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Chapter 11

EARLY UPPER ATMOSPHERIC RESEARCH WITH ROCKETS*

Thor Bergstralh and Ernst Krause†

In late 1945, the Naval Research Laboratory established the Rocket Sonde Research Section to "investigate the physical phenomena in, and the properties of, the upper atmosphere". While investigating sourses of rockets adaptable for high altitude research, it was found that U.S. Army Ordnance had obtained a considerable number of V2 rockets from Germany and was contemplating firing them in the near future. Since one of the purposes the Army Ordnance had in mind was to obtain data on the upper atmosphere, they invited interested service and university groups, including the Rocket Sonde Research Section, to join in this part of the program.

On 16 January 1946, a meeting was convened at the Naval Research Laboratory to discuss the proposed V2 upper atmosphere research program, and at this meeting a V2 Upper Atmosphere Research Panel was formed to coordinate activities and ensure the most efficient use of the limited number of boosters. Panel membership was limited to persons actually working on the program, and consisted of personnel from the U.S. Army Air Forces' Air Materiel Command, the Applied Physics Laboratory, the Army Signal Corps Engineering Laboratories, Harvard University, Princeton University, the University of Michigan, the National Bureau of Standards, General Electric Co., and the Naval Research Laboratory.

Assembly, firing, and tracking of the V2s were the responsibility of the White Sands Proving Ground of Army Ordnance, with General Electric Co. operating under Army Ordnance contract [1]. The Aberdeen Ballistic Laboratory and the Army Signal Corps were responsible for tracking the vehicle to provide an accurate knowledge of its position and velocity throughout the trajectory. Data were obtained through optical, radar with beacon, and doppler tracking to provide critical information such as fuel burnout time, maximum altitude, and range at impact during and immediately after each flight. Detailed trajectory information required considerable analysis of flight data and was available on a longer time scale.

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† The Aerospace Corporation, El Segundo, California, U.S.A.

It was considered necessary to maintain the overall configuration and weight distribution of the missile essentially unchanged for aerodynamic and stability reasons. Therefore, the 2,200-lb. warhead had to be replaced by an equivalent-weight nosecone instrument chamber, instruments, electronics, and batteries. The first design [2] of a research warhead was constructed of 3/8-in. (0.95 cm) cast steel by the Naval Gun Factory and consisted of three sections: a nosetip, a forward conical section, and a main body, as shown in Figure 1. The nosetip section was used primarily for mounting atmospheric measurement devices, and the main body for housing equipment that required pressurization. The basic warhead was modified on some flights to accommodate special requirements [3].

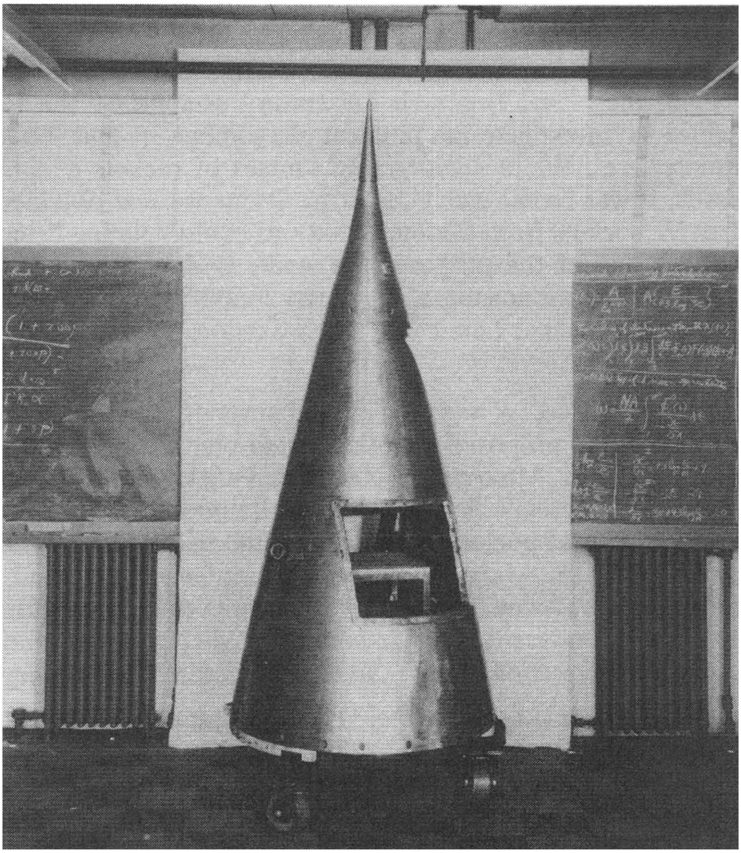

Figure 1 Research "warhead" for peacetime V2, 1946.

Research instrumentation and related equipment were also installed in various parts of the missile body, and a typical arrangement is shown in Figure 2. The telemetry transmitter and storage batteries for primary power were individually pressurized and generally installed in the control chamber just aft of the nose section. Cameras for photographing the Earth were mounted in the mid-section between the oxidizer and fuel tanks in some rockets. Solar spectrographs, antennas for ionospheric transmission studies, and telemetry antennas were installed in the tail fins.

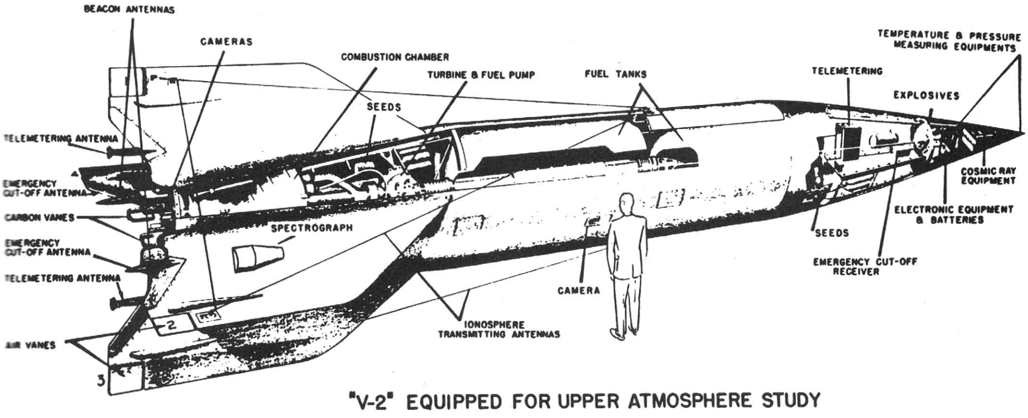

Figure 2 V2 modified for upper atmosphere research, 1946.

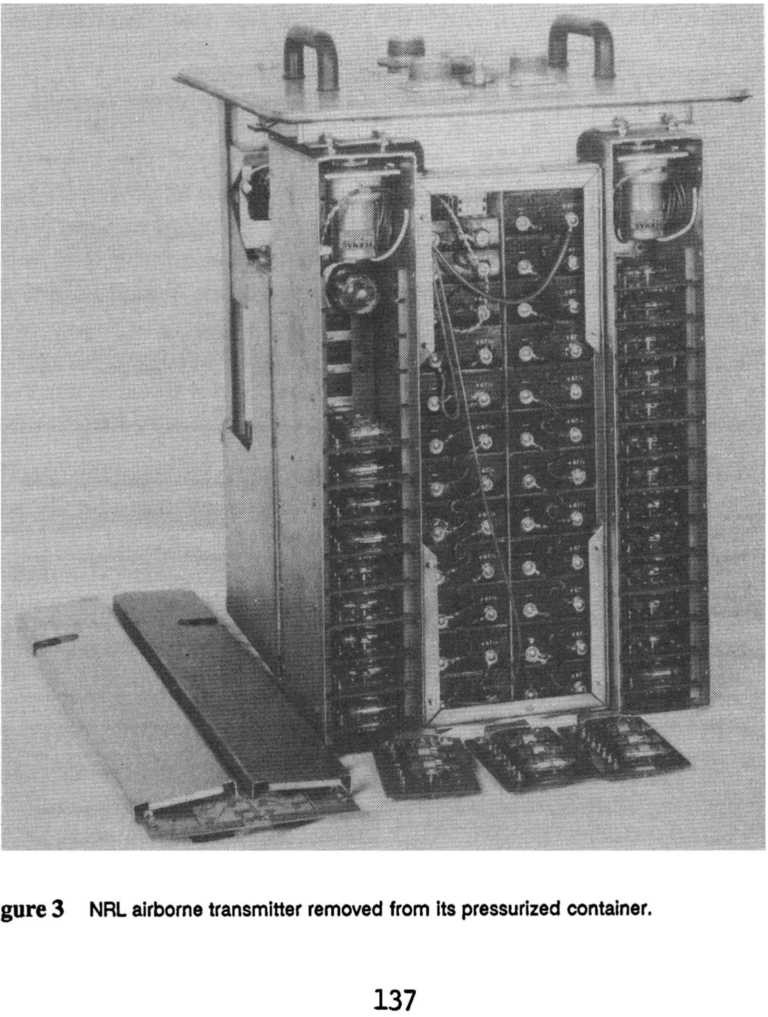

Figure 3 NRL airborne transmitter removed from its pressurized container.

At the outset of the program, radio telemetry was selected as the prime method of data recovery. A group at the Naval Research Laboratory [4,5] developed a 23-channel pulse-time-modulated airborne transmitter having a peak rf power of 1,200 w at 1,000 MHz. A later version provided 30 channels with a peak power of 3 Kw at 1,000 MHz. Up to 15 channels were equipped with mechanical subcommutators for slowly varying data such as temperature and pressure, so that a total of 345 channels of data could be transmitted at a sampling rate of 1 cps. Figure 3 shows the transmitter removed from its pressurized container. The circuitry for each channel was contained on a plug-in unit for ease of servicing. The entire unit was about 14 X 14 X 22 in. (35.5 X 35.5 X 56 cm) and weighed less than 150 lb. (68 kg).

Two independent ground receiving and recording stations were operated for each flight to provide redundancy. Each consisted of a 1,000-MHz antenna, receiver, video amplifier, multichannel decoder, and recording equipment. A typical record is shown in Figure 4. The top and bottom channels provided timing signals. The subcommutated channels at the top represent pressure and temperature information, each individual deflection corresponding to a different gauge. The roll gyroscope channel shows no roll since the vehicle was stabilized at this time in the flight.

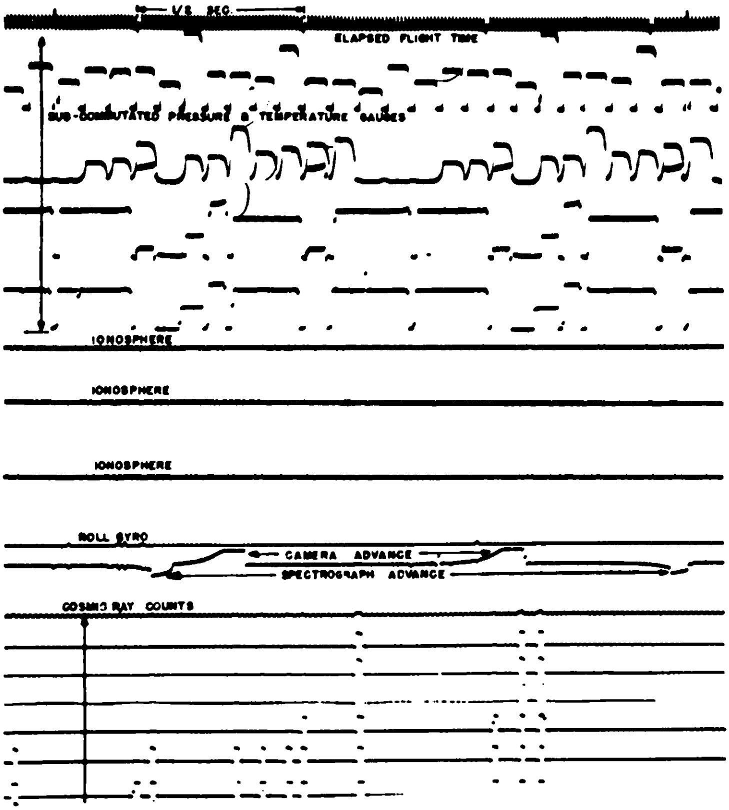

Figure 4 Typical radio telemetry record from V2 flight.

Preflight checkout was provided by a "relay" antenna system using a small dipole close to the transmitting antenna to pick up the radiated signal, which was then re-radiated from another dipole on a nearby 40-ft. pole. In this manner the telemetry flight configuration could be checked before launch. The Naval Research Laboratory provided telemetry services for all of the flights in the program.

The recovery of data by telemetering was not always completely satisfactory. Only limited spectrographic data could be transmitted, and films from cameras and biological specimens required physical recovery. Although efforts were made to provide ejection capsules provided with drag mechanisms by both the Army and the Naval Research Laboratory, these efforts were abandoned when physical recovery was successfully achieved by breaking up the missile prior to reentry into the denser atmosphere. TNT charges were attached to the four structural members of the control chamber and detonated by both a timer mechanism and a radio destruct signal at an altitude of about 60 km. After separation both the warhead and the afterbody exhibited high drag and poor stability, resulting in sufficiently low impact velocities so that equipment could be recovered in fair condition. Spectrographs, frame and motion picture cameras, and photographic data recorders were successfully recovered from flights that achieved altitudes of 170 km. In most cases the films were in excellent condition, including those taken by cameras for which no special precautions had been taken to protect the film. One solar spectrograph was recovered twice in such good condition that it only required recalibration before being flown.

The number of V2s was limited, and other boosters were added to the program. The Aerobee, which was first used in 1947, was a single-stage, liquid propellant rocket with a nominal payload of 68 kg and a corresponding peak altitude of about 110 km. Later versions were capable of higher altitudes. The Viking, designed and built under the technical direction of the Naval Research Laboratory, more closely resembled the V2, but employed a more efficient structural design and a gimbal-mounted motor for attitude control. Viking 11 carried a payload of 455 kg to an altitude of 254 km.

The Naval Research Laboratory program encompassed four fields of high altitude research: (1) atmospheric pressure, temperature, and composition measurements, (2) cosmic rays, (3) the ionosphere, and (4) solar physics, involving both the ultraviolet and x-ray spectra of the Sun.

ATMOSPHERIC PROPERTIES

Prior to the beginning of the V2 program, the physical properties of the atmosphere had been well explored over the first 30 km of altitude by balloon-borne instruments. Above that altitude the model of the thermosphere was based on ground-based observations of meteors, sound propagation, the ionosphere, and the aurora and airglow. The data from these observations were reflected in the National Advisory Committee for Aeronautics (NACA) tentative standard atmosphere. The advent of the sounding rocket offered an opportunity for direct measurements, and the early rocket results indicated a significant departure from the NACA standard atmosphere.

The Naval Research Laboratory undertook to measure the pressure at various locations on the rocket and reduce the measured pressures to ambient pressures and densities. Gauges were installed in the nose of the rocket to measure the stagnation pressure, which was reduced to ambient density by means of the Rayleigh formula

$$P = 0.92\rho v^2 + 0.46p + \dots$$

for a diatomic gas, where p and ρ are the ambient pressure and density and v is the rocket velocity [6]. The relation holds for supersonic velocities and up to about 100 km, or more, even for angles of attack somewhat in excess of 10 deg. At higher altitudes the density measurements were obtained from the pressure changes as measured on the side of the rolling rocket. In this method, gauges were mounted in the side of the rocket and, at high altitudes and well after powered flight, the rocket axis was oriented perpendicular to the velocity vector and the rocket was caused to roll. Pressure readings were then modulated with a period equal to the roll period of the rocket. The ambient air density is related to the amplitude of the modulation [7]. A measurement of the density at an altitude of 219 km on a Viking flight on 7 August 1951, when corrected for an atmospheric wind, was determined to be 1×10^{-7} gm/m^3 with an accuracy of 20 percent.

To obtain the ambient pressure versus altitude, gauges were installed on the surface of the nosecone and on the rocket body just forward of the tail fins. The pressure readings from the nosecone gauges were reduced to ambient values by means of the Taylor Maccoll theory [8]. Theoretical studies and German wind tunnel data [9] had shown that the pressure at the surface of the rocket at points from 6 to 13 rocket diameters from the nose is equal to the ambient pressure within a few percent over a wide range of Mach and Reynolds numbers. The validity of this result was checked by comparing measurements made approximately simultaneously up to the balloon ceilings, and by comparing measurements made in different rockets with varying velocities.

The large dynamic range of pressures encountered in flight required a variety of pressure gauges: bellows-type gauges for 760 to 20 mmHg, Pirani-type gauges for 2 to 3×10^{-3} mmHg, and Philips ionization gauges for over 10^{-3} to 10^{-6} mmHg. A new type of gauge known as the Havens cycle gauge[10] was developed and used over a pressure range from 1 atm to about 10^{-3} mmHg. In this gauge a bellows containing a Pirani element is cyclically moved by a motor, causing a pressure modulation about the Pirani element. The modulation produces an ac signal that can be amplified. The average pressure in the bellows is equal to the outside pressure communicated into the chamber through a small hole if the pumping time is long compared to the cycling rate.

The motions of the rocket introduced measurement difficulties. To correct for the effects of small angles of attack, similar gauges were mounted on opposite sides of the rocket and their average value was used as the normal zero angle of attack pressure. When the rocket had a steady roll there would be a point in each revolution where equal pressures would occur in the two opposing gauges, and the reading at that point was taken to be the surface pressure for zero angle of attack. Obtaining ambient pressures near the peak of the trajectory was complicated by outgassing of both the rocket and the gauge surfaces, which was overcome by taking advantage of the rocket roll. The roll motion caused a modulation in the pressure reading, and, for a long mean free path, the modulation was directly proportional to the product of the ambient density and the component of the relative air velocity perpendicular to the gauge opening [11].

Typical results are shown in Figures 5 and 6, taken from [6]. Figure 5 presents the density versus altitude as determined from five flights over New Mexico and one Viking flight at the equator. Figure 6 shows pressure data from six New Mexico flights and the one flight at the equator. The difference between summer and winter pressures over New Mexico is indicated by the dashed line.

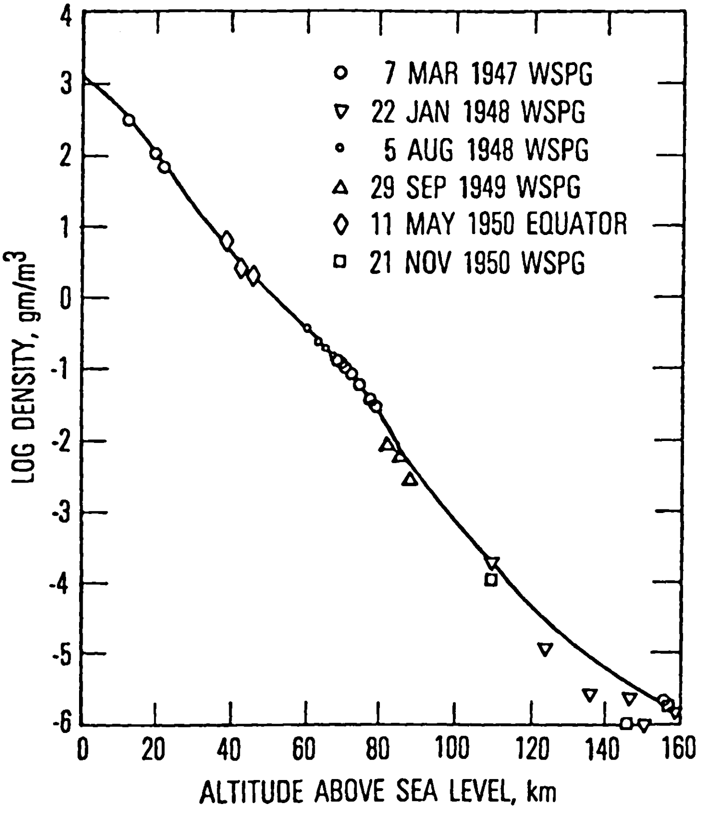

Figure 5 Log density versus altitude determined from five V2 flights from White Sands Proving Ground and one Viking flight at the equator.

The density data from Figure 5, plus the 219-km point obtained on a later Viking flight, are compared to the mean value of the Cospar International Reference Atmosphere 1972 [12] in Figure 7. A similar comparison is made for the pressure data [6] in Figure 8. The density points lie within the high and low values of the solar cycle up to the highest point shown. At altitudes of 90 km and below, the rocket pressure data agree with the CIRA mean within 10 percent, but above 100 km the variance becomes somewhat greater and the early rocket data tend to show somewhat higher values.

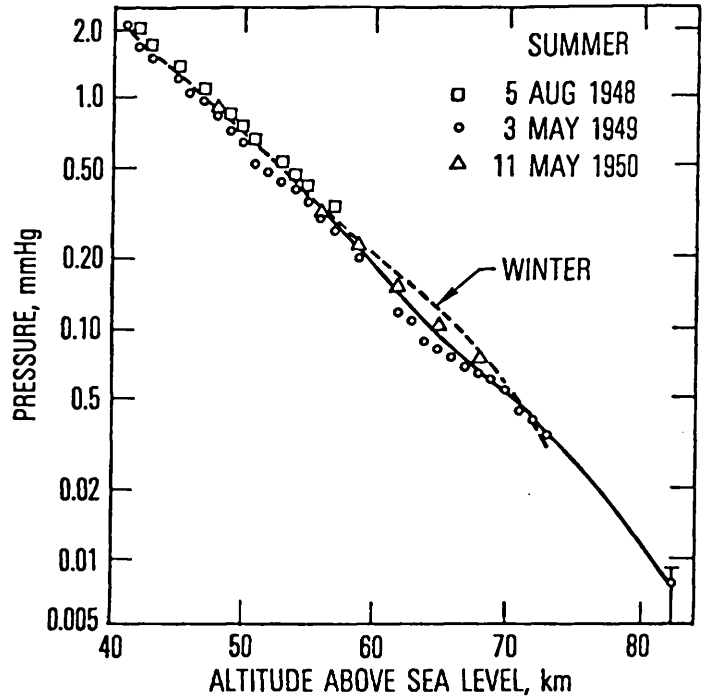

Figure 6 Pressure data from six White Sands and one Viking equator flights.

Atmospheric temperature was not measured directly, but was calculated from the pressure and temperature data. The average temperature versus altitude, as derived from the early rocket flights, is shown in Figure 9. The temperature calculation depends upon the average molecular mass in the atmosphere; and, in this figure, the composition was assumed to be molecular nitrogen and molecular oxygen with an average mass of 29. The altitude-temperature relationship below 100 km is in good agreement with the latest standard atmosphere. At higher altitudes, as shown by the CIRA points in the same figure, the temperature rises more rapidly with altitude than the values derived from the fairly limited rocket data from the first flights. The high-altitude variation could be expected, since the uncertainty in the pressure and density measurements increased with altitude.

Although early rocket measurements were geographically limited by launch facilities, and limited in number by the availability of rockets, they provided a good picture of atmospheric conditions at altitudes previously unexplored. In the following decades the data have been greatly extended by rockets and rockoons launched at a large number of sites, and more recently by satellites, to provide a greatly improved understanding of the upper atmosphere.

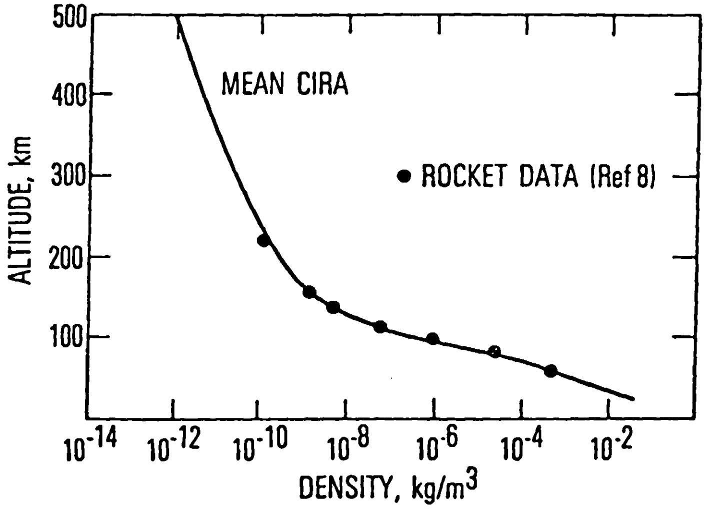

Figure 7 Density data from Figure 5 plus 219-km altitude Viking flight compared to Cospar International Reference Atmosphere (CIRA).

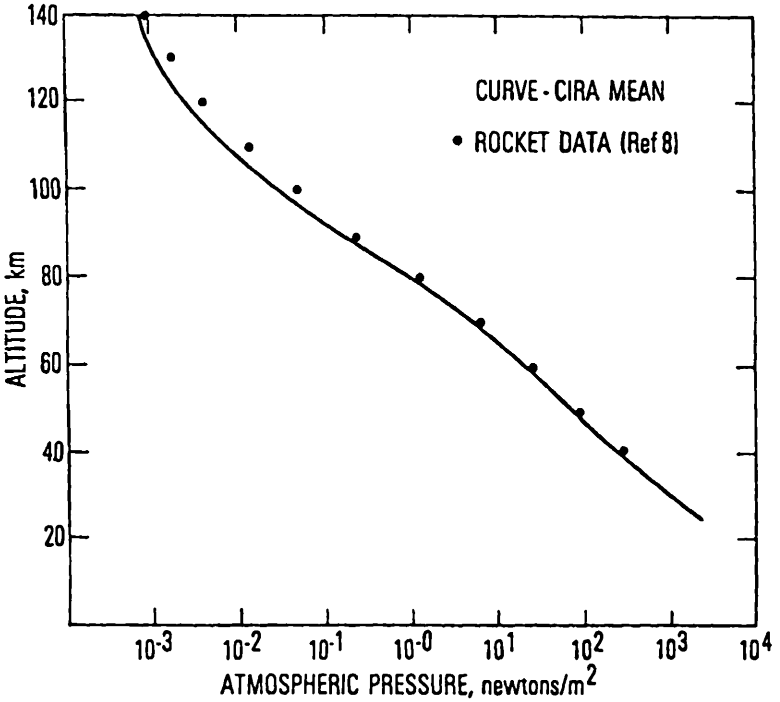

Figure 8 Pressure data from Figure 6 compared to mean Cospar International Reference Atmosphere (CIRA).

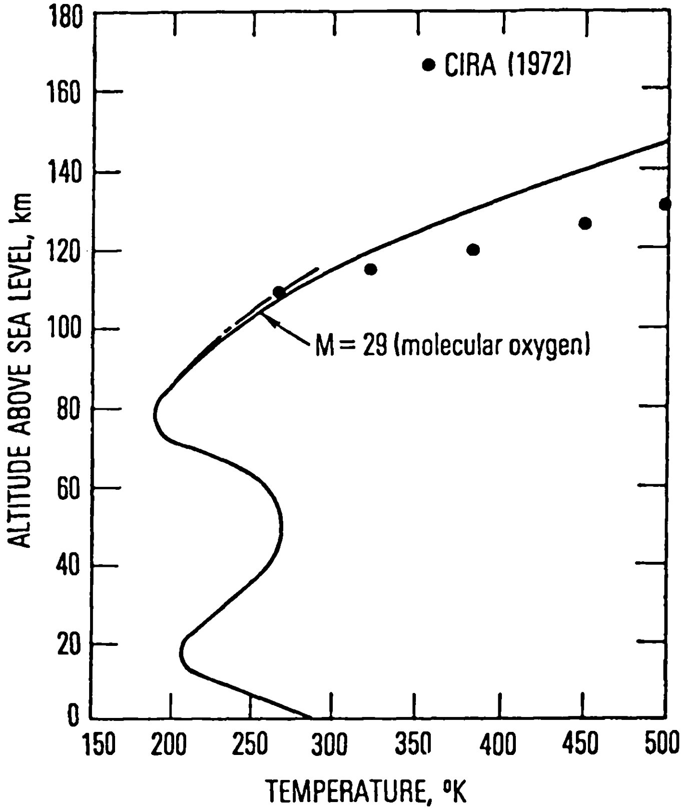

Figure 9 Average temperature versus altitude from early rocket flights compared to CIRA data.

COSMIC RADIATION

The availability of the V2 as a sounding rocket offered a new opportunity for a determination of the nature and intensity of the primary cosmic radiation. At that time, ground-based, mountain-top, and balloon-borne experiments had determined the distribution of both the total and the "hard" cosmic radiation throughout the lower atmosphere. These experiments indicated that at least the major portion of the primary radiation interacted with components of the atmosphere at altitudes where the pressure was as low as 2 cmHg, and identified the sea-level penetrating radiation as mesons produced in the interactions. Since only secondary and tertiary mesons, photons, and electrons penetrated to the altitudes then achievable with balloons, the fluence, composition, and energy distribution of the primary radiation had to be inferred from the secondaries. The nature and behavior of the secondaries had led most of the workers [13,14] in the field to the conclusion that the primary radiation consisted largely of very high energy protons, although the presence of gamma rays and electrons could not be ruled out.

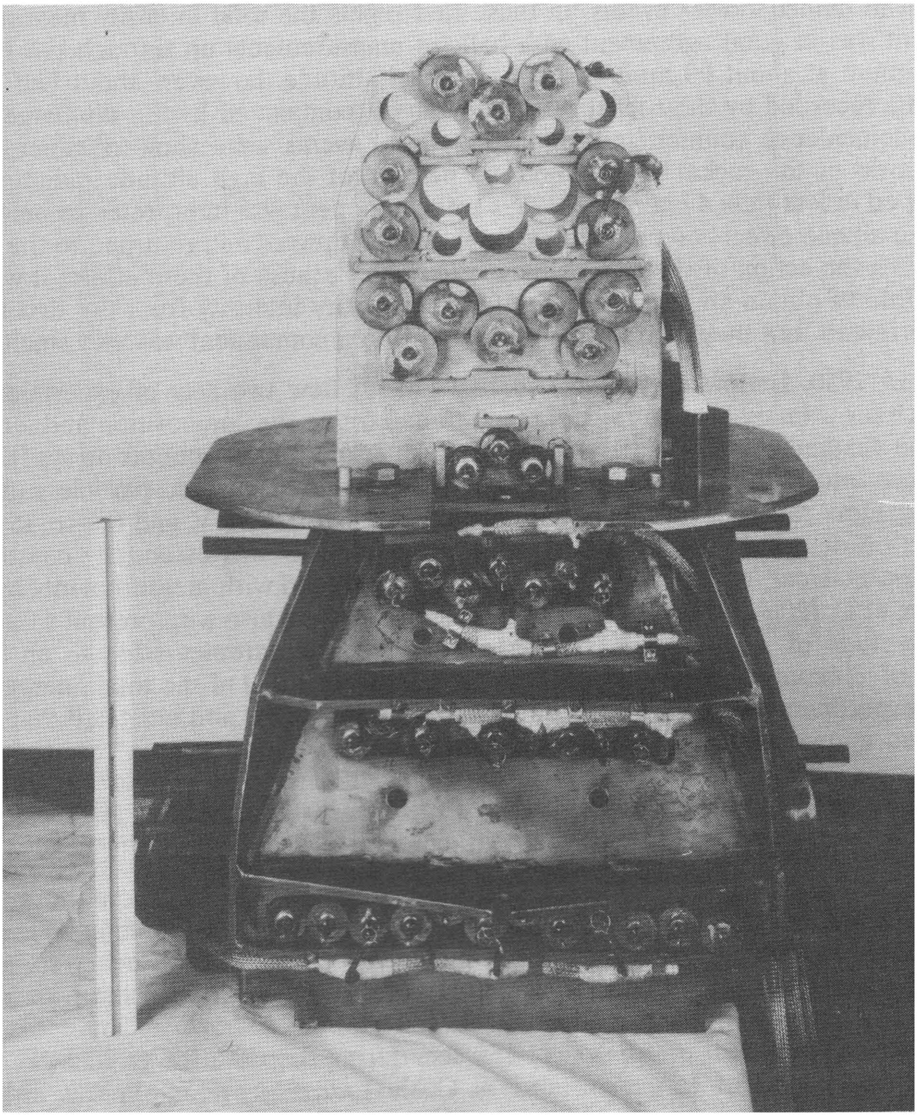

Figure 10 NRL Geiger counter telescope.

Although the V2 could carry instruments to the region of the primaries, it was not an ideal platform for cosmic ray research for two reasons. First, the rocket spent only 2 to 3 minutes of its total flight time at the very high altitudes it could attain. Since the primary flux in terms of particles/cm^2-sec was known to be low, only about 100 primary events could be expected to be detected in each flight, with the size of the instrumentation carried. Secondly, the V2 had a large burnout mass and tended to replace the atmosphere as a source of secondaries. Early Naval Research Laboratory experiments used Geiger counter telescopes [15,16,17] such as shown in Figure 10, containing lead absorbers to obtain intensity and penetration measurements. Out-of-line counters were employed in an anti-coincidence arrangement to detect shower events. In these first flights the total intensity measured on ascent was in good agreement with balloon measurements up through the Pfotzer maximum at about 90 mmHg. At the highest altitude, however, about half of the events recorded by the rocket telescope were accompanied by the discharge of an anti-coincidence counter, indicating that these events were showers generated in the mass of the rocket itself. About 35 percent of the high altitude radiation was stopped in less than 4 cm of lead. This soft component was interpreted as being due to the albedo effect -- secondary particles ejected upward and returned to the Earth through the action of the Earth's magnetic field. Because of these effects it was not possible to obtain an accurate value for the primary intensity from the first rocket experiments, but they did indicate that the electron component was very small.

In 1950, Perlow and his co-workers [18,19] flew two sets of experiments to search for primary gamma radiation and to determine the composition and intensity of the charged primary radiation. The first experiment used counter arrays in coincidence and anti-coincidence, such that both the total charged-particle radiation and gamma radiation in the energy ranges of 3.4 to 90 MeV and 0.1 to 15 MeV could be detected. The total charged-particle intensity was essentially constant at 0.12 particle/cm^2/sr above 45 km altitude, which agreed with measurements by Van Allen, et al. [20], of the Applied Physics Laboratory and also with present values for the latitude of White Sands, New Mexico. Their measurements led to an upper limit of gamma-ray energy flow of less than 1 part in 1,000 of the total energy flow. The experiments were carried in both day and night flights and indicated that there was no appreciable diurnal effect in either the ionizing or gamma radiation. The absence of a diurnal effect was confirmed by the use of a similar apparatus in Skyhook balloon flights in which a statistical accuracy of about 3 percent was achieved. Both results agree with present data.

The second experiment employed a counter telescope incorporating proportional counters to determine the composition and intensity of the charged primary radiation. Lead absorbers were used to measure the range of the penetrating particles, and out-of-line counters were used to measure the range of the penetrating particles, and out-of-line counters were used to detect showers. A total of 263 events were detected in a period of 150 sec, during the time the rocket was at an atmospheric depth of 2.5 gm/cm^2, or less. Of the total, 148 events were discarded as being due to showers generated in the rocket, and 90 of the remaining events were associated with particles with a range in excess of 60 gm/cm^2. The ionization of the 90 events was measured in each of two proportional counters and plotted against the minimum ionization level as determined as sea level (Figure 11). Two peaks, centered about $I/I_o = 1$ and $I/I_o = 4$, were obtained and were interpreted as being due to protons and alpha particles. Using an I/I_o value of 2.5 as the division between protons and alpha particles, Perlow obtained a proton-to-alpha particle ratio of 5.3, which is somewhat lower than the presently accepted value for that latitude. Although the histogram shows one particle with $Z = 6$, the statistics did not support any conclusions as to the presence of heavier particles in the spectrum. Perlow's value of 0.07 particle/cm^2-sec as the primary fluence agrees with later determinations for penetrating particles at the latitude of White Sands as well as the altitude achieved by the rocket.

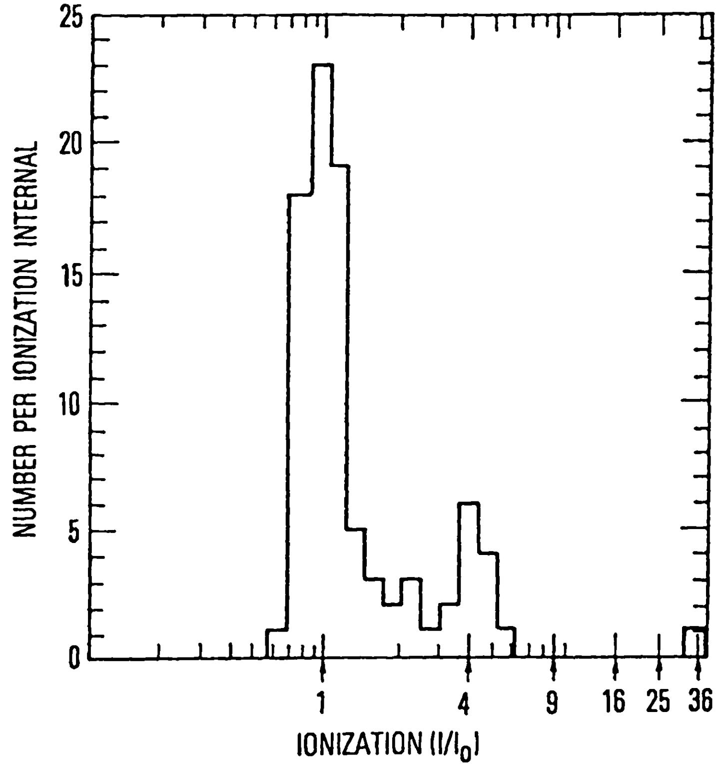

Figure 11 Charged primary radiation plotted against minimum ionization as determined at sea level. Peaks determined as due to protons and alpha particles.

In addition to the counter telescope experiments, a few cloud chambers were flown. A 6-in. chamber was flown in a V2 to an altitude of 159 km on 22 January 1948 [21]. Two lead plates, each 1 cm thick, crossed the chamber, and stereo photographs were taken at 25-sec intervals. As in the counter experiments, the major share of the events detected were associated with showers originating in the rocket. The most significant event detected in this flight was a single track contained in a photograph taken at 145-km altitude when the outside atmospheric pressure was about 10^{-5} mmHg. The track penetrated both plates and created heavy ionization. Since a proton with sufficient energy to penetrate the lead with very little scattering would have near minimum ionization, the possibility that the track was caused by a proton was ruled out. The event was interpreted as being due to an alpha particle of energy greater than 400 MeV, or to a more highly charged nucleus of correspondingly greater energy. In the same year, a group at the University of Minnesota [22] also found evidence for heavy primary cosmic ray nuclei in emulsions and with cloud chambers flown above 90,000 ft with Skyhook balloons.

IONOSPHERIC MEASUREMENTS

As in the other fields of high-altitude research, the ionosphere had been probed quite extensively with ground-based instrumentation. Both cw and pulsed-radio methods had been used with considerable success in obtaining information as to the layer heights and the variable nature of the ionospheric effects. Ground-based probing, however, was limited in several respects. Radio probing could only measure the index of refraction, or ion concentration at certain heights where reflection occurs at a critical frequency, but did not permit measurements on the details of the concentration above the regions of maximum density. The heights obtained were apparent heights, which were higher than the true heights, since the velocity of the radio waves in the ionized regions below the maxima could not be directly determined. Also, ground probing did not permit a determination of the ratio of free electrons to ions, since the latter do not respond to, or affect, the radio waves to any significant extent.

The high altitude rocket provided a potential for overcoming some of the limitations of ground-based ionospheric probing in several ways. Radio signals could be passed from high altitude to the ground through the ionized region without the need for meeting a reflection condition. As the rocket moved upward, the effects on the transmission over a specific region could be measured. Also, direct measurements of ion concentrations were possible with Langmuir probes mounted in the nose of the rocket, and with rf ion spectrometers. By using vertical incidence sounding during the rocket flight, the rocket and ground measurements could be combined to aid in interpretation of the data. However, the relatively infrequent launches were a considerable handicap in studying a region with such great and frequent temporal variations as characterize the ionosphere. Each flight could only provide a snapshot of the ionospheric conditions at the time and place of the launch.

The principal method undertaken at the Naval Research Laboratory [23,24] consisted of the transmission of two harmonically related crystal-controlled cw radio frequency signals from the rocket to ground-based receiving and recording equipment. The fundamental frequency was selected to be just slightly above the maximum critical frequency for the regions that the rocket would penetrate. The higher harmonic was selected so that the velocity of propagation would be essentially unaffected by the ionosphere, i.e., the frequency-dependent index of refraction was nearly unity for all points between the rocket and the ground. The two receiving stations on the ground were located 6 miles apart in the plane of the trajectory, and, with the short-range, high-altitude trajectory of the rocket, nearly vertical propagation was obtained.

Under these conditions, the phase velocity of the fundamental would be increased above the speed of light, whereas that of the harmonic, or reference, frequency was unchanged. After multiplying the received fundamental frequency of the harmonic factor, it was beat against the reference frequency to obtain a phase beat frequency that was a function of the radial velocity of the rocket and the effect of the ionosphere on the fundamental frequency. Since the velocity of the rocket could be determined by independent means, the beat frequency contained the information from which the index of refraction could be calculated. In this method there are actually two downcoming rays -- one ordinary and one extraordinary -- resulting from magneto-ionic splitting. The rays were separated at the receiving stations, so that both the ordinary and extraordinary indices of refraction could be calculated. Using the Goubau modification of the Appleton-Hartree equation, the values of electron density as a function of altitude were deduced.

The implementation of this technique on a vehicle such as the V2 required the solution of a number of difficult instrumentation problems. Although equipment was carried on the first V2s launched back in 1946, the first limited success was achieved on a midday flight on 7 March 1947 [25]. At that time the magneto-ionic components of the signal were not received separately and the data were very difficult to analyze. It was immediately noted that the fundamental signal was lost on ascent at an altitude of 111 km and reappeared on descent at the same altitude. The ground-based ionogram taken at the time of flight indicated the occurrence of a sudden ionospheric disturbance just before launch, and the signal dropout was attributed to the resultant sporadic E ionization. When the data were later successfully analyzed [26], the measurements showed a rapid and almost linear rise of electron density from about 85 km to the dropout altitude of 111 km, with a peak value of about 2×10^5 electrons/cm^3 at the 111-km point. The next attempt, on 22 January 1948, yielded similar results, with a signal dropout at 100 km.

On later flights on V2, Viking, and Aerobee-Hi rockets, measurements were made to an altitude of 260 km. The results obtained in four flights above White Sands are shown in Figure 12 [26-28]. These data show the same general rapid rise in electron density from 80 to 85 km to the 100-km region, followed by a slower and continuous increase to the maximum altitude obtained. The May 1954 and June 1956 profiles are similar, but the latter curve shows a denser ionosphere, which is consistent with the corresponding increase in solar activity. Both daytime and nighttime measurements into the E layer were made at Fort Churchill, Canada, later in the program [29]. The daytime profile was quite similar to that at White Sands, but very low densities (2×10^4 electrons/cm^3) were observed at night up to an altitude of 170 km.

The first measurement of the F-layer peak was made by W.W. Berning [30] of the Ballistics Research Laboratory on a Bumper-WAC firing on 24 February 1949, in which a WAC Corporal rocket was launched at altitude after being boosted by a V2. His data taken near a solar activity maximum showed a peak density of about 2×10^6 electrons/cm^3 at an altitude of about 32 km and a decrease in density to 400 km. Later NASA high-altitude rocket flights [31,32] indicated the F_2 peak in the 300-km region, with slowly decreasing electron densities to very high altitudes. Soviet scientists, also using the Naval Research Laboratory (NRL) two-frequency techniques with sounding rockets, obtained electron density profiles in good agreement with the NRL results [33].

The program of rocket-borne measurements of ionospheric electron densities that was begun in 1946 with the V2 made significant contributions to the understanding of the ionosphere. The concept of the ionosphere as discrete layers of high charge density separated by regions of considerably lower density was altered by the measurements showing that the density remained high between the E and F regions. The steep electron density gradient in the bottom edge of the E region was established early in the program. In the following decade, as rockets capable of higher altitudes became available, the region of the F2 maximum and beyond were explored, both in the U.S. and the USSR. The altitude of the F2 maximum was found to remain fairly constant in the 300-km region, although the charge density varies by as much as an order of magnitude between sunspot minima and maxima.

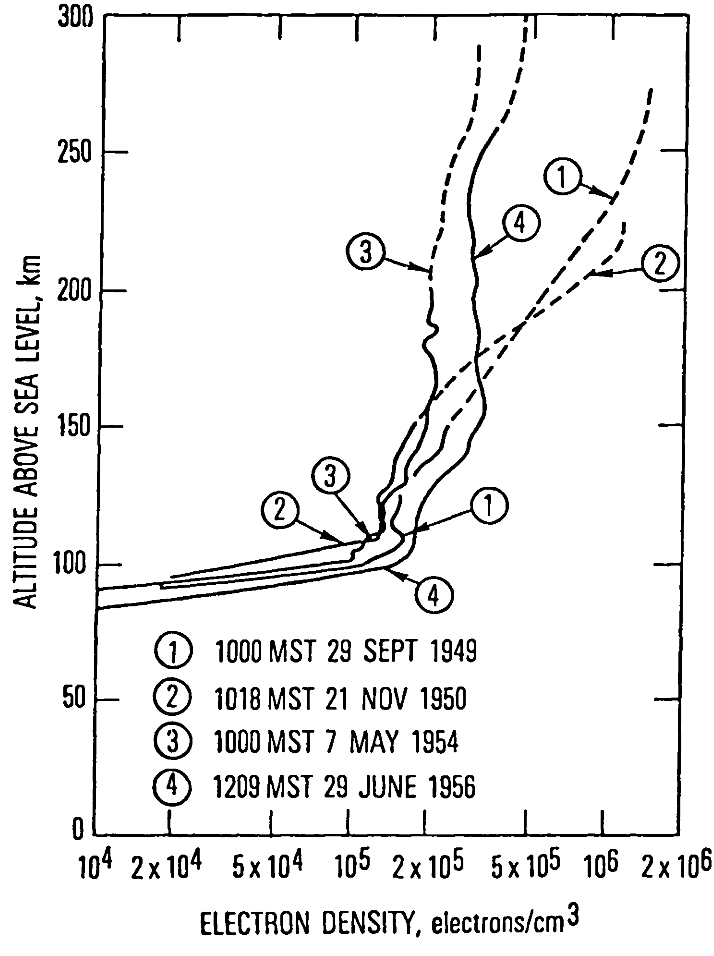

Figure 12 Electron density measurements to 260-km altitude obtained for White Sands flights using V2, Viking and Aerobee rockets.

SOLAR ASTRONOMY

The interest in rockets for solar astronomy is illustrated by Figure 13. The curve shows the altitude in the atmosphere at which the fluence of solar radiation is decreased to e^{-1} of its value at the top of the atmosphere when the Sun is immediately overhead. The atmosphere effectively absorbs all of the radiation at wavelengths shorter than 3,000 Å by a variety of processes. Between 300 and 2,000 Å the ozone layer is essentially opaque to the Sun's radiation. At shorter wavelengths the radiation is strongly absorbed by molecular oxygen, and the region of greatest interaction is at an altitude of about 100 km; however, narrow bands between 1,000 and 1,300 Å penetrate more deeply and interacts with all of the constituents of the atmosphere and is absorbed at even higher altitude. The wavelengths below 100 Å are x-rays with energies of 125 eV and greater and penetrate to altitudes of 100 to 120 km.

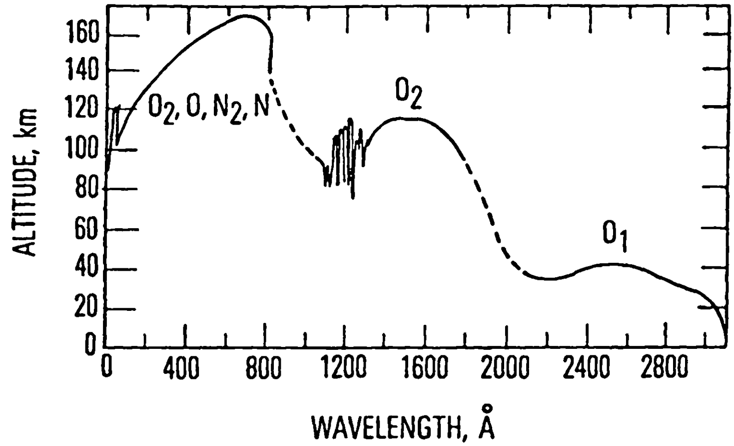

Figure 13 Earth's atmosphere: altitude and wavelength (see text).

The earliest investigations by the Naval Research Laboratory employed grating spectrographs to obtain solar spectra in the ultraviolet at frequent intervals during the rocket ascent [34,35]. By comparison of spectra obtained at different altitudes, the change in the ozone over the slant path between pairs of spectra was determined using known absorption coefficients of ozone from laboratory measurements. A curve of the total slant path ozone as a function of altitude was developed, and the vertical distribution was determined from the slope of the slant path curve. Spectra obtained at altitudes above the ozone layer provided data on the solar radiation to a lower wavelength limit set by the then unknown absorption by the atmosphere above the peak of the rocket trajectory.

A major problem for the operation of a spectrograph in a rocket was the need for an extremely wide useful field of view to compensate for the roll and yaw motions [34]. Instead of conventional slits, lithium fluoride beads 2 mm in diameter were used as the entrance apertures. The spheres, which were transparent down to 1,100 Å in the ultraviolet, acted as short-focused wide-angle lenses and provided a conical field of view 140 deg in diameter. Two entrance paths were provided on opposite sides of the grating normal, to double the probability that the Sun would be in the field of view of the instrument. Dispersion was provided by a 40-cm radius, 15,000-line-per-inch concave diffraction grating ruled on aluminum. Plane mirrors were used to fold the optical path to provide a compact spectrograph. the spectra were photographed on 35-mm film that was exposed frame by frame. The time of each exposure was telemetered so the altitude for each exposure could be determined from the rocket trajectory. Figure 14 shows one of the first spectrographs flown on the V2.

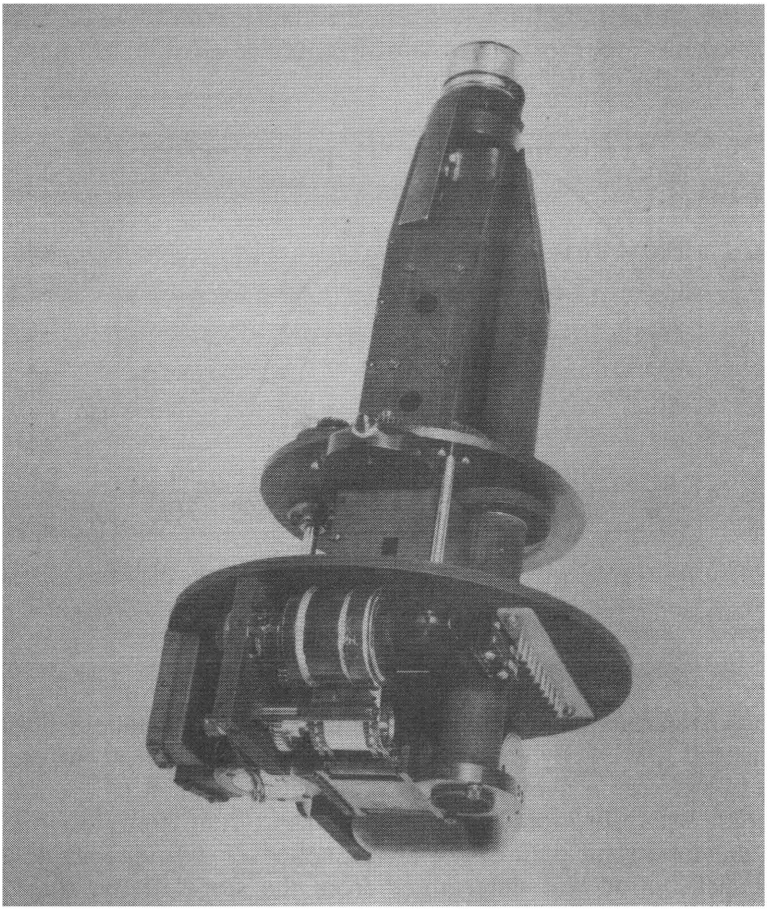

Figure 14 One of first spectrographs flown on the V2 rocket.

The first successful use of the instrument was on a V2 flight on 10 October 1946. Spectra were obtained from the ground to an altitude of 88 km, as shown in Figure 15, and the total slant range ozone between the spectrograph and the Sun for each altitude and the vertical distribution of ozone was determined. Ozone measurements were also successful on one flight in 1948 and two flights in 1949 [36]. An excellent determination of ozone was made on 14 June 1949 when the rocket was flown near sunset, resulting in a long slant path to the Sun. Two spectrographs were flown, one identical to the earlier instruments, and the second a dual device consisting of two spectrographs in a single housing. The ozone determinations from the three sets of spectra were in good agreement and showed a peak concentration of ozone at about 27-km altitude, with the concentration decreasing approximately exponentially above 35 km. The concentration of ozone above New Mexico as determined in three flights is shown in Figure 16, based on the data given [34,35,36].

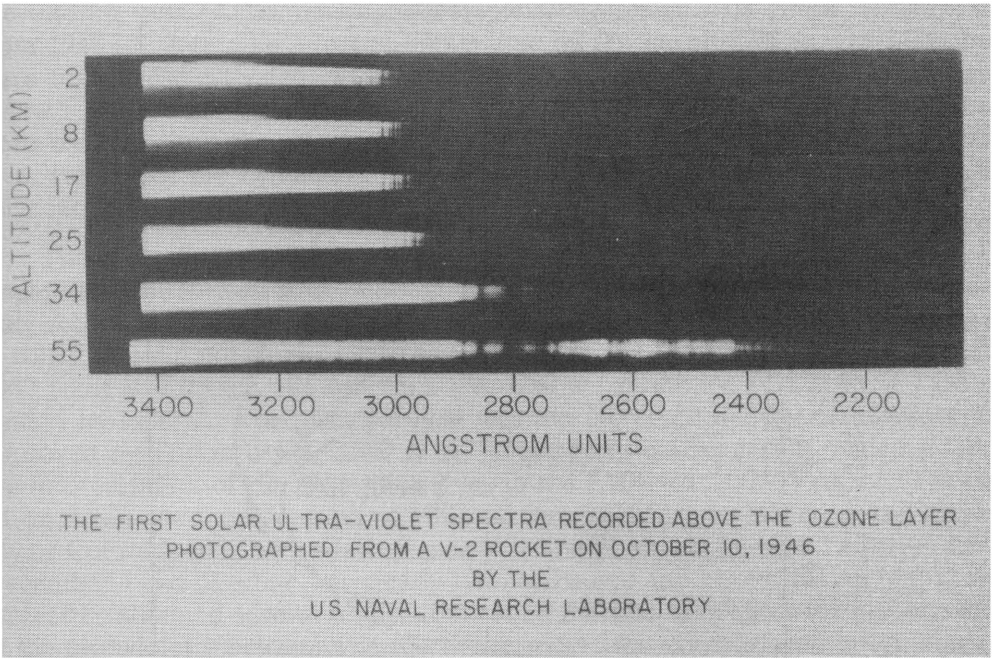

Figure 15 Spectra obtained from V2 flights between 1946 and 1949.

Additional composition measurements were obtained with a radio-frequency mass spectrometer developed for upper atmosphere research at the Naval Research Laboratory [37]. The spectrometer was designed to measure the ratio of argon to molecular nitrogen at altitudes above 95 km in order to obtain data on the diffusive separation of atmospheric gases. The first successful flight of the instrument was on an Aerobee rocket flown at night on 13 February 1953 [38]. Eighty-five samples were obtained on ascent between 96.8 and 137.3 km and eighty-seven samples on descent. In this early experiment the argon to molecular nitrogen ratio remained essentially constant with altitude, indicating that there was no diffusive separation of the atmospheric gases at this altitude. In later flights at Fort Churchill, Canada, a diffusive separation of argon relative to nitrogen was detected by the same group. Another version of the instrument was also used in Viking and Aerobee rockets to measure ion composition from 9 to 46 atomic mass units.

In addition to the measurements of ozone concentration, the data obtained at altitudes above the ozone layer extended the knowledge of the solar spectrum into the ultraviolet region. Considerable success was achieved early in the program. The spectra of Figure 15 obtained in October 1946 [39] showed a progressive extension into the ultraviolet above 25 km, and above 55 km the ozone absorption was sufficiently reduced to permit recording to about 2,100 Å. These spectra were the first measurements of the Sun's radiation at wavelengths below the 2,900-Å atmospheric cutoff, and represented the beginning of a new field of astronomy which, in the next two decades, contributed greatly to the knowledge of solar emissions and processes.

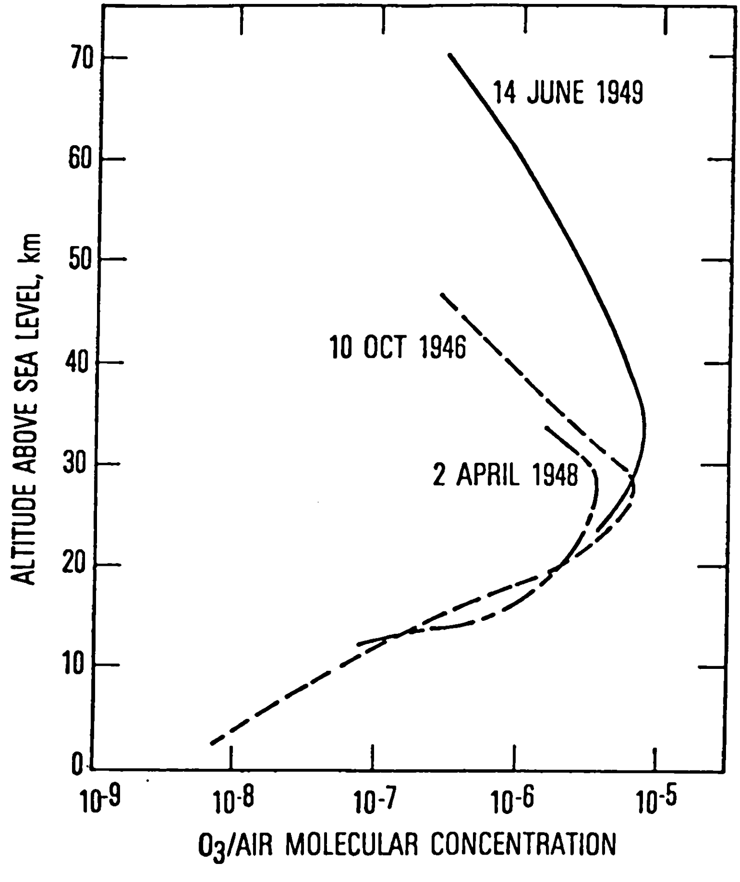

Figure 16 Concentration of ozone above New Mexico determined from three rocket flights.

Additional spectra covering the 2,900- to 2,100-Å region were obtained at altitudes up to 75 km in flights in March and October 1947 [40]. the curve of the average radiant energy of the Sun was extended from the previous 2,900-Å limit to about 2,200 Å and showed that the ultraviolet intensities were well below the values that had been predicted for a 6,000°-K blackbody [41].

The data made it possible to identify the principal contributors to many of the Fraunhofer absorption lines observed in the 2,950- to 2,300-Å region [42].

In the first 3 years of the program, the spectrographs were rigidly mounted in rockets that were unstabilized after fuel burnout. As a result of the roll, yaw and pitch motions, the Sun was generally well off the axis as the instrument at high altitudes. The lithium-bead entrance apertures provided a large field of view and partially overcame the difficulty. Nevertheless, it became evident that longer continuous exposures would be required to record the low-intensity ultraviolet radiation below 2,100 Å and that stabilization of the spectrograph would be required. In the interim, sets of thermoluminescent phosphor plates were flown in three V2s from 1948 to 1950 in an effort to obtain data on the far ultraviolet. The phosphors were manganese-activated calcium sulfate which absorbed energy at wavelengths below 1,340 Å and released the energy as visible luminescence when heated. Filters were used to limit the wavelength bands to which the phosphors were exposed. With the device the Lyman-α line of hydrogen at 1,216 Å was first detected in the solar radiation [44].

The first effort to overcome the problem of rocket motion was the use of a single-axis turntable on both Aerobee and Viking rockets in 1952. The photoelectrically activated turntable kept the entrance aperture pointed at the Sun, as the rocket rolled, but did not correct for yaw and pitch. In the Viking flight of 15 December 1952 using this device, the spectrum obtained at an altitude of 158 to 163 km extended to 1,850 Å. The principal gain was the increased density of exposure and improved resolution below 2,500 Å as compared to earlier results, which aided in the interpretation of the absorption lines in the 2,900- to 2,000-Å region. The next advance was the incorporation of a biaxial Sun follower, developed at the University of Colorado [46], with which Rense [47] first photographed the Lyman-α line in December 1952. The line was clearly visible; Tousey and his coworkers [48] shortly thereafter obtained several intense images of the line, as well as further extension of the ultraviolet spectrum. The roll of the rocket was counteracted by rotating the entire Aerobee nose section, and yaw and pitch were corrected by swinging the spectrograph in trunions driven by the biaxial servo system. With this system, and with a redesigned spectrograph [49], the NRL group achieved excellent results in a number of flights after 1954 and extended the data on the solar spectrum into the far ultraviolet. An excellent summary of the results of this work is presented in Tousey's Henry Norris Russell lecture of 1966 [50].

Another Naval Research Laboratory group, headed by Herbert Friedman, undertook intensity measurements in limited wavelength bands of the far ultraviolet by means of photon counters. Sets of detectors sensitive to portions of the solar x-ray and far ultraviolet radiation of the Sun were first flown in a V2 in September 1949 [51], the counter measurements marked the beginning of the new field of x-ray astronomy that has led to many important advances in astrophysics.

The detectors employed were basically Geiger counters in which the spectral response was controlled by the gaseous filling and the transmission characteristics of thin-film windows [53]. In the first experiment two sets of four counters were installed on opposite sides of the rocket warhead, with the exposed windows parallel to the warhead surface. The x-ray counters were most sensitive at about 2 Å, with decreasing sensitivity to 10 Å where the 0.005-in. beryllium window was essentially opaque. The ultraviolet photon counters were designed to be sensitive in three bands at 1,100 to 1,350 Å, 1,425 to 1,650 Å, and 1,725 to 2,100 Å, with the short wavelength cutoff set by the lithium fluoride, synthetic sapphire, and quartz windows. The counting rate was obtained by integrating the charge flow through the counter in an RC circuit and applying the resultant voltage to the telemetering system. As the rocket rolled at high altitude, the window aperture of each counter swept through one exposure to the Sun for each roll. The telemetered record was a series of spikes with about eight data points per exposure, showing that the detectors responded only when viewing the Sun.

A number of significant results were obtained from the data gathered in the first flight. The x-ray counters did not respond until an altitude of 87 km was reached, which indicated a high-energy cutoff at about 7 Å. Above that altitude the counting rate increased and the counters reached their maximum counting rate before the peak of the trajectory at 150 km. Based upon the data and the calibrated sensitivity of the counters, the total fluence at the top of the atmosphere was calculated to be about 10^{-4} erg cm^{2} sec^{1} for wavelengths shorter than 10 Å. Although the fluence was less than the 10^{-2} to 10^{1} erg cm^{-2} sec^{-1} required for the E-layer ionization, this first experiment supported the theory [54] that solar x-rays were the major source for E-layer information on the basis that most of the energy was in x-rays at wavelengths between 10 to 100 Å. The data on x-ray threshold altitude and intensity variation with altitude were confirmed in other flights, [55,56], and in November and December of 1953 the x-ray measurements were extended to longer wavelengths, using counters sensitive in three bands; 8 to 20 Å, 44 to 60 Å, and 44 to 100 Å [57]. These first data on x-ray wavelengths longer than 10 Å showed an x-ray distribution approximated by a 700,000°-K grey body, and a total emission of about 10^{-1} erg cm^{-2} sec^{-1}, which was absorbed in the atmosphere between 110 and 130 km. The 1953 experiment confirmed the earlier tentative conclusions that the energy in the solar x-ray fluence was adequate to account for the ionospheric E-layer.

The counters sensitive to the 1,100- to 1,350-Å band showed that the radiation in this band penetrated the atmosphere to about 70-km altitude. Above that altitude the counting rate increased and a symptotically approached a maximum as the rocket approached the 150-km apogee of its trajectory. The increase in intensity followed the calculated absorption curve for the Lyman-α line of hydrogen, indicating that this line was the major contributor to the energy within the band. The experimental evidence that the Lyman-α radiation penetrated well below the E-layer also supported the suggestion [58] that it was the energy source for the D-layer ionization. Similar measurements in following flights confirmed the depth of penetration and showed that better than 90 percent of all of the radiation from the Sun in the 1,180- to 1,300-Å band was in the single 1,216-Å emission line of hydrogen and that the background radiation in the 1,200-Å region was inconsistent with a 6,000°K blackbody temperature for the Sun.

The 1,425- to 1,650-Å counters covered the wavelength band in which the absorption coefficient for oxygen is a maximum. The data obtained from these counters in the early flights also contributed significant results. The rise in counting rate in the 100-km region indicated transition of atmospheric oxygen from molecular to atomic. However, molecular oxygen was found to exist well above the

E region, and by 1955 [59,60] the complete departure of the molecular oxygen distribution from that predicted by photochemical equilibrium had been established. The relatively weak oxygen transition as shown by the counter experiments was consistent with the deduced solar intensities. The combination of the spectrographic and photon-counter intensity data in the ultraviolet then showed that the solar blackbody temperature dropped from 5,000°K at 1,200 Å to about 4,000°K at 1,200 Å.

SOLAR FLARE MEASUREMENTS

Although solar flares produce large changes in the solar output and sometimes spectacular effects in the atmosphere, they are generally short-lived. The possibility of obtaining information on flare radiation by means of rocket astronomy was a formidable challenge. In the summer of 1956 a series of small rockets instrumented with photon counters was launched from the U.S.S. *Colonial* in the Pacific Ocean about 350 miles southwest of San Diego [61]. The solid propellant rockets were carried aloft by large balloons early in the morning and permitted to drift throughout the day, while the Sun was monitored for signs of a flare. If no flare occurred, the rocket was launched near sunset and quiet Sun data were recorded. Solar monitoring was performed by the solar observatories at Sacramento Peak, New Mexico, and Climax, Colorado, U.S.A., which were in radio communication with the ship.

On 20 June 1956 a small flare occurred and the rocket was launched in time to reach peak altitude within 10 minutes of the time the flare was first visually observed. The flare was classified as being between class 1 and a subflare and did not create any radio fadeout.

The rocket was instrumented with an ion chamber to measure the Lyman-α radiation and a photon counter with a beryllium window sensitive to 1- to 8-Å x-rays. The Lyman-α radiation was essentially unchanged from that measured with a quiet Sun, but the x-ray intensities and wavelengths were quite different. The x-rays extended to wavelengths of 3 Å, as compared to a quiet-Sun short wavelength limit of 7- to 8-Å, and the intensity in this band was measured as about 5×10^{-3} erg-cm^{-2}sec^{-1}. In 1957, two-stage solid rockets capable of reaching an altitude of 400,000 ft. were launched on flare warning from San Nicolas Island, 60 miles off the coast of California [62]. Solar x-ray and Lyman-α were obtained during class 1^+, 2, and 3^+ flares. Again, there was no increase in the intensity of Lyman-α over quiet Sun conditions, but strong x-ray enhancement was measured for each flare, with the intensity and photon energy increasing with the flare magnitude.

The first decade of rocket astronomy provided experimental verification of a number of theories concerning the interaction of solar radiation with the Earth's atmosphere. It became clear that, under quiescent Sun conditions, the ionospheric D-layer was accounted for by the Lyman-α emission energy, and the E-layer by x-rays with wavelengths longer than 8 Å. The intensities of these radiations had been experimentally determined. It had also been established that the solar x-rays increase both in intensity and photon energy during flares, and that these higher energy x-rays penetrate deeper into the atmosphere to cause the enhanced ionization and lowering of the D-layer associated with the larger flares [63]. The distribution of the ozone and oxygen transition layers had been mapped and several thousand emission and absorption lines in the solar and coronal radiation had been identified. The later extension of rocket astronomy to the investigation of stellar x-ray sources [64] and night sky airglow [65,66] measurements is well-known.

The rocket-borne research investigations, begun with the V2 in 1946, provided a rich return in information on the upper atmosphere, cosmic rays, the ionosphere, and solar radiation. Some secondary experiments yielded unexpected results. Beginning in 1947, cameras were carried in V2s and Vikings to aid in defining the orientation of the rockets from photographs of the Earth. The photographs were useful for this purpose, but also provided information on large-scale cloud formations that could not be obtained from ground observations. Figure 17 is a composite of four photographs taken when the rocket was at an altitude above 160 km. These first high-altitude photographs cover an area of about 1.3 million km^2 of the southwestern United States and northern Mexico [67].

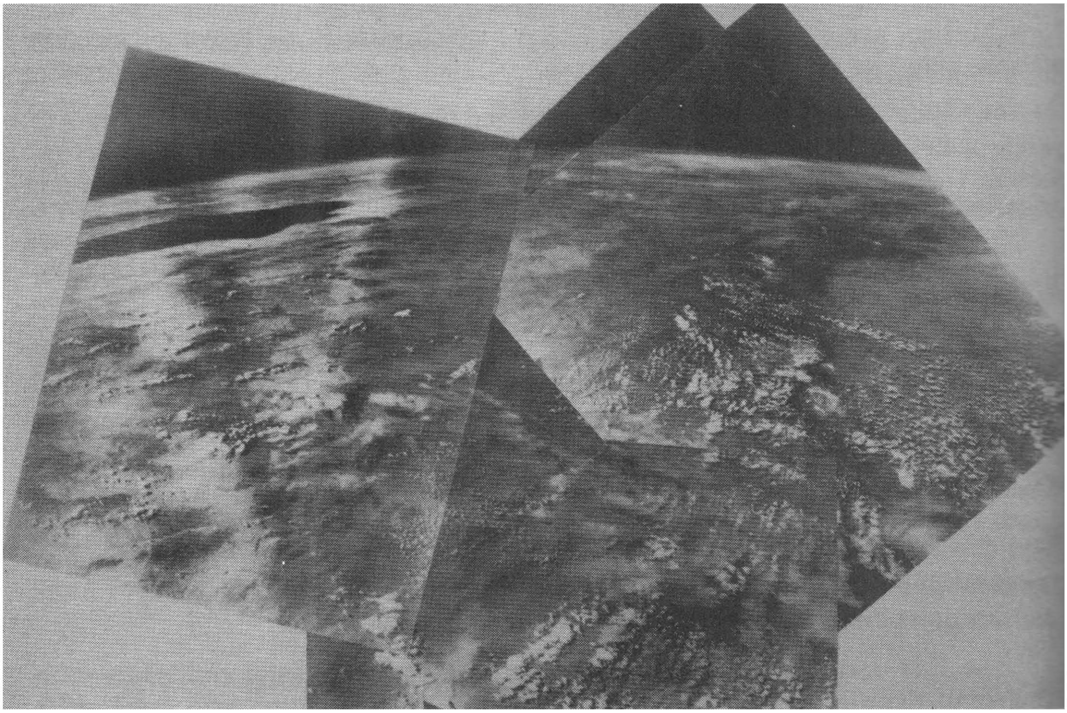

Figure 17 Composite of four photographs of southwestern U.S. and northern Mexico taken in 1947 by rocket-borne camera.

In addition to the experiments themselves, very valuable information and experience were gained with respect to operations in rocket and in space environments. The telemetry system developed for the V2 pioneered the recovery of data from space by electronic means. The problems of providing continuous communication with a gyrating vehicle were worked out, as were power-supply energy management and preflight checkout techniques. All of the lessons, sometimes painfully learned by the space pioneers, were of great value to the later space programs.

REFERENCES

1. C.F. Green, "Utilization of the V2 (A4) in Upper Atmosphere Research," *Rocket Exploration of the Upper Atmosphere*, (New York: Pergamon Press, Inc. 1953), p. 28.
2. J.T. Mengel, *Upper Atmosphere Research Report No. I*, Report R-2955, Naval Research Laboratory (1 October 1946).
3. T.A. Bergstralh, *Upper Atmosphere Research Report No. III*, Report R-3120, Naval Research Laboratory, (April 1947).
4. V.L. Heeren, et al., "Telemetering from V2 Rockets," *Electronics* 20, 100-105 (1947).
5. C.H. Smith, "Telemetering from Rockets," *Upper Atmosphere Research Report No. III*, Report R-3120, Naval Research Laboratory (April 1947).
6. R.J. Havens, R.T. Koll, and H.E. La Gow, *J. Geophys. Res.* 57, 59-72 (1952).
7. Homer E. Newell, *High Altitude Rocket Research* (New York: Academic Press, Inc., 1953).
8. G.D. Taylor and J.W. Maccoll, *Proc. Roy. Soc.* 139, 278 (1933).
9. N. Best, et al., *Phys. Rev.* 70, 985 (1946).
10. R.J. Havens, R. Koll, and H.E. La Gow, *Rev. Sci. Inst.* 21, 596-598 (1950).
11. H.E. La Gow, "Physical Properties of the Atmosphere Into the F_1-Layer," *Rocket Exploration of the Upper Atmosphere*, eds. R.L.F. Boyd and M.J. Seaton (New York: Pergamon Press, Inc., 1954).
12. D.A. Strickland, ed., *Cospar International Reference Atmosphere -- 1972* (Berlin: Akademie-Verlag, 1972).
13. Marcel Schein, W.P. Jesse, and E.D. Wallan, *Phys. Rev.* 56, 615 (1941).
14. T.E. Johnson, *Rev. Mod. Phys.* 11, 208 (1939).
15. S.E. Golian, E.H. Krause, and G.J. Perlow, *Phys. Rev.* 70, 223 (1946).
16. G.J. Perlow and J.D. Shipman, Jr., *Phys. Rev.* 71, 325 (1947).
17. S.E. Golian and E.H. Krause, *Phys. Rev.* 71, 918 (1947).
18. G.J. Perlow and C.W. Kissinger, *Phys. Rev.* 81, 552 (1951).
19. G.J. Perlow, et al., *Phys. Rev.* 88, 321 (1952).
20. A.V. Gangnes, J.F. Jenkins, and J.A. Van Allen, *Phys. Rev.* 75, 57 (1949).
21. S.E. Golian, et al., *Phys. Rev.* 75, 524 (1949).
22. Phyllis Frier, et al., *Phys. Rev.* 74, 231 (1948).
23. J.C. Seddon and J.W. Siry, *Upper Atmosphere Research Report No. I*, Report R-2955, Naval Research Laboratory (1 October 1946).

24. J.C. Seddon, "Propagation Measurements in the Ionosphere with the Aid of Rockets, *Rocket Exploration of the Upper Atmosphere*, eds. R.L.F. Boyd and M.J. Seaton (New York: Pergamon Press, Inc., 1954).

25. T.R. Burnight, J.F. Clark, Jr., and J.C. Seddon, *Upper Atmosphere Research Report No. IV*, Report R-3171, Naval Research Laboratory (1 October 1947).

26. J.C. Seddon, *J. Geophys. Res.* 58, 323 (1953).

27. J.E. Jackson and J.C. Seddon, *J. Geophys. Res.* 61, 749 (1956).

28. J.E. Jackson and J.C. Seddon, *J. Geophys. Res.* 63, 197 (1958).

29. J.E. Jackson and J.C. Seddon, V SCAG I (1958).

30. W.W. Berning, *J. Meteorol.* 8, 175 (1951).

31. J.E. Jackson, *J. Geophys. Res.* 66, 3055 (1961).

32. S.. Bauer and E.J. Jackson, *J. Geophys. Res.* 67, 1675 (1962).

33. V.I. Krasovsky, V SCAG I (1958).

34. F.S. Johnson, J.D. Purcell, and R. Tousey, *J. Geophys. Res.* 56, 583-594 (1951).

35. F.S. Johnson, J.D. Purcell, and R. Tousey, "The Ultraviolet Spectrum of the Sun," *Rocket Exploration of the Upper Atmosphere*, eds. R.L.F. Boyd and M.J. Seaton (New York: Pergamon Press, Inc., 1954).

36. F.S. Johnson, et al., *J. Geophys. Res.* 57, 157-176 (1952).

37. J.W. Townsend, Jr., *Rev. Sci. Inst.* 23, 538 (1952).

38. J.W. Townsend, Jr., E.B. Meadows, and E.C. Pressley, "A Mass Spectrometric Study of the Upper Atmosphere," *Rocket Exploration of the Upper Atmosphere*, eds. R.L.F. Boyd and M.J. Seaton (New York: Pergamon Press, Inc., 1954).

39. W.A. Baum, et al., *Phys. Rev.* 70, 781 (1946).

40. E. Durand, J.J. Oberly, and R. Tousey, *Upper Atmosphere Research Report III,* Report R-3120, Naval Research Laboratory (April 1947).

41. E. Durand, J.J. Oberly, and R. Tousey, *Upper Atmosphere Research Report III,* Report R-3171, Naval Research Laboratory (October 1947).

42. E. Durand, J.J. Oberly, and R. Tousey, *Phys. Rev.* 71, 827 (1947).

43. E. Durand, J.J. Oberly, and R. Tousey, *Astrophys. J.* 109 (1949).

44. R. Tousey, K. Watanabe, and J.D. Purcell, *Phys. Rev.* 83, 792 (1951).

45. N.R. Wilson, et al., *Astrophys. J.* 119, 590 (1954).

46. D.S. Stacey, et al., *Electronics* 27, 80 (1954).

47. W.A. Rense, *Phys. Rev.* 91, 299 (1953).

48. F.S. Johnson, J.D. Purcell, and R. Tousey, *Phys. Rev.* 95, 621 (1954).

49. F.S. Johnson, et al., *Astrophys. J.* 127, 80 (1958).

50. R. Tousey, *Astrophys. J.* 149, 239 (1967).

51. H. Friedman, S.W. Lichtman, and E.T. Byram, *Phys. Rev.* 83, 1025 (1951).

52. T.R. Burnight, *Phys. Rev.* 76, 175 (1949).

53. H. Friedman, *Proc. IRE* 37, 791 (1949).

54. E.O. Hulburt, *Phys. Rev.* 53, 344 (1938).

55. E.T. Byram, et al., *J. Opt. Soc. Am.* 42, 876 (1952).

56. E.T. Byram, et al., *Phys. Rev.* 91, 1278 (1953).

57. E.T. Byram, T.A. Chubb, and H. Friedman, *J. Geophys. Res.* 61, 251 (1956).

58. J.R. Bates and M.J. Seaton, *Proc. Roy. Soc. (London)*, B63, 129 (1958).

59. E.T. Byram, T.A. Chubb, and H. Friedman, *Phys. Rev.* 98, 1594 (1955).

60. H. Friedman, *Physics of the Upper Atmosphere*, ed. J.A. Ratcliffe (New York: Academic Press, Inc., 1960) p. 133 ff.

61. T.A. Chubb, et a., *J. Geophys. Res.* 62, 389 (1957).

62. H. Friedman, et al., *Ann. Géophysique*, 14, 232 (1958).

63. T.A. Chubb, H. Friedman, and W.R. Kreplin, *J. Geophys. Res.* 65, 1831 (1960).

64. E.T. Byram, T.A. Chubb, and H. Friedman, *Astrophys. J.* 139, 1135 (1964).

65. R. Tousey, *Ann. Géophysique*, 14, 186 (1958).

66. J.E. Kupperian, Jr., et al., *Ann. Géophysique*, 14, 329 (1958).

67. T.A. Bergstralh, Naval Research Laboratory Report R-3083 (April 1947).