PHYSICAL REVIEW
LETTERS

VOLUME 14 15 FEBRUARY 1965 NUMBER 7

SPATIAL DISTRIBUTION, ENERGY SPECTRA, AND TIME VARIATIONS OF ENERGETIC ELECTRONS ($E > 50$ keV) AT 17.7 EARTH RADII*†

Michael D. Montgomery, Sidney Singer, J. P. Conner, and E. E. Stogsdill
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received 7 December 1964; revised manuscript received 21 January 1965)

Observations[1-4] of energetic electrons in the outer radiation belts, near the magnetopause, and far outside the magnetosphere have heretofore been made with instruments on satellites in highly elliptical orbits. The Vela nuclear-test-detection satellites, however, are in nearly circular orbits, which are advantageous in that mapping at a constant radius of both the subsolar and antisolar, and dawn and dusk, regions of an orbit can be accomplished in one orbit period. Utilizing data from both Vela satellite launches, we wish to describe here measurements of the spatial distribution, energy spectrum, and time variations of electrons with energy >50 keV, at 17.7 Earth radii. These measurements show that the energetic electron events cluster about the geomagnetic equatorial plane, and that a strong dawn-to-dusk asymmetry exists. The energy spectra can be approximately fitted with a power-law curve, whose exponent may change during the course of an event; and large variations in flux level have been observed to occur in times comparable to one second.

Pertinent spacecraft and orbit details are given in Table I. The particle-detecting instruments on the Launch-I spacecraft are wide-angle scintillation detectors,[5] designated as $M4$, sensitive to electrons with energy >85 keV.[6] The Launch-II spacecraft contain $M4$ detectors, another wide-angle scintillation detector ($M5$), and a gold surface-barrier silicon particle detector. The $M5$ detector is sensitive to electrons with energy >50 keV, and is more sensitive than the $M4$ detector; its anode current is sampled for a period of a few milliseconds once each second. Energy spectra from the solid-state detector in the

Table I. Vela satellite and orbit parameters.

	Launch-I spacecraft		Launch-II spacecraft	
	1A	1B	2A	2B
Launch date	17 October 1963		17 July 1964	
Period (hours)	108	108.5	100.3	100.0
Apogee (Earth radii)	19.3	19.4	17.4	18.6
Perigee (Earth radii)	16.8	16.9	17.0	15.8
Mean radius (Earth radii)	17.7		17.7	
Inclination of orbit plane to ecliptic plane (degrees)	60	59	60.5	62.1
Spin rate (rps)	2.1	2.1	2.1	2.01

energy range 50-475 keV for electrons and 180-570 keV for protons are obtained by using a seven-step programmed pulse-height analyzer. The light-tight window for this detector consists of two 250-μg/cm^2 nickel foils supported on 95% transmission electromesh nickel screens. The effect on the measured energy spectra of electron scattering on these foils and the 100 μg/cm^2 of gold in contact with the detector has been found to be small, both by direct measurement with electron sources and by calculations using recent measurements of Cosslett and Thomas.[7] The energy spectra to be presented below have been corrected for this effect and also for broadening due to system noise of about 20 keV full width at half-maximum. The counting time at each analyzer step is 11/16 sec so that the data are averaged over somewhat more than one spacecraft revolution. The directional geometric factor for the solid-state detector is 0.04 cm^2 sr.

Launch-I instruments have often detected fluxes whose magnitudes range from 2×10^4/cm^2 sec (threshold) to over 10^6/cm^2 sec, while on the night side of the magnetosphere. The Launch-II spacecraft see such events on almost every pass through that region. These events cannot be due to bremsstrahlung from soft (<10-keV) electrons or to penetrating protons with energies >2 MeV because unrealistically high fluxes (2×10^{-12} and 10^5/cm^2 sec for electrons and protons, respectively) would be required, and particularly because of the results of the Launch-II solid-state detector pulse-height analysis. In the following discussion, the spatial distribution results are taken primarily from the Launch-I data, and energy spectra and time-variation data from Launch II. A comparison of the $M4$ detector signals from the two sets of spacecraft indicate that the Launch-I and -II electron events are quite similar in their characteristics.[8]

The results of over nine months of electron flux measurements by spacecraft 1A and 1B are shown in Fig. 1. The lines represent those portions on the spacecraft trajectory where the average electron flux appreciably exceeded the $M4$ detector threshold. At most other portions of the orbit, the residual electron flux is estimated to be less than ~100/cm^2 sec, which is the minimum signal detectable above the solid-state detector background.[9] The duration of any particular event may be from less than one to greater than 20 hours, depending in part on how long the spacecraft remains near the magnetic equator.

Several conclusions can be drawn from a comparison of Figs. 1(a) and 1(b): (a) The events are seen to cluster about the geomagnetic equatorial plane (and not the ecliptic plane). The spatial distribution in ecliptic coordinates is apparently dominated by the seasonal motion of the Earth's magnetic dipole. (b) The data show a strong dawn-to-dusk asymmetry. We believe that the asymmetry is not due to a simple "tilt" of the magnetosphere relative to the earth-sun line, since Bame *et al.*[10] have shown that the tilt is too small in magnitude and of the wrong sign to be consistent with the asymmetry we observe. Nor can the asymmetry be the result of gross differences between electron energy spectra at the dawn and dusk portions of the orbit, since preliminary Launch-II results show that the energy spectra at both places are similar. A possible conclusion is that the acceleration mechanism which produces these energetic electrons operates with far greater frequency on the dawn side of the magnetosphere.

The $M5$ and solid-state-detector data show that typical electron events observed on the dawn side of the orbit have three phases: (a) the *main phase*, and (b) the *early* and *late phases*. The main phase is relatively stable, and is the period during which the flux reaches its maximum values. Flux variations are usually slow and often exhibit an exponential behavior, with time constants of 100 to 200 seconds. During the early and late phases rapid flux variations occur, and the flux frequently doubles its value in less than one second. In addition, increases of one decade from background in less than one second have been seen in data from the $M5$ detector. However, the high degree of time correlation between the $M5$ and solid-state detectors indicates that large flux variations do not frequently occur in times *short* compared to one second. The extremes in rapid flux variations tend to be observed near the boundaries of the region in which electron events are observed. Since the spacecraft orbital velocity of 2 km/sec is, by itself, unable to produce the observed fastest time variations in the flux, it is likely that the results of an acceleration process are being directly observed, or that a well-ordered confining boundary for electrons of different energies is sweeping past the space-

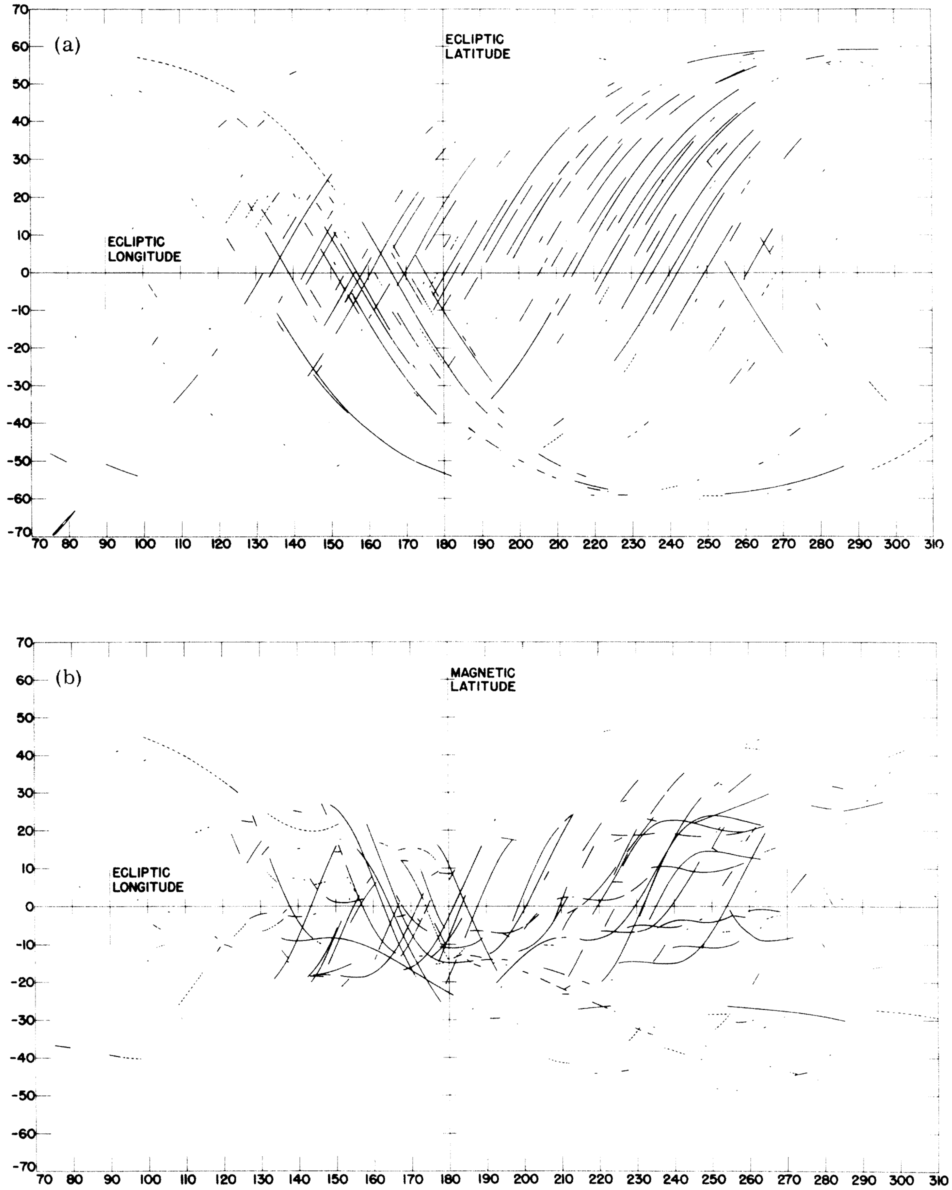

FIG. 1. Spatial distribution of Launch-I electron events. The lines represent those portions of the orbit where the average electron flux significantly exceeded the $M4$ detector threshold. Where the flux barely exceeded threshold, the orbit line is dashed. The 1A orbits are not distinguishable from those of 1B in this Figure. (a) Distribution in solar ecliptic coordinates. Ecliptic longitude is 0° at local noon, and is 90° at local dusk. Ecliptic latitude is the angle of elevation measured from the plane of the ecliptic. (b) Distribution in ecliptic-magnetic coordinates. Magnetic latitude is measured from the (dipole) geomagnetic equatorial plane. The maximum absolute values of ecliptic and magnetic latitudes which can be reached by the spacecraft are 60° and 47°, respectively.

craft. The former possibility appears to be the more likely one.

Typical maximum flux values, as seen by the solid-state detector, range from 10^4 to 10^5 particles/cm^2 sec sr. However, in view of the azimuthal anisotropies of some events as observed by Bame _et al._,[10] the true peak flux values may be somewhat larger. The most intense event to date (peak flux ~3×10^6/cm^2 sec sr) was observed on 11 August 1964, commencing at about 1620 U.T., as the spacecraft entered the region where events are usually observed. The event probably was already in progress at that time, and its unusual inten-

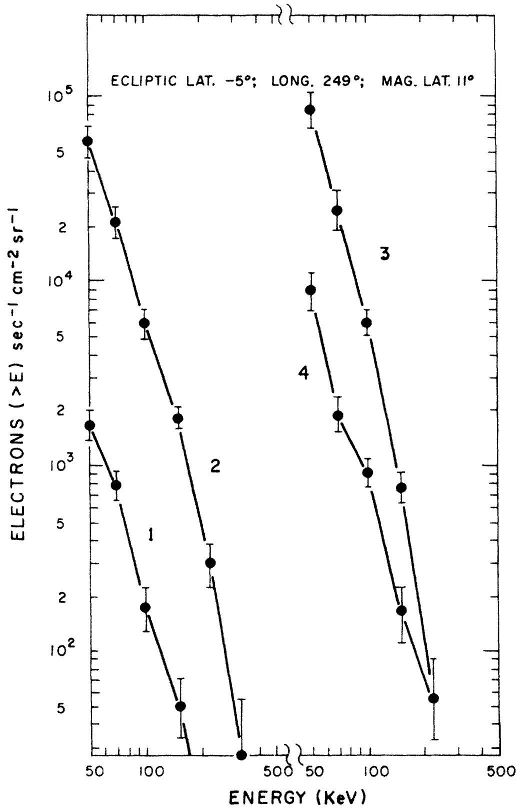

FIG. 2. Integral energy spectra for electrons as measured by the Vela Launch-II solid-state detector. The points indicate flux above 50, 70, 100, 150, 220, and 325 keV, and the error bars represent absolute uncertainties due to calibration and counter statistics. Curve 1 is taken from the rising portion of a local maximum during the stable phase; curve 2, approaching the maximum; curve 3, at the maximum; and curve 4, just before the onset of rapid fluctuations which characterize the late phase.

sity may be associated with the sudden commencement[11] reported earlier in the day.

Some typical electron integral energy spectra are shown in Fig. 2. The low-energy portions of curves 1, 2, and 3 are fitted reasonably well by power-law curves with exponents of -3.2, -3.4, and -4.2, respectively. Curve 4 is a poorer fit; this is typical of spectra at the end of the main phase. Figure 2 implies that the spectrum is relatively soft during a local maximum; however, this behavior is not necessarily typical. These spectra are, in general, harder than those described by Frank[1] for a much lower altitude ($L = 7.1$), where the power-law exponent was typically -2.

Electron events have also been observed on the subsolar side of the Earth, while the spacecraft are in or near the transition region.[12] Such events usually last a few minutes, and are characterized by rapid flux variations in which the maximum level usually does not exceed 10^3 electrons/cm^2 sec sr. There is also evidence that in these same regions of space infrequent, short-lived events consisting of protons with energies between 180 and 500 keV maximum fluxes of 10^3/cm^2 sec sr are seen. Had these particles been electrons, their energies would have been well above the detection thresholds of the $M5$ and Geiger counter[13] detectors on the spacecraft; but little if any signal was seen from these other detectors during the proton events. The energy spectra of the protons are similar to those of the electrons when account is taken of the additional energy loss in the detector window, and they agree in general with the spectra obtained by Fillius and McIlwain[14] at much lower altitudes.

Because the $M5$ detector is insensitive to protons below 800 keV, and because a very good point-by-point flux correlation is obtained between the $M5$ detector and the solid-state detector, we conclude that the electron energy spectra and flux levels obtained from the solid-state detector and presented here are not influenced by a significant proton component.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†The Vela Nuclear Test Detection Satellite Program is sponsored jointly by the Advanced Research Projects Agency of the Department of Defense, and the U. S. Atomic Energy Commission, and is administered by the Space Systems Division of the Air Force.

[1] L. A. Frank, thesis, State University of Iowa, June 1964 (unpublished); L. A. Frank, J. A. Van Allen, and H. K. Hills, J. Geophys. Res. 69, 2171 (1964).

[2] K. A. Anderson, private communication.

[3] J. W. Freeman and J. A. Van Allen, J. Geophys. Res. 68, 2121 (1963).

[4] C. Y. Fan, G. Gloeckler, and J. A. Simpson, Phys. Rev. Letters 13, 147 (1964).

[5] S. Singer, J. P. Conner, W. D. Evans, M. D. Montgomery, and E. E. Stogsdill, Proc. Intern. Space Sci. Symp. (COSPAR), 1964 (to be published).

[6] The thresholds of 85 and 50 keV (corresponding to thicknesses of 3.4 and 2.3 mg/cm^2, respectively) for the $M4$ and $M5$ detectors, respectively, are estimates of the energy for which the transmission through the light-tight beryllium window is ~50%.

[7] V. E. Cosslett and R. N. Thomas, Brit. J. Appl. Phys. 15, 883 (1964); V. E. Cosslett and R. N. Thomas, Brit. J. Appl. Phys. 15, 1283 (1964).

[8] Because of the close similarity between Launch-I

and Launch-II electron events, we have assumed here that residual electron fluxes observed with Launch-II instruments can also be used to describe Launch-I events.

[9] Many of the observed background counts appear to be due to minimum-ionizing particles, and the total background counting rate of 0.3/sec is comparable with that expected from an interplanetary energetic cosmic-ray flux of ~0.3/sr sec.

[10] S. J. Bame, J. R. Asbridge, H. E. Felthauser, R. A. Olson, and I. B. Strong, to be published.

[11] Solar-Geophysical Data, Part B (National Bureau of Standards Central Radio Propagation Laboratory, Boulder, Colorado).

[12] N. F. Ness, C. S. Scearce, and J. B. Peek, J. Geophys. Res. 69, 3531 (1964).

[13] In addition to the $M4$, $M5$, and solid-state detectors, Launch-II instrumentation also included two Geiger-Müller counters, with electron and proton thresholds of ~50 and ~125 keV, and 0.6 and 2.5 MeV, respectively.

[14] R. W. Fillius and C. E. McIlwain, Phys. Rev. Letters 12, 609 (1964).