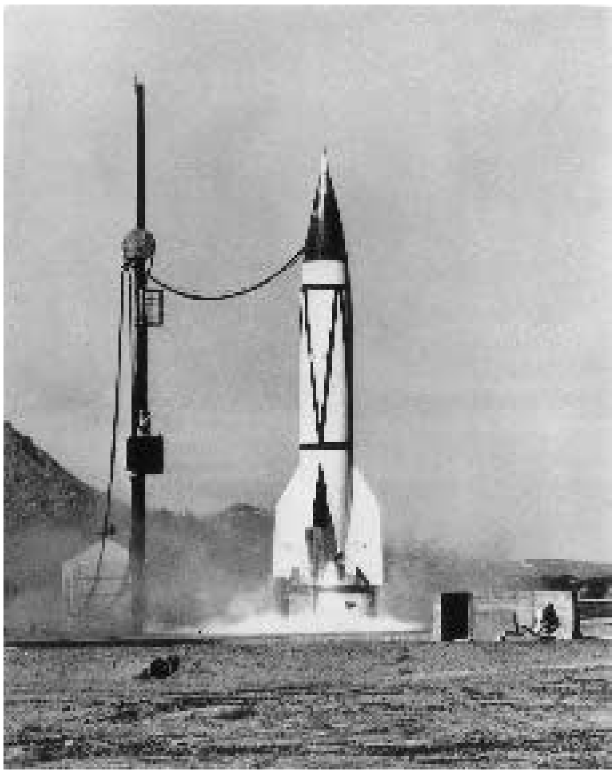

Figure 2 A V-2 rocket just prior to launch at the White Sands Proving Ground in New Mexico. About 45 feet tall and 5 feet in diameter it was fueled by 10 tons of alcohol and liquid oxygen. The rocket is shown connected by an umbilical cable to the firing line. To service the rocket and its payload a portable ladder was brought up. Only later was a gantry provided from which each level of the rocket could be reached comfortably. A successful flight could reach 170 km and last for 450 sec. (NRL.)

about 120 km (Figure 3). It appeared that a thermal corona at one to two million deg C made a good fit with the ionization requirement of the E-region.

The Lyman alpha detector and the extreme ultraviolet detector showed how those radiations shaped the bottom of the ionosphere and the upper part of the reflecting E-region. Lyman alpha, originating in the hot solar chromosphere at 10,000 K and higher, contains most of the energy in the extreme ultraviolet and is absorbed between 75 and 90 km but does not interact with any of the major constituents, oxygen or nitrogen, atomic or molecular. Only later on did M. Nicolet, the brilliant Belgian atmospheric scientist point out that it could ionize nitric oxide, a trace constituent present at only 10^8 molecules per cm^{-3}. with almost 100% efficiency and thus have control of D-region. Radiation in the Schumann region produced no ionization but played a very important role in shaping the high ionosphere by dissociating molecular oxygen. By the process of dissociative

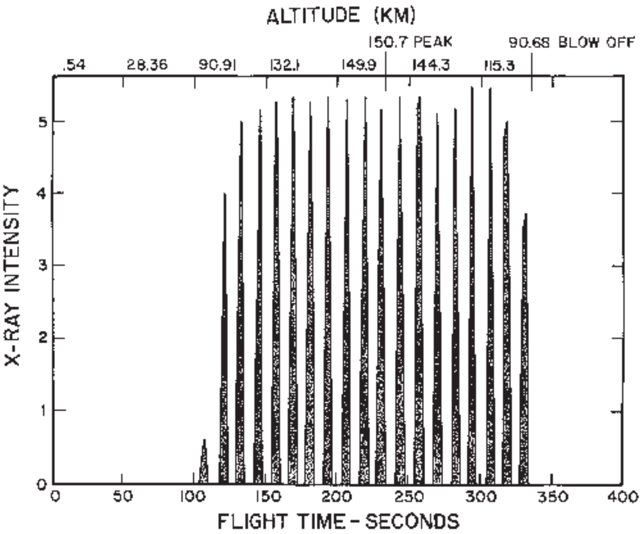

Figure 3 The first measurement of the penetration of solar X-rays into the upper atmosphere made by a V-2 rocket in 1949. The 8 A X-ray signal was modulated by the spin of the rocket as the Sun came into view once each roll period. X-rays were first detected at about 90 kilometers and reached peak intensity at about 130 km. (U.S. Naval Research Laboratory.)

recombination, molecular oxygen controls the rate of neutralization of F-region electron density much more effectively than atomic oxygen.

The 1949 measurement of harder X-rays (1–8 Å) led to several years of broad band photometry of solar X-rays that extended the range of the spectrum, primarily with the aid of simple filters of beryllium, aluminum, titanium, mylar, formvar, etc. serving as the window materials of the photon counters. It seems in retrospect that the NRL group was almost alone in that decade of pioneering studies of the Sun. The X-ray spectral distribution from 1 Å to 44 Å resembled thermal emission from a thin corona at a temperature of a few million degrees. Successive measurements at intervals of months to years showed flux variations of as much as a factor of 7 for X-rays (8–20 Å) over the sunspot cycle. Such variability was consistent with ionospheric electron density variations in the E-region, supporting a direct connection between solar X-rays and E-region. But the observed variability over a solar cycle made it clear that the concept of X-ray emission from a spherically symmetrical solar corona was very inadequate. Instead it seemed that the corona was structured in condensations, formed over sunspots, that produced enhanced X-ray emission. To resolve the question of spatial origin would require an X-ray scan of the solar disk or an X-ray photograph. Both methods were successfully applied at the end of the decade. The X-ray photograph was obtained with primitive pinhole photography (Figure 6); the scan required a very special combination of a total solar eclipse and an array of rockets launched from the deck of a ship.

SOLAR FLARES

Of all the forms of solar activity, flares are the most spectacular. A solar flare creates a strong impact on the terrestrial environment, producing prompt shortwave radio blackout that may last for two to three hours. The after-effects may persist for one or two days in the form of great auroral displays, and ionospheric and magnetic storms that seriously degrade shortwave radio communications.

The new arsenal of rockets that became available late in the 1950s made it possible to plan a program of solar flare studies. Although the supply of V-2 rockets was exhausted by 1952 it was replaced by smaller Aerobees and two staged rockets that mated the Deacon with a Nike booster or a Skyhook balloon. The latter combinations were particularly attractive for studies that required a form of instant rocketry. Launch from shipboard at sea offered range safety. By sailing downwind the ship could achieve nearly zero relative wind conditions for inflation and release of the balloon with its suspended rocket. The well deck aboard the U.S.S. Colonial measured 392 feet by 41 feet which we could use to store three trailer-truckloads of helium while the broad helicopter deck above served admirably for the balloon operations. The lumbering ship could make a speed of 15 knots which was slower than the expected drift of the balloon at altitude. To assure radio contact with the balloon payload we were assigned a destroyer, the U.S.S. Perkins that could track the balloon with a speed of 28 knots. Finally a crew of 650 sailors was tasked to man the ship for the naval chase.

Each day as inflation began, the polyethylene balloon, most of it draped in tight folds resembling the stem of an onion, rose 100 feet above the deck, crowned by a 20 foot bulge filled with 5000 cubic feet of helium that would expand further to thirty times that volume at altitude. The 12-feet long Deacon rocket dangled at the end of a 100-foot nylon line (Figure 4). At 80,000 feet, when a flare was observed in visible light, a radio command would fire the rocket and send it upward, piercing the balloon and rushing ahead another 50 or 60 miles through the ionosphere.

An NRL proposal for a naval expedition as part of the International Geophysical Year (IGY) to launch ten Rockoons for solar flare studies with the support of the USS Colonial, an LSD with a large helicopter deck, was approved by the Office of Naval Research. Our ship was a sea-going drydock. The operational plan was to release a Rockoon each morning on ten successive days and allow it to float at 80,000 feet until the onset of a solar flare was detected, when it would be fired. One flare was successfully observed

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