NASA SP-289

APOLLO 15

Preliminary Science Report

PREPARED BY
NASA MANNED SPACECRAFT CENTER

Scientific and Technical Information Office 1972
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

10. Solar-Wind Spectrometer Experiment

Douglas R. Clay,[a] *Bruce E. Goldstein,*[a]
Marcia Neugebauer,[a] *and Conway W. Snyder*[a†]

With the deployment of the Apollo 15 lunar surface experiments package, two identical solar-wind spectrometers (SWS), separated by approximately 1100 km, are now on the lunar surface. The spectrometers provide the first opportunity to measure the properties of the solar plasma simultaneously at two locations a fixed distance apart. It is hoped that these simultaneous observations will yield new information about the plasma and its interaction with the Moon and the geomagnetic field. At the time of preparation of this report, magnetic tapes of only 20 hr of simultaneous data had been received. These data are discussed in this preliminary report.

The SWS experiment was designed with the objective of measuring protons and electrons at the lunar surface. Solar-wind and magnetic-field measurements by the Lunar Orbiter Explorer 35 spacecraft (refs. 10-1 to 10-5) have established that no plasma shock is present ahead of the Moon and that the solar wind is not deflected significantly by the Moon. Since then, the SWS experiment of Apollo 12 (ref. 10-6), the charged-particle lunar environment experiment of Apollo 14 (ref. 10-7), and the suprathermal ion detector experiments of Apollo 12 and 14 (refs. 10-8 and 10-9) have established that solar-wind protons reach the lunar surface without major deflection. In addition, magnetometer experiments at the Apollo 12 and 14 sites (refs. 10-10 and 10-11) detected local magnetic fields with strengths of 30 to 100 gammas.

The scientific objective of the Apollo 15 SWS experiment is an investigation of the following phenomena.

(1) *Lunar photoelectric layer.*—measure electron-charge fluxes at the lunar surface.

(2) *Interaction of the solar wind with the local magnetic field.*—determine the change in proton direction and bulk velocity by comparison with interplanetary data.

(3) *Lunar limb shocks.*—determine if lunar limb shocks are detectable at the experiment site during dawn or dusk.

(4) *Solar-wind monitor.*—use the experiment to measure solar-wind conditions.

(5) *Motion and thickness of bow shock and magnetopause.*—make direct, simultaneous comparisons with data taken at the Apollo 12 site.

(6) *Plasma fluctuations.*—study time-dependent phenomena such as waves and plasma discontinuities modified by the local magnetic field and lunar photoelectron layer.

INSTRUMENT DESCRIPTION

The basic sensor in the SWS is a Faraday cup, which measures the charged-particle flux entering the cup by collecting the ions and by using a sensitive current amplifier to determine the resultant current flow. Energy spectra of positively and negatively charged particles are obtained by applying fixed sequences of square-wave ac retarding potentials to a modulator grid and by measuring the resulting changes in current. Similar detectors have been flown on a variety of space probes (ref. 10-3).

To be sensitive to solar-wind plasma from any direction (above the horizon of the Moon) and to ascertain the angular distribution of the solar-wind plasma, the SWS has an array of seven cups. Because the cups are identical, an isotropic flux of particles would produce equal currents in each cup. If the flux is not isotropic but appears in more than one cup, analysis of the relative amounts of current in the collectors can provide information on the direction of plasma flow and its anisotropy. The central cup faces

[a]Jet Propulsion Laboratory, California Institute of Technology.
† Principal investigator.

the vertical, and the remaining six symmetrically surround it, each facing 60° from the vertical. The combined acceptance cones of all cups cover most of the upward hemisphere. Each cup has a circular opening, five circular grids, and a circular collector. The function of the grid structures is to apply an ac modulating field to incoming particles and to screen the modulating field from the inputs to the sensitive preamplifiers (fig. 10-1). The entrance apertures of the cups were protected from damage or dust by covers which remained in place until after the departure of the ascent portion of the lunar module (LM). The response of this cup to ions and electrons has been measured by laboratory plasma calibrations at various plasma conditions. The angular dependence for ions, averaged over all seven cups, is shown in figure 10-2 and agrees quite well with the calculated response. The result for electrons is similar at small angles, but has a large-angle tail caused principally by secondary electrons ejected from the modulator grid. This mode of response can occur only when the modulator voltage is negative (i.e., the electron-measuring portion of the instrument operation).

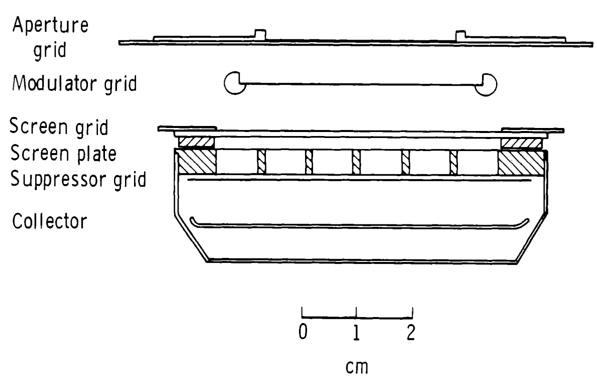


FIGURE 10-1.–Faraday cup sensor.

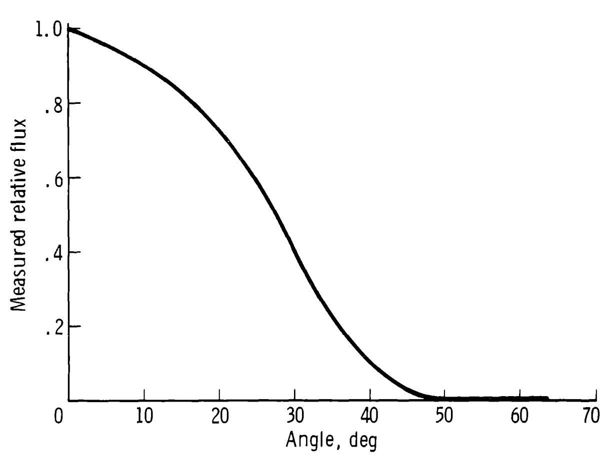


FIGURE 10-2.–Angular response of Faraday cup.

The electronics package for the instrument is in a temperature-controlled container, which hangs below the sensor assembly. The electronics package includes power supplies, a digital programer that controls the voltages in the sensors as required, the current-measuring circuitry, and data-conditioning circuits.

The instrument operates in an invariable sequence in which a complete set of plasma measurements is made every 28.1 sec. The sequence consists of 14 energy steps spaced by a factor of $\sqrt{2}$ for positive ions and seven energy steps spaced by a factor of 2 for electrons. In high range, the energy varies from 50 to 10 400 eV for ions and from 10 to 1480 eV for electrons; and, in low range, each level is reduced by a constant factor of 1.68. The range is changed by ground command. A large number of internal calibrations is provided, and every critical voltage is read out at intervals of 7.5 min or less.

The sequence of measurements starts at the lowest-energy-proton step. Eight measurements--each of seven cups and the combined output of all cups--are taken during the 1.22 sec at each step. Following the 17.1 sec required for all 14 proton steps in ascending energy, 2.5 sec of calibration measurements are made; and, finally, 8.5 sec of electron data are taken sequentially from lowest to highest energy levels.

INSTRUMENT DEPLOYMENT

The SWS was deployed without difficulty near the end of the first extravehicular activity period on July 31, 1971. The spectrometer is shown on the lunar surface prior to dust-cover removal in figures 10-3 and 10-4. A portion of the deployment procedure provided for proper orientation of the instrument. The orientation was facilitated by a shadowing device (to aline in an easterly direction) and a pendulum suspension from the supporting legs (for self-leveling in one dimension). A study of the shadowing as seen in the photographs indicates preliminary values of 1° clockwise rotation (as seen from above), 2° slope to the east, and 2-1/2° slope to the north. All values are well within the specified tolerance of 5°.

Cups numbered 1 to 6 are ordered in a clockwise (as seen from above) manner, with cup 1 pointing to

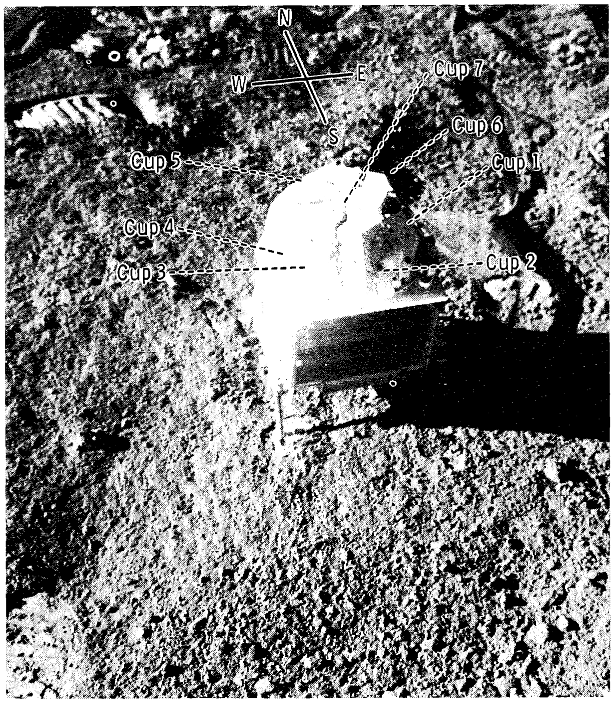


FIGURE 10-3.–Solar-wind spectrometer experiment deployed on the Moon as viewed from the north prior to dust-cover removal (AS15-86-11594).

FIGURE 10-4.–Solar-wind spectrometer experiment as viewed from the south prior to dust-cover removal. Shadowing patterns, especially on the surface of cup 3, give information about orientation of the deployed instrument (AS15-86-11593).

the east. The cup centered in the vertical direction is designated number 7. As a consequence of the SWS orientation and the 26.07° N latitude of the Apollo 15 site, the particles coming directly from the Sun enter cup 1 during lunar dawn. The direction of the average solar plasma is below cup 1 at sunrise and traverses a path between cups 1 and 2; between cups 1, 2, and 7 at midmorning; between cups 2 and 7; and is nearly midway between cups 2, 3, and 7 at midday. In a symmetric manner, the plasma passes between cups 3 and 7; between cups 3 and 4; and, finally, below cup 4 at sunset.

Shortly after deployment, at 19:37:10 G.m.t. on July 31, the SWS was turned on to provide background data with sensor covers in place. Approximately 1 hr after LM ascent, at 18:07:32 G.m.t. on August 2, the covers were removed by command from Earth, and detection of solar plasma began.

INSTRUMENT PERFORMANCE

Sampling of the housekeeping and calibration data for the first 2 months has indicated that the SWS has operated properly. The thermal control of the instrument is completely adequate, with electronics-package temperatures ranging from 254 to 328 K and sensor temperatures from 163 to 344 K. These values agree well with those of the SWS on Apollo 12 and provide confidence that this instrument also will have a long life of stable operation.

METHOD OF ANALYSIS FOR POSITIVE-ION SPECTRA

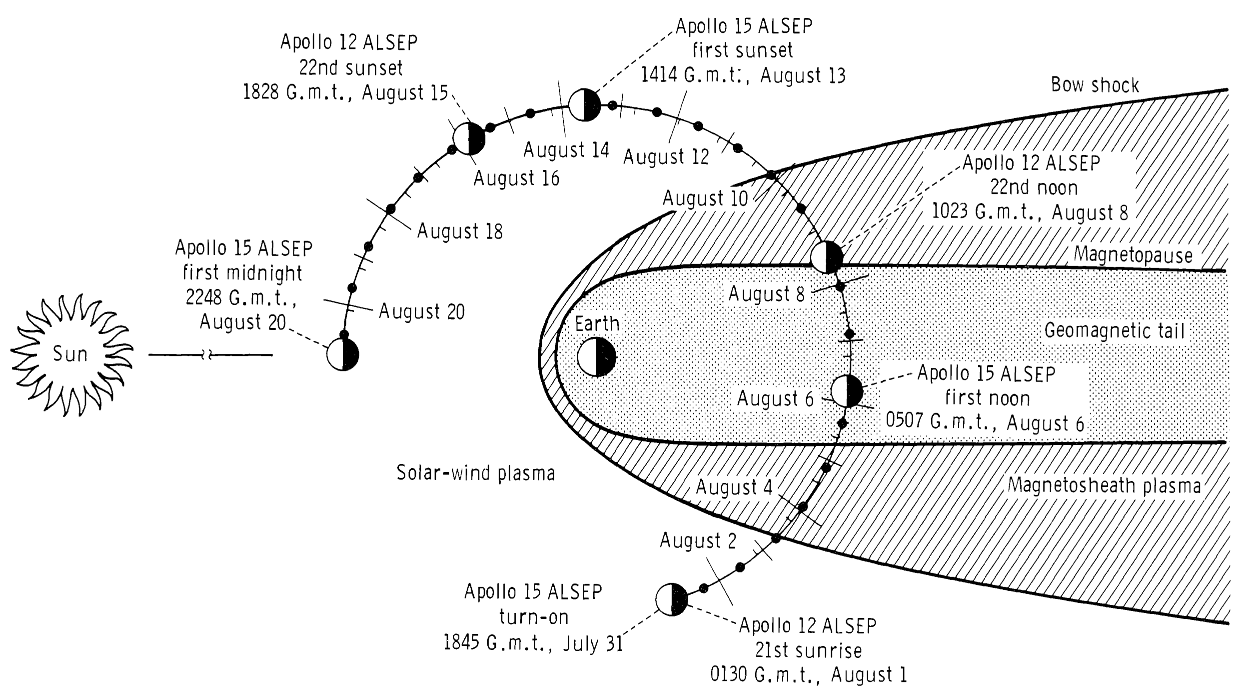
The usual method of obtaining solar-wind parameters (bulk velocity including direction, proton density, and most-probable thermal speed) is described in the following paragraphs.

The digital numbers for the 14 energy windows and the seven cups are converted to currents at the collectors. From the sums of current over all energies for each cup, the cups that have collected plasma are identified; and, if more than one cup, angles of plasma incidence are estimated. The current ratios from two cups can give only one angle; therefore, current in three cups is required to define the two angles of bulk velocity. For a plasma of velocity between Mach 4 and 20 (as interplanetary solar wind usually is), the geometry and the sensor array typically provide significant currents in two cups, with measurable currents in one or three cups occurring less often. For times when one or more angles are unknown, the assumption is made that the undetermined angle is that of the average solar wind; the average angles used are dependent upon time (i.e., the position of the Sun in the lunar sky corrected by 5° in the ecliptic plane for aberration caused by the motion of the Moon about the Sun).

The angles and the spectrum of currents then are combined to get a differential flux distribution for the cup with the largest total current, including corrections for transparency as a function of angle. A curve-fitting program then fits (in a least-squares sense) two gaussian curves to the data in the six to eight energy windows about the peak. The six degrees of freedom for the fitting are reduced to five by assuming that the bulk velocity of hydrogen and helium ions is the same. This analysis provides estimates of the hydrogen density, hydrogen velocity, hydrogen most-probable thermal speed, helium density, and helium most-probable thermal speed. Because the angular response of the cup is somewhat dependent upon the thermal speeds (higher thermal speeds yielding greater transparency for an incoming plasma at large angles), the curve fitting is reiterated when the thermal-speed results are significantly different from those initially assumed.

ION OBSERVATIONS

The SWS at the Apollo 15 site has detected solar plasma with parameters characteristic of both interplanetary solar wind and magnetosheath plasma. (See fig. 10-5 for nominal plasma regions near the Earth and the Moon.) A time plot of bulk speed and proton density for a portion of August 2 is shown in figure 10-6. The upper two curves for Apollo 15 SWS measurements show plasma detected at the time of the dust-cover removal (18:07 G.m.t.). Shown on the same time scale are SWS measurements from the Apollo 12 site. There is good agreement in relative changes for all parameters at each site. The plasma properties at the Apollo 12 site seem to fluctuate



Note: Positions at 0000 G.m.t. on dates noted.

ALSEP = Apollo lunar surface experiments package.

FIGURE 10-5.—Solar plasma regions in the vicinity of the Earth and the Moon. Moon positions are shown relative to the Earth-Sun line.

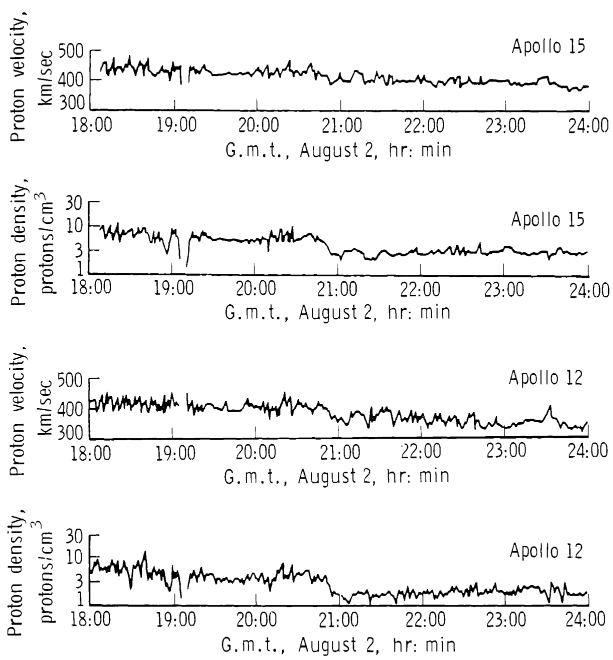


FIGURE 10-6.–Proton velocity and density at the Apollo 12 and 15 sites for 6 hr of August 2.

somewhat more. The spectra at both sites for the period between 18:00 and 19:00 G.m.t. show typical magnetosheath plasma, with large and frequent changes in velocity, density, and thermal speed. The mean thermal speed of protons was approximately 82 km/sec during this period. This relatively high value is characteristic of magnetosheath plasma. A gap can be seen in data plotted from 19:05 to 19:10 G.m.t., when the density became unusually low. This condition was observed at both Apollo sites and subsequently will be discussed in more detail.

Several crossings of the bow shock of the Earth are apparent in the interval from 19:00 to 21:00 G.m.t. The spectra between 21:00 and 24:00 G.m.t. are typical of interplanetary solar wind, with relatively small fluctuations of parameters and smaller thermal speeds (approximately 63 km/sec for this interval). The identification of these regions is corroborated by the signatures of the magnetic field as seen by the lunar surface magnetometer.

The orientation of the Apollo 12 SWS is similar to that of the Apollo 15 SWS, but the Apollo 12 SWS is closer to the equator (2.97° S latitude). Near 18:00 G.m.t. on August 2, the solar-wind direction (corrected for aberration) was 11-1/2° below the axis of the easterly facing cup of the Apollo 12 SWS. At this position, plasma enters only one cup; thus, all angles used in the analysis are those of the assumed average plasma. At the same time, the assumed average solar-wind direction at the Apollo 15 SWS is midway between cups 2 and 1 (29-1/2° from the normal of each) and 41° off the vertical (from the normal of cup 7). On many occasions, enough plasma is detected in cups 2, 1, and 7 to determine the two angles of the plasma velocity. These results show a deviation from the assumed angle of approximately 15° west but still near the ecliptic plane.

Both the proton velocity and the density appear to be lower at the Apollo 12 SWS. A detailed investigation of a few cases has shown that the density discrepancy can be reduced to 30 percent by assuming that the solar-wind direction at the Apollo 12 site is the same as that at the Apollo 15 site.

The obvious need arises for all angles of solar plasma to be known simultaneously at both spectrometers. As more data become available for analysis, it is anticipated that such times will occur. This condition is most likely to occur during the afternoon when the Moon has passed the bow shock and when the Apollo 12 SWS has data in both the vertical and westerly cups. In the past, there have been many occasions when a third cup is also detecting plasma so that all angles are calculable. At these fortunate times, it is further anticipated that the deflection of the plasma by the local magnetic or electric fields will be discernible.

The general features of plasma speed and density as the Moon approached the geomagnetic tail on August 4 are shown in figure 10-7. There are several gaps in the graph where the density dropped well below the threshold of detection of the SWS (less than 0.15 proton/cm^3). This response is typical in the geomagnetic-tail region. Several such passages are

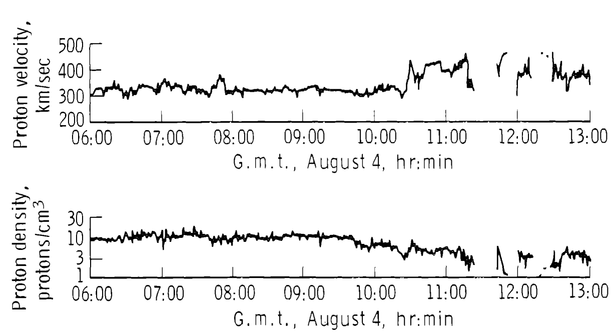


FIGURE 10-7.–Proton velocity and density for 7 hr of August 4 when Apollo 15 site first entered the geomagnetic-tail region.

shown near 11:30 and 12:15 G.m.t. The Moon passed into the geomagnetic tail at 23:02 G.m.t. on August 4, 1971.

When discontinuities in plasma parameters occur (such as at bow-shock and magnetopause crossings), it is hoped that one velocity component for the discontinuity can be determined by comparisons of simultaneous measurements at the Apollo 12 and 15 sites.

ELECTRON AND PROTON ENERGY SPECTRA

Between 19:05 and 19:10 G.m.t. on August 2, a sharp drop in solar-wind density was observed, as shown in figure 10-6. An expanded version of the data (fig. 10-8) shows proton and electron energy spectra for the period 19:00 to 19:12 G.m.t. The third and fourth rows of this figure display ion energy spectra measured by the Apollo 15 and 12 instruments, respectively, derived from the measurements in which all seven Faraday cups are connected electronically. (The gaps in the data are caused by periodic calibration measurements.) Raw-data numbers are plotted; these are approximately proportional to charge flux. Both instruments show a simultaneous drop in proton charge flux at 19:04 G.m.t. and a recovery at 19:11 G.m.t. Also, the total charge flux summed over all channels seems to vary more at the Apollo 12 site. This difference in variation might be caused by the interaction of the plasma with the strong local magnetic field at the Apollo 12 site. Alternatively, directional fluctuations in the ecliptic plane would yield greater changes in the charge-flux measurements at the Apollo 12 site than at the Apollo 15 site.

The data numbers measured in cups 1, 2, and 7 and summed over all energy channels are displayed at the bottom of figure 10-8. These currents indicate that the protons substantially change direction from 19:03 to 19:05 G.m.t. Because a cup measures less current when the protons enter at a greater angle to the cup normal, some decrease in charge flux at both sites can be attributed to a change of angle; but most is caused by a change in density. The relative lack of change of current in cup 1 lends no support to the possibility of ecliptic directional changes causing proton flux fluctuations at the Apollo 12 site.

The electron energy spectra measured at the Apollo 15 site are shown in figure 10-8; the first row represents cup 4, and the second row represents cup 5. Both cups point well over 90° away from the solar direction and are, therefore, uncontaminated by secondary electrons generated inside the cup by protons or by photons. The data numbers plotted

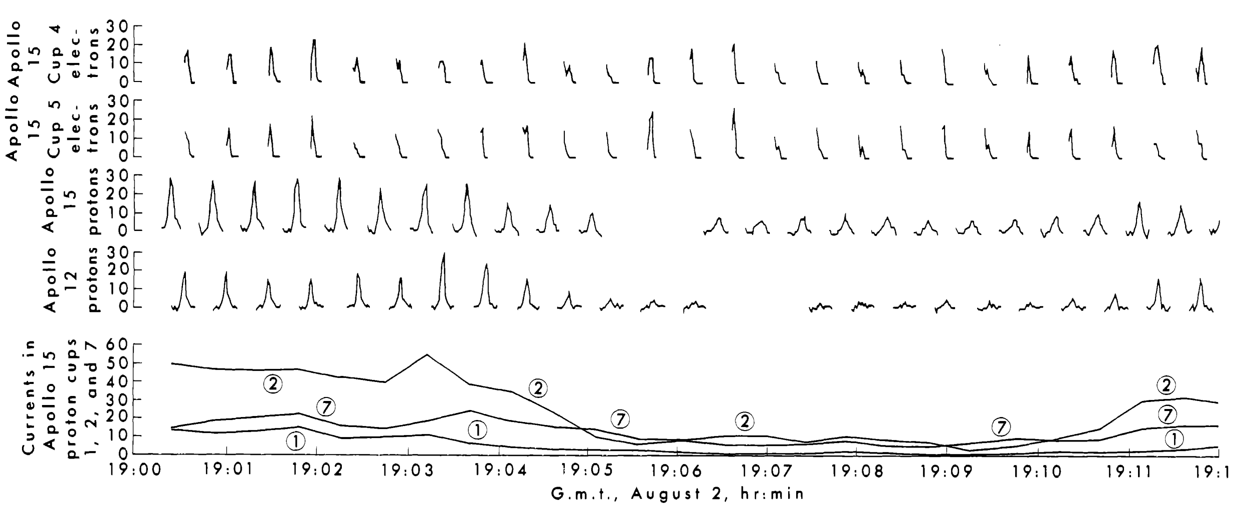


FIGURE 10-8.–Apollo 15 and Apollo 12 SWS data from August 2. The first two rows are electron charge-flux spectra measured by cups 4 and 5 of the Apollo 15 instrument. The next two rows are total ion charge-flux spectra obtained at the Apollo 15 and Apollo 12 sites. The three lines at the bottom are charge flux summed over energy channels measured in cups 1, 2, and 7 of the Apollo 15 instrument.

have not been corrected for the response of the cup as a function of incident electron energy. Therefore, the shapes of the electron spectra plotted are somewhat distorted. The error is almost the same for all electron spectra, so electron spectra can be compared directly to each other.

It should be noted that, in many cases, the spectra observed in cups 4 and 5 are similar in shape and magnitude. In the high-density proton region, cup 4 has a tendency to observe more electrons than cup 5; but, in the low-density region, this relation is reversed. This phenomenon might be caused by changes in orientation of the magnetic field. Also, electron fluxes and proton fluxes do not seem to be strictly proportional from spectrum to spectrum. This fact suggests that a large portion of the electrons observed may be lunar photoelectrons.

Some electron spectra plotted have two peaks. Also, in some cases, the magnitude and shape (energy distribution) measured in cups 4 and 5 are considerably different. Because the time between measurements for cups 4 and 5 in a given energy channel is 0.151 sec, fluctuations with frequencies near 5 Hz are implied. The spectra of protons from the summed cups and from cups 1, 2, and 7 (not shown) show no rapid oscillations. With the aid of magnetic-field data, it may be possible to attribute electron fluctuations to changes in field direction.

SUMMARY AND RESULTS

This report is based on examination of 4 days of Apollo 15 data and 1 day of Apollo 12 data within the same time interval. The Apollo 15 instrument is performing as expected. Solar-wind plasma, magnetosheath plasma, and magnetopause crossings have been observed. Proton measurements at the Apollo 15 and Apollo 12 sites show similar behavior. When angular estimates at both instruments become available, detailed comparisons of velocity and density estimates will be made.

Rapid fluctuations (5 Hz) have been observed in the electron spectra. Interpretation of this phenomenon requires knowledge of magnetic-field direction changes. Complete data and detailed comparison with other solar-wind experiments will be required before comprehensive conclusions can be drawn.

REFERENCES

10-1. Colburn, D. S.; Currie, R. G.; Mihalov, J. D.; and Sonett, C. P.: Diamagnetic Solar-Wind Cavity Discovered Behind Moon. Science, vol. 158, no. 3804, Nov. 24, 1967, pp. 1040-1042.

10-2. Sonett, C. P.; Colburn, D. S.; and Currie, R. G.: The Intrinsic Magnetic Field of the Moon. J. Geophys. Res., vol. 72, no. 21, Nov. 1, 1967, pp. 5503-5507.

10-3. Ness, N. F.; Behannon, K. W.; Taylor, H. E.; and Whang, Y. C.: Perturbations of the Interplanetary Magnetic Field by the Lunar Wake. J. Geophys. Res., vol. 73, no. 11, June 1, 1968, pp. 3241-3440.

10-4. Ness, N. F.; Behannon, K. W.; Searce, C. S.; and Cantarno, S. C.: Early Results from the Magnetic Field Experiment on Lunar Explorer 35. J. Geophys. Res., vol. 72, no. 23, Dec. 1, 1967, pp. 5769-5778.

10-5. Lyon, E. F.; Bridge, H. S.; and Binsack, J. H.: Explorer 35 Plasma Measurements in the Vicinity of the Moon. J. Geophys. Res., vol. 72, no. 23, Dec. 1, 1967, pp. 6113-6117.

10-6. Snyder, Conway W.; Clay, Douglas R.; and Neugebauer, Marcia: The Solar-Wind Spectrometer Experiment. Sec. 5 of Apollo 12 Preliminary Science Report, NASA SP-235, 1970.

10-7. O'Brien, Brian J.; and Reasoner, David L.: Charged-Particle Lunar Environment Experiment. Sec. 10 of Apollo 14 Preliminary Science Report, NASA SP-272, 1971.

10-8. Freeman, J. W., Jr.; Balsiger, H.; and Hills, H. K.: Suprathermal Ion Detector Experiment (Lunar Ionosphere Detector). Sec. 6 of Apollo 12 Preliminary Science Report, NASA SP-235, 1970.

10-9. Hills, H. K.; and Freeman, J. W., Jr.: Suprathermal Ion Detector Experiment (Lunar Ionosphere Detector). Sec. 8 of Apollo 14 Preliminary Science Report, NASA SP-272, 1971.

10-10. Dyal, Palmer; Parkin, Curtis W.; and Sonett, Charles P.: Apollo 12 Magnetometer: Measurement of a Steady Magnetic Field on the Surface of the Moon. Science, vol. 169, no. 3947, Aug. 21, 1970, pp. 762-764.

10-11. Dyal, P.; Parkin, C. W.; Sonett, C. P.; DuBois, R. L.; and Simmons, G.: Lunar Portable Magnetometer Experiment. Sec. 13 of Apollo 14 Preliminary Science Report, NASA SP-272, 1971.