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IN NUCLEAR SCIENCE ABSTRACTS

Vela Satellite Measurements†

James H. Coon
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

1. INTRODUCTION

The satellite orbit chosen for the Vela Satellite Program was such as to avoid the primary regions of particle radiation trapped in the earth's magnetic field. The orbit was chosen to be circular at about 17 earth radii distance from the center of the earth in order to be outside the regions of durable trapping of particles. During each orbit the satellites traverse a region of interplanetary space on the sunward side of the earth beyond the

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influence of the earth's magnetic field. Then they pass into the transition region, through the magnetospheric boundary, across the tail of the magnetosphere, and back out through the transition region into interplanetary space again. It appears likely that particles in these regions of space constitute sources or sinks of particles for the trapped radiation zones, and are therefore valid subject matter for the present discussions of the trapped radiations.

Information about the characteristics of the low and medium energy particle radiations in the regions of space traversed by the Vela satellites has been and is being acquired by the satellites; the present report will summarize observations to the extent that the present state of analysis permits. As with many space programs, complete analysis has not kept up with the acquisition of data on magnetic tape. Some of the results to be presented here will be observations which, in a preliminary analysis, appear to be typical or representative of conditions which are varying. Because of the fluctuating nature of radiations in space, their characterization frequently requires statistical study over long periods of time, and detailed correlations with other related observations are required for purposes of interpretation. Also, special periods of extreme or unusual conditions should be selected for more detailed study and for comparisons with additional types of correlated signals. These kinds of more complete analysis have so far been carried out to a limited extent only, but are being continued with accelerated effort. Although some of this work has been published, (Singer et al., 1964; and Montgomery et al., 1965) and reported at meetings, (Argo et al., 1964; Bame et al., 1965; Asbridge et al., 1965; and Strong et al., 1965) it is anticipated that as analysis continues and more data are

acquired, more complete reports will be published by members of the Space Science Group at Los Alamos Scientific Laboratory. This staff has provided most of the information on the space radiation measurements presented in this report.

In this report there will be no attempt to review the present state of knowledge relevant to the diverse observations reported. Instead, the terminology of recent literature will be employed, and a few brief remarks, references, and comparisons will be given to provide some orientation as to the significance of the observations reported.

2. VELA SATELLITE PROGRAM

To provide an understanding of some of the motivations of the work to be reported here, a few brief statements about the program, and in particular about the character of the instrumentation onboard the satellites may be useful. A primary objective of the Vela Satellite Program is to carry out research and development on methods of detecting nuclear explosions in space by means of satellites. A major goal is to develop capabilities for policing an international treaty banning the testing of nuclear weapons.

Selection of types of satellite-borne instruments, and determination of their design to detect nuclear explosions, depends critically on two factors. The first of these is the nature of the output radiations from a nuclear explosion in space. The second is the nature of the background

radiations in the environment encountered by the instruments. Radiations from a nuclear explosion are comparatively well known, and are of sufficient intensity to be easily detected by state-of-the-art instruments over distances comparable to the earth-sun distance, unless background radiations produce interfering signals. Many features of the radiation background signals are still unknown, particularly over the full 11-year cycle of solar activity. Thus the Vela Satellite Program conducts basic investigations of those types of background radiations to which the nuclear weapon detectors are thought to be most susceptible.

From the above statements it may be correctly inferred that there are two general types of instruments on the Vela satellites. One type, to be referred to as type A, is designed specifically to detect and identify radiations characteristic of a nuclear explosion, in spite of background radiations. Type B instruments on the other hand, are designed to study selected natural radiations, which may interfere with the operation of the type A instruments, or with the interpretation of data recorded by the instruments. It is, in some cases, particularly advantageous to observe signals from the background radiations simultaneously with both types of instruments on the same satellite. It has been found, as might be expected, that type A instruments, with their associated signal processing and data handling circuits, are relatively poor or even useless for investigating the natural radiations. Thus the total complement of radiation sensors on the satellites is not effectively devoted to scientific study, but instead a rather small fraction of it.

To date there have been three pairs of Vela satellites put into orbit. The first pair carried only type A instrumentation, while the second and third carried additional instrumentation of type B. The first pair, referred to as the Vela 1 satellites, have obtained some information of scientific interest, but the additional instruments of type B onboard the Vela 2 and 3 satellites greatly increase the capability of obtaining basic information on the natural radiations.

3. ORBITAL COVERAGE AND COORDINATE SYSTEMS

Because of its importance in presenting results in a later section of this chapter, a description of orbital coverage and coordinate systems will now be presented. As mentioned above, there have been three Vela satellite launches. The launch dates were 17 October 1963, 17 July 1964, and 20 July 1965. Each launch has placed a pair of 300 pound satellites into approximately circular orbits, all of which are approximately coplanar, and the direction of motion is counter clockwise as viewed from above the northern hemisphere, i.e., from above the ecliptic plane. The orbit parameters are as follows: the period is 100 to 111 hours; apogee is in the range 17 to 20 R_e (distance from center of earth in earth radii); perigee is in the range 16 to 18 R_e ; inclination of the orbit plane to the ecliptic plane is 55° to 62° ; and the inclination of the orbit plane to the earth's equatorial plane is 35° to 40° . The satellites are spin stabilized with a spin rate of 2.0 to 2.2 rps, and the spin axis makes an angle of $\sim 60^\circ$ with the ecliptic plane. In addition, on launches 2 and 3, a smaller third

satellite weighing approximately 10 pounds was lofted into a highly elliptical orbit. Experiments on these small satellites will not be reported on here.

Some features of the geometrical sampling of points in space by satellites in the orbit described above are illustrated in Figure 1, in which circular orbits are drawn as they would appear at different seasons of the year in the solar ecliptic coordinate system. The earth is taken to be at the origin which is the center of this sphere, the X axis extends from the earth toward the sun, the Y axis extends in the ecliptic plane toward the "dusk" meridian, and the Z axis extends perpendicular to the ecliptic plane into the northern hemisphere. The earth moves in the minus Y direction in its orbit around the sun. In this coordinate system the satellite orbit plane rotates seasonally, so that during two periods of the year the satellites cross the ecliptic plane near the dawn and dusk meridians, and 3 months later the crossings are near the subsolar and antisolar points. The region of space sampled by the Vela satellites once every 6 months are points within a spherical shell of 17 to 18 R_e average radius, except points for which ecliptic latitude exceeds $+60^\circ$ in the northern hemisphere or -60° in the southern. Figure 2 is similar to Figure 1, except that areas of coverage are indicated in terms of regions in the magnetosphere and beyond.

The unusual features of the Vela orbits are: (1) points are sampled in the magnetopause and nearby transition region at distances up to 16 R_e from the ecliptic plane; compared with most space research spacecraft, this is relatively far from the ecliptic plane; and (2) because of the 4-day

Fig 1

REGIONS COVERED
BY VELA ORBITS

Fig 2

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circular orbit, points on opposite sides of the magnetosphere are sampled in rapid sequence. Relatively little information can be acquired about dependence of radiations on radial distance from the earth; such information is a major objective of the Explorer series of satellites with very eccentric orbits.

As of August 1, 1965, the six satellites continue to function and provide useful data.

4. INSTRUMENTATION

In this section will be presented a brief description of the characteristics of the instruments employed on the Vela satellites for making observations of low or moderate energy charged particles. These instruments detect electrons, protons, or alpha particles, and measure parameters such as flux, energy spectrum, and direction distribution over a selected range of values. Five types of instruments are employed as described below. The first type listed, the M4 detector, was on both Vela 1 and Vela 2 satellites. The remaining four types were on the Vela 2 satellites. The Vela 3 satellites carried improved instruments of these same types, and also some new types. These will not be described here, because no results from the Vela 3 satellites are presented in this report. Although all the Vela 3 instruments are functioning as planned, and the observations are significantly more sophisticated, there was not sufficient time since launch to prepare results for this report.

Data are obtained from the instruments by two very different methods. The first of these is during actual real time tracking of a satellite by a ground station. During such times the information rate is 256 bits per second. In the second method a relatively small fraction of information from the instruments, 256 times less than during real time tracking, is held in storage on the satellite for subsequent transmission. Most of the useful data of scientific interest is acquired during real time tracking, which is typically one hour out of every four. There is, however, a considerable amount of additional real time tracking for special purposes of obtaining data during particular times or regions of the orbit.

a. M4 Scintillation Detectors

There are eight to ten of these detectors on each of the Vela 1 or Vela 2 satellites. They employ thin screens of cesium iodide scintillator viewed by photomultiplier tubes, and covered with thin films of beryllium. They respond to electrons of energy greater than ~ 85 keV ($\sim 50\%$ transmission of electrons thru 3.4 mgm cm^{-2} Be) and to solar x-rays. Differentiation of these two types of radiation is based on (1) the character of signal modulation, or on (2) comparisons with signals from other instruments on-board the same satellite, or on (3) comparisons with signals from instruments on one of the other Vela satellites.

The solid angle viewed by these detectors is $> 2\pi$ steradian and no attempt is made to investigate directional effects for charged particles. The flux threshold is $\sim 2 \times 10^4$ electrons $\text{cm}^{-2} \text{ sec}^{-1}$ omnidirectional.

There is a capability for measuring flux level in 7 steps on the Vela 1 satellites or 14 steps on the Vela 2 satellites up to $\sim 10^6$ electrons cm^{-2} sec^{-1} .

b. M5 Scintillation Detectors

One set of these detectors on each of the Vela 2 satellites are similar to the M4 detectors described above, but have elements with greater sensitivity, wider dynamic range of measurement, and lower electron energy threshold. These detectors measure electrons of energy greater than ~ 50 keV ($\sim 50\%$ transmission of electrons thru 2.3 mgm cm^{-2} Be) with a flux threshold of $\sim 10^3$ electrons cm^{-2} sec^{-1} omnidirectional.

c. Electrostatic Analyzer

The electrostatic analyzer employs a pair of concentric hemispherical electrodes between which a potential is applied for deflection of charged particles into an electron multiplier particle counter. Polarity of the applied potential may be reversed, so that either positive or negative particles may be detected. Particle energy per unit charge over the range 0.3 to 20 keV is measured in 14 steps by successively stepping the magnitude of the applied potential. Qualitative information is also obtained about electrons of $\sim 100 - 200$ eV energy.

Information about directional distribution of particle motions is obtained by employing the spinning motion of the satellite for direction

scanning. Details of the directional information obtained depend in a complicated way on several factors including the geometry of the acceptance aperture of the instrument, satellite spin rate, satellite spin axis orientation, and on the scanning time sequence whereby particles are observed at successive azimuthal angles by successive time delays after a signal is received by a sun sensor. In the simplified case for which particle motion is assumed to be parallel to the ecliptic plane, eight directions in the ecliptic plane are viewed, five of these being equally spaced within $\pm 12^\circ$ of the sunward direction, and one each toward the dawn meridian, toward the dusk meridian, and in the antisolar direction. In this case angular resolution is $\sim \pm 3^\circ$, and angular error is less than 0.2 degree. For particles moving in directions not parallel to the ecliptic plane the angular acceptance is broad, the total angle being 95° . This broad angle is related to the fact that particles may enter the instrument from a fan-shaped region over a total angle range of $\sim 5^\circ$ by 95° .

The time required to acquire information for a complete energy spectrum and directional distribution is 128 seconds during real time tracking. Because successive portions of the data are acquired at 1 second intervals, a change in the character of the radiation can sometimes be sensed with 2 second time resolution.

d. G.M. Counter

A G.M. counter is employed for measuring electrons of energy greater than 40 keV. Particles are accepted from a cone of 35° half angle. The

axis of this cone is perpendicular to the spin axis of the satellite and parallel to the axis of the entrance aperture of the electrostatic analyzer. Information about direction of motion of particles is obtained in the same manner as for the electrostatic analyzer, but the capability is modified by the difference in geometry of the acceptance aperture. In particular, the angular resolution for observing directional distributions in the ecliptic plane is much broader.

e. Solid State Detector

A single element gold surface-barrier silicon particle detector was carried on the Vela 2 satellites. It was designed to measure electron energy spectrum in the range 50 to 475 keV for electrons, or in the range 180 to 570 keV for protons. Electrons and protons can be distinguished by comparison of solid state and G.M. count rates. Energy spectrum is measured in 7 steps, by successive stepping of a pulse height analyzer. The area-solid angle product is $0.04 \text{ cm}^2 \text{ sterad}$, and although the entrance aperture cone is about 20° half angle, no directionality is attempted; counts are accumulated and averaged over more than one satellite revolution period. Minimum detectable flux of electrons is $\sim 100 \text{ cm}^{-2} \text{ sec}^{-1}$ and flux levels up to $\sim 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ may be measured.

5. OBSERVATIONS AND RESULTS

A summary of some of the more significant results obtained by the Vela satellites to date will be presented primarily from an observational point of view. In order to introduce a degree of coherence in presenting observations which are in some cases not closely associated in terms of basic relationships, the results will be presented in a sequence corresponding to the gross flow of particles through the regions of space traversed by the satellites. These regions are illustrated in Figure 3 which shows the general topography of the radiation zones in and beyond the distant magnetosphere as developed by space research during the past few years. The observations to be reported here begin with the flow of particles in interplanetary space, where the solar wind is not disturbed by the earth's magnetic field. From this region particles flow through the bow shock into the transition region, and around the magnetospheric boundary (magnetopause); some of the particles may then pass through the magnetopause into the tail of the magnetospheric cavity, although most of the plasma apparently flows on parallel to the magnetopause for much greater distances. Thus the results will be presented in five sections entitled:

- (a) Interplanetary Medium
- (b) Bow Shock
- (c) Transition Region
- (d) Magnetospheric Boundary
- (e) Magnetospheric Cavity

a. Interplanetary Medium

Fig 3

On the sunward side of the orbit the Vela satellites traverse a region of interplanetary space where the solar wind is undisturbed by the earth's magnetic field, except possibly for rare precursors on the sunward side of the bow shock. It is not clear whether there are precursors extending out as far as the sunward apogee points reached by the satellites. During a part of the time when the Vela 2 satellites are in this region, the electrostatic analyzers measure energy spectra, flux density, and directional distributions of the positive ions in the solar wind. From these observations preliminary analysis allows some statements about bulk velocity, flow directions, effective or apparent temperature, ion density, and the proportion of alpha particles in the solar wind. In addition, limited observations on electrons can be reported, though most of the solar wind electrons have energies too low to be detected by the instruments.

Data for the period from launch on 17 July 1964 through February 1965 has been analyzed in some detail. About 25% of the time during this period at least one of the Vela satellites was in the interplanetary solar wind region, with electrostatic analyzers operating to observe the solar wind positive ions. Examples of three observed positive ion spectra are shown in Figure 4, which illustrates the variable character of the solar wind. These spectra are similar to those observed by others, (Snyder and Neugebauer, 1963; and Wolfe and Silva). The data for one spectrum is acquired in about 2 minutes, during which time directional information is also acquired. More than 10^5 positive ion energy and directional distributions in the solar wind were recorded during the 7-month period mentioned

EXAMPLES OF SOLAR WIND SPECTRA

Fig 4

above. The important features of the spectra illustrated in Figure 4 are: (1) the width of the spectrum which is influenced by the temperature; however it is found that usually the main group in the velocity distributions can be fitted to Maxwellian distributions only qualitatively, and sometimes not even qualitatively; in addition, a high velocity tail of $\sim 10\%$ is usually present; (2) the absolute proton energy values, from which can be derived an average proton velocity, which is a measure of bulk plasma velocity; and (3) the integral under the curve which is a measure of flux density. Of the three spectra shown in Figure 4, the left one shows intermediate spectrum width, while the others are extreme, but not uncommon, examples of broad and narrow spectra. Spectra of this and intermediate character are observed to be present whenever the instrument is operating in the positive ion mode. Analysis is underway to look for possible correlations between a broad spectrum (high temperature), high average proton energy (high bulk velocity), and high flux density.

The observed bulk velocity versus time derived from data of this kind for a 3-month period is plotted in Figure 5, along with reported values of A_p representing the daily average magnetic disturbance observations at ground level. Several interesting features are apparent in this figure. There is an indication of a base line bulk velocity of 320-330 km per sec which may be characteristic of the solar wind escaping from the quiescent sun during this epoch. Usually the bulk velocity is enhanced and variable, with a variable period of the order of hours or days, and, although detailed correlation studies have not yet been made, it is apparent that these enhancements are correlated with solar activity near

Fig 5

the central meridian as seen from the earth. The greatest observed velocity is 720 km per sec. The peaks in the bulk velocity plot generally recur at intervals of ~ 27 days, persisting through several solar rotation periods. The correlation with A_p is good, though it is interesting to note that A_p tends to be a maximum at the time of a sharp rise, rather than at the peak of the bulk velocity.

Figure 6 is another type of observed positive ion energy distribution, where a distinct alpha particle group is observed at the position where the energy per unit charge is twice that of the proton. The zeros along the abscissae line in this figure indicate the positions of other instrumental energy channels, where the observed count was zero. Because the instrumental channel widths are narrow compared with their spacing, there is a deficiency such that there are gaps where particles cannot be observed. At the time of this observation the proton and alpha particle energies were narrow and happened to fall into two channels. Usually the alpha particles are not so well resolved and sometimes they escape detection. However, the analysis of many such observations shows the alpha particle proportion is variable, from less than 1% up to $\sim 20\%$, and the estimated average is 3 to 6%.

In the lower part of Figure 7 is illustrated the instrumental deficiency mentioned above, i.e., the narrow energy channels with wide gaps between them. A similar instrument carried on the Vela 3 satellites fills in these gaps with four times as many channels.

Figure 7 also shows the directional capabilities of the electrostatic analyzer, and the lower half of Figure 8 shows three typical observed proton

Fig. 6

ELECTROSTATIC ANALYSER ANGULAR AND ENERGY PROPERTIES

Fig 7

directional distributions. The center one of these three distributions is typical of the solar wind in interplanetary space, and it can be noted that the component of motion in the ecliptic plane was nearly at 180° , i.e., nearly along the sun-earth line. These directional distributions are typically $\sim 10^\circ$ full width at half maximum, but are sometimes as narrow as $\sim 2^\circ$. When corrected for the aberration due to the earth's motion around the sun, examination of many distributions of this kind indicates the average solar wind direction (its component in the ecliptic plane) is radially outward from the sun within $\pm 2^\circ$. Unambiguous fluctuations of $\pm 6^\circ$ or more, i.e., non-radial flow direction, are commonly observed.

Systematic analysis of temperatures and flux densities in the solar wind have not been made. Effective longitudinal temperatures, derived from the width of the energy spectra, are typically $\sim 10^5$ K or less, and typical positive ion densities are 3 to 5 per cm^3 . These values are in general agreement with other observations, (Snyder and Neugebauer, 1963; and Wolfe and Silva).

Other observations by the Vela satellites on particles in the interplanetary medium include occasional energetic electrons of energy > 40 keV, and protons > 180 keV, with energy spectrum information measured by the solid state detector. Further analysis is required to attempt to determine whether these are associated with precursors on the sunward side of the bow shock, or associated with disturbances inherent in the solar wind as it propagates away from the sun.

In addition, fluxes of electrons of energy ~ 150 to 500 eV are not infrequently observed with the electrostatic analyzer, and the measured flux density of electrons of $E > 350$ eV is in the neighborhood of 10^7 cm^{-2} sec^{-1} . These electrons appear to be solar wind electrons, which are more readily observed with this instrument when the temperature of the solar wind makes excursions to relatively high values.

b. Bow Shock

Twice during each orbit the Vela satellites pass through the region of the so-called bow shock, or hydromagnetic shock wave, (Axford, 1962; Kellogg, 1962; Ness et al., 1964) where the solar wind plasma, carrying the interplanetary magnetic field, is subjected to violent interactions as a result of collision with the earth's magnetic field. Reference to Figures 1, 2, and 3, again will provide orientation as to sampling of points near the bow shock by the Vela satellites. It may be noted that points near the subsolar point are not sampled.

As the Vela satellites traverse the expected bow shock regions, a few R_e beyond the magnetopause, sudden and drastic changes in the character of the solar wind particles are observed. Figure 8 illustrates how the observed proton energy and directional distributions change form at the bow shock. These data were obtained by the electrostatic analyzer during a part of one orbit on October 4, 5, and 6, 1964. The trend shown here repeats itself consistently on other orbital passes. Within the transition region on the dawn side of the orbit the energy spectra are

(a)

(b)

relatively broad; as the satellite moves in its orbit the energy spectra suddenly become much narrower, the average proton energy increases, and the spectrum is characteristic of the interplanetary solar wind; then as the satellite continues around to the dusk side of the orbit, the spectrum suddenly becomes broad again, with a decrease in proton energy. As one passes from interplanetary space through the bow shock into the transition region, the positive ion density is observed to increase, typically by a factor of 1.5 to 2. Referring to the directional distributions in the lower part of Figure 8, we find a similar sequence of sudden changes, where the distribution is relatively broad ($\sim 50^\circ$ full width at half maximum) in the transition region, and narrow ($\sim 10^\circ$ full width at half maximum) in interplanetary space. These changes are sometimes observed to occur in times no greater than 2 seconds. On some passes the changes occur several times within a few tens of minutes, as if the bow shock is shifting out and in rapidly because of fluctuations in the solar wind. If this interpretation is correct, the position of the bow shock is observed to shift by distances up to several R_e .

Electron data for this same orbital pass of October 5, 1964 are shown in Figure 9. These observations will not be described in detail, but the character of the electron flux also goes through sudden and violent changes at the bow shock.

An overall view of the changes in proton and electron fluxes is consistent with the concept that as the solar wind encounters the bow shock, a turbulence is established in which energy is removed from the solar wind protons, solar wind electrons acquire energy, and the direction

Fig 9

of motion of the particles is made more random. The omnidirectional flux of electrons of energy sufficient to be observed by the instruments increases from $\sim 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ or less for $E > 350 \text{ eV}$ outside the bow shock, up to $\sim 5 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ inside the transition region. The temperature of the protons rises from typical values of $\sim 10^5^\circ\text{K}$ or less in interplanetary space to 10^6°K or more. The observed temperature of the electrons inside the bow shock is typically $\sim 10^6^\circ\text{K}$, and $\sim 5 \times 10^6^\circ\text{K}$ is not uncommon.

c. Transition Region

Many of the characteristics of the charged particles observed by the Vela satellites in the transition region have been described in the above section on the bow shock, and will not be repeated. Two additional results will be given here. One of these concerns the plasma streaming direction as derived from the proton directional distributions observed by the electrostatic analyzer. These directions apply, of course, only to points in the transition region traversed by the Vela satellites. Although a statistical analysis has not yet been made, inspection of scores of distributions indicates the plasma streaming direction usually deviates from the sun-earth line by about 10° or more in a sense so as to indicate that the plasma is streaming parallel to the magnetopause, as observed by others, (Bridge et al., 1965). It should be remembered that the electrostatic analyzer senses the component of motion parallel to the ecliptic plane accurately, but not the perpendicular component of motion.

The second result to be reported here is the observation of a population asymmetry in fluxes of electrons on the dawn and dusk sides of the transition region. This effect is observed with all five types of detectors described in section 4 above on instrumentation. Especially the electrons of $E > 40$ keV are observed relatively rarely in the dusk side transition region, at least an order of magnitude less frequently than on the dawn side. The question of the persistence of this asymmetry is an important one. The asymmetry observations over rather long periods of time will be reported on more fully in section e below, because the asymmetry extends into the magnetospheric cavity.

d. Magnetospheric Boundary

It appears that the location of the magnetospheric boundary, or magnetopause, can be identified with the electrostatic analyzers on the Vela satellites by sudden appearance or disappearance of ~ 0.5 to 5 keV streaming protons which persist in the transition region, but which are usually absent in the magnetospheric cavity. The topmost portion of Figure 9 illustrates this observation and shows characteristics of the proton spectrum observed by the electrostatic analyzer for the pass of October 4, 5, and 6, 1964. The interpretation of this chart is as follows. In the center of the chart the proton spectra are observed to be sharp, and the satellite is in interplanetary space. Toward the edges of the chart the proton spectra become broad, and the satellite is in the transition region. On the left hand side, which is the dawn side, the

spectrum fluctuates several times between sharp and broad as if the bow shock is shifting in and out. At the positions labeled B the protons disappear completely, and the interpretation is that the satellite is inside the magnetospheric cavity. This "proton boundary" appears to coincide with the magnetopause locations as determined by magnetic field and particle observations of others, (Ness et al., 1964; and Frank and VanAllen, 1964). By observations on successive satellite orbits, it is found that the position of the proton boundary varies by distances of up to several R_e , indicating location instability to about the same degree as is observed for the bow shock.

For the one year period following the Vela 2 launch in July 1964, a dawn-to-dusk asymmetry in the location of the proton boundary has been studied. Many determinations of the proton boundary, during seasons when the satellites cut through the ecliptic plane near the magnetopause, indicate the average boundary locations were at $\sim 95^\circ$ ecliptic longitude on the dusk side, and at $\sim 255^\circ$ (instead of the symmetrical angle of 265°) on the dawn side. This implies a tilt of $\sim 5^\circ$ in the ecliptic plane. The magnitude and direction of this tilt provide evidence for symmetry of the magnetospheric boundary with respect to the solar wind direction, which suffers an aberration of $3 - 5^\circ$ because of the earth's orbital motion around the sun.

At the time of a dawn-side proton boundary traversal by one of the satellites, particularly when the orbit crosses the proton boundary near the magnetic equatorial plane, there sometimes appear striking relationships between the proton fluxes and energetic (> 40 keV) electron fluxes.

An example is illustrated in Figure 10, at a time when the satellite is emerging from the magnetospheric cavity into the dawn-side transition region. Energetic electrons were being observed by the G.M. counter. As time progressed, simultaneous observations of 0.3 - 20 keV protons were made. There is a striking correlation between a high flux of electrons and a low flux, or absence of observable protons, and vice versa. Observations of this phenomenon have also been made in which the flux of lower energy electrons of 0.3 to 20 keV correlate directly with the flux of > 40 keV electrons. This phenomenon of anticorrelation between proton and electron fluxes may well be related to the location instability of the magnetopause described above. The time interval covered in Figure 10 is about 4000 seconds, during which time the satellite has moved about $1.5 R_e$.

e. Magnetospheric Cavity

A little less than half the Vela satellite orbit is in the tail of the magnetosphere. Points near $17 R_e$ are sampled at all ecliptic latitudes up to 60° and magnetic latitudes up to about 50° , and at distances up to $\sim 16 R_e$ from the ecliptic plane. The "null plane" or "neutral sheet" (Ness, 1965) is traversed at points fairly near the antisolar point once each orbit during seasons of one to two months before and after the time when the earth can eclipse the satellite. Several results on the particle observations by the Vela satellites in these regions of the magnetosphere will now be presented.

Interesting aspects of the topography of energetic electrons have been found (Montgomery et al., 1965). Energetic electrons are frequently observed in the tail of the magnetosphere by the M4 and M5 scintillation detectors which are sensitive to electrons of energy greater than ~ 85 keV and ~ 50 keV respectively (see section 4). The spatial distribution of fluxes $> 2 \times 10^4 \text{ cm}^{-2} \text{ sec}^{-1}$, as observed by the M4 detectors on the Vela 1 satellites is shown in Figures 11 and 12. These observations were made on about 70 successive orbits for each of the two satellites, from October 1963 through July 1964. It appears that these events are related to the events reported by Anderson et al. (1965). The presence of the electron flux persisted at the moving satellite for periods from less than one to more than 20 hours, with the satellite moving at a speed of about one R_e per hour. Lack of continuous persistence for periods of days is evidenced by the fact that as one satellite followed the other into nearly the same region, about two days later, it sometimes encountered a similar electron flux environment, and sometimes not. Although detailed temporal persistence is lacking, it is evident from Figures 11 and 12 that there is a persistent clustering of the electron flux within $\pm 6 R_e$ ($\pm 20^\circ$ latitude) of the plane of the magnetic equator, and no strong ordering about the ecliptic plane. Thus it appears the earth's magnetic dipole field plays an important role in the population distribution of these energetic electrons. A plot of the data in solar magnetospheric coordinates shows poorer clustering about magnetospheric latitude than about simple geomagnetic latitude. Although the spatial distribution plots of Figures 11 and 12 are not weighted to account for the time during which the

SPATIAL DISTRIBUTION OF THE ELECTRON SIGNALS: OCT, 1963 — JULY, 1964

SPACECRAFT 1801 (1A) — 1851 (1B) —

SPATIAL DISTRIBUTION OF ELECTRON SIGNALS: OCT, 1963 — JULY, 1964

SPACECRAFT 1801 (IA) — 1851 (IB) —

satellites occupy the different regions, an investigation of this point leads to the conclusion that the general statements made above are unaltered.

Another striking result apparent from Figure 12 is a dawn-to-dusk asymmetry in the population of the energetic electrons, there being a relative void on the dusk side for ecliptic longitudes less than $\sim 130^\circ$. A similar asymmetry has also been demonstrated by analysis of data from the G.M. counters on Vela 2 satellites during a 3 month period from August through October 1964, and is illustrated in Figure 13. This figure also illustrates the asymmetry in the location of the observed proton boundaries as described earlier. In these energetic electron observations the presence of energetic electrons beyond the magnetopause in the transition region on the dawn side was commonly observed.

Several other interesting features of the behaviour of particles in or near the null plane have been observed. One of these is a pronounced streaming of the energetic (> 40 keV) electrons away from the earth, outward in the tail of the magnetosphere. This also represents streaming in the antisolar direction. These observations were made with the G.M. counters, and samples of the directional distribution measurements which demonstrate streaming are illustrated in Figure 14. The observed distributions alternated between these streaming distributions and more nearly isotropic distributions, of the order of half the observations showing streaming. Streaming distributions have been observed to persist over time intervals of a few minutes to a few hours. Flux values of the streaming electrons range up to $\sim 10^5 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$. The 0.3 to

STREAMING ELECTRONS DIRECTIONAL DISTRIBUTIONS E > 40 KeV

20 keV electrons are observed not to be streaming, but rather are found to be typically isotropic. An isotropic component of the > 40 keV electrons is also frequently present and appears to be a high energy tail of the lower energy group of electrons.

According to reported IMP 1 measurements, (Ness, 1965) the magnetic field lines in the region of these streaming electrons are directed either toward or away from the earth depending on whether one is above or below the null plane, and the field strength is 10 to 30 gamma. Thus it appears that the electron streaming is along these field lines, or along the null plane itself.

In Figure 15 we see a mapping of points where the streaming > 40 keV electrons were observed during 15 orbits for each satellite in the period from September 1 to November 3, 1964. In this plot there are usually several points where streaming electrons were observed during the same orbit. Mapping of points for a longer time would be expected to extend the distribution of points on this plot to cover a wider range of ecliptic longitude, and possibly it would cover the same general region as that covered by energetic electrons in Figures 11 and 12. It may be concluded from Figure 15 that the streaming electrons cluster more closely to the geomagnetic equatorial plane than to the ecliptic plane. It is also found that clustering about solar magnetospheric latitude is not as pronounced as about geomagnetic latitude.

The existence of the streaming energetic electrons in no way implies an absence of a postulated drift of lower energy electrons in this region toward earth (Axford et al., 1965) with an Alfvén speed of $\sim 100 \text{ km sec}^{-1}$.

Fig 15

Fig 15

Several other characteristics of the particles in the tail have been observed. One of these involves a study of the flux and spectrum of electrons in the energy range from 50 to 475 keV, which is measured by the solid state detectors. The integral spectra typically are fitted reasonably well by power-law curves with exponents in the range -3 to -4. Interesting temporal relationships are observed (Montgomery et al., 1965).

Another set of measurements, made with the electrostatic analyzers, extends the energy spectrum and flux observations to the lower energy electrons, which constitute the bulk of the electron flux. The energy of these electrons typically peaks in the range 1 to 6 keV, with fluxes up to $\sim 5 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$. Frequently the velocity distribution can be fitted quite well to a Maxwellian distribution, and the average temperature is observed to be ~ 20 to $30 \times 10^3 \text{ }^\circ\text{K}$ (values up to 60×10^3 have been observed), to be compared with values usually near $1 \times 10^6 \text{ }^\circ\text{K}$ in the transition region.

The lower energy electrons are present whenever electrons with higher energies are observed. Thus the spatial distribution of the lower energy electron population is similar to the distributions shown in Figures 11, 12, 13, and 15. The spatial distributions and fluxes of all the electrons indicate that the particles are associated with the "neutral sheet" (Ness, 1965; and Axford et al., 1965) in the tail of the magnetosphere. Whenever the orbits pass through the $\pm 20^\circ$ geomagnetic latitude range in the magnetospheric tail, electrons are always observed. The exact locations, intensities, spectra, and angular distributions vary with time within these latitude limits. More analysis is underway to provide additional mapping and statistical descriptions of these characteristics.

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FIGURE CAPTIONS

- Figure 1: Spatial coverage by the Vela satellite orbits. In this 3 dimensional view, selected circular orbits of the Vela satellites around the earth, whose position is at the center of the figure, are indicated, along with the x, y, and z axes of the solar ecliptic coordinate system. See text for further descriptive comments.
- Figure 2: Spatial coverage by the Vela satellites in terms of regions in the magnetosphere and beyond. The form of the diagram is similar to that of Figure 1.
- Figure 3: Regions in the ecliptic plane sampled by the Vela satellites. The circle in this figure is not a satellite orbit, but is rather the approximate locus of points sampled in the ecliptic plane during 6 months time.
- Figure 4: Examples of three positive ion spectra observed by the Vela 2 satellites in the interplanetary medium. Note successive energy channels are equally spaced logarithmically. The width of the vertical bars indicates instrumental channel width, and $\Delta E/E$ is constant. At intermediate energies between bars the instrument is not sensitive.
- Figure 5: Bulk velocity of solar wind plasma in interplanetary space versus time, derived from observed proton energy spectra. The points plotted near the symbol A_1 represent the nature of individual determinations which are made every 2 minutes, though in this figure only a few points per hour can be plotted. The

heavy solid lines are smoothed curves through such points. The faint dashed lines are usually estimates based on observations in the transition regions, during times when there was no data being acquired in interplanetary space. Also plotted are reported values of A_p , the daily average magnetic disturbance. In this figure the A_p curve sometimes appears to start rising before a rise in V_0 . This is not actually observed, and appears on this plot only because of the one-day resolution of the A_p values.

Figure 6: A non-typical positive ion energy distribution in the interplanetary medium, showing a distinct alpha particle group. The zeros indicate locations of an instrumental energy channel, where the observed count was zero.

Figure 7: Instrumental characteristics of the electrostatic analyzer on the Vela 2 satellites.

Figure 8: Examples of three observed positive ion spectra are shown in the upper half of the figure. These observations were made during a part of one orbit on October 4, 5, and 6, 1964. The three directional distributions, one corresponding to each energy distribution and measured at the same time, are shown in the lower half of the figure. In these directional plots 180° signifies a component of motion in the ecliptic plane in the direction from the sun toward the satellite, or earth.

Figure 9: Some characteristics of the proton and electron fluxes during a typical half orbit on October 4, 5, and 6, 1964, when one of the Vela 2 satellites passed from the dawn side proton

boundary, out through the transition region into the interplanetary medium, and back into the dusk side transition region. The time scale at the bottom applies to all 5 portions of the figure. In the top portion of the figure, the points labeled "B" at the beginning and at the end of the plot represent positions of the "proton boundary." The region where the proton spectrum is indicated to be broad is interpreted as the transition region, while the long central region where proton spectrum is sharp is interpreted as interplanetary space. Oscillations between sharp and broad near 1800 hour on October 4 is interpreted as possibly a shifting of the bow shock position.

Figure 10: Example of observed anticorrelation of energetic (> 40 keV) electron flux and proton flux near the dawn side magnetopause.

Figure 11: Spatial distribution of energetic (> 85 keV) electron fluxes observed by M4 scintillation detectors, in solar ecliptic coordinates. Solid lines represent regions where the electron flux was $\geq \sim 10^5 \text{ cm}^{-2} \text{ sec}^{-1}$ as the satellite moved along the indicated coordinate positions. Dashed lines represent regions where flux was $\geq \sim 2 \times 10^4 \text{ cm}^{-2} \text{ sec}^{-1}$, which is the instrumental threshold. Limit of ecliptic latitude reached by the satellite is 60° .

Figure 12: The data of Figure 11 is replotted with satellite positions located in terms of geomagnetic latitude instead of ecliptic latitude. Limit of geomagnetic latitude reached by the satellite is 47° .

Figure 13: Spatial distribution of energetic (> 40 keV) electrons observed by the G.M. counters during more than a 3 month period from August through October 1964. On this plot a satellite moves along paths having the form of the two solid lines shown, these two lines being paths on 7-18-64 and 10-31-64 as indicated. The satellites traversed successive paths between these two lines, and points are plotted where the energetic electron flux was observed to exceed $\sim 10^4 \text{ cm}^{-2} \text{ sec}^{-1}$.

Figure 14: Samples of observed directional distributions of > 40 keV electrons in the tail of the magnetosphere near the antisolar region. The angle 180° on these polar diagrams represents streaming of electrons in the antisolar direction.

Figure 15: Spatial distribution of positions where streaming electrons of energy > 40 keV were observed during the period September 1 to November 3 selected for analysis. The format of the plot is similar to that of Figure 13.