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LAWRENCE LIVERMORE LABORATORY
University of California, Livermore, California

PITCH-ANGLE DISTRIBUTIONS OF ENERGETIC ELECTRONS IN THE
EQUATORIAL REGIONS OF THE OUTER MAGNETOSPHERE -OGO-5 OBSERVATIONS

H. I. West, Jr.

R. M. Buck

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Key

PITCH-ANGLE DISTRIBUTIONS OF ENERGETIC ELECTRONS IN THE
EQUATORIAL REGIONS OF THE OUTER MAGNETOSPHERE - OGO-5 OBSERVATIONS*

Harry I. West, Jr. and Richard M. Buck
University of California Lawrence Livermore Laboratory
Livermore, California

1. INTRODUCTION

Pitch-angle distributions (PAD) of energetic electrons relate to a wide variety of magnetospheric processes. Wave-particle interactions (turbulence, instabilities) act on a time scale comparable to the particle gyro period; betatron acceleration is important on time scales of the bounce period to minutes; and drift-shell effects are important on time scales α the azimuthal drift period. A study of pitch-angle effects, in turn, provides information on the static and dynamic aspects of field topology. Our interest in this paper is primarily with the drift-shell effects.

Prior to OGO-5 it was well known that in the inner belt and much of the outer belt the normal loss-cone distribution (peaked at 90° to $\vec{B}$) prevails. ATS experimenters had observed the butterfly PAD (flux depression at $\sim 90^\circ$ to $\vec{B}$) in the nighttime magnetosphere and Serlinitso (1966) and Haskell (1969) had observed this distribution in the more distant nighttime magnetosphere; the experimenters recognized the importance of drift-shell splitting in causing the butterfly PAD. Despite the attractiveness of pitch-angle data very few really detailed measurements were available prior to OGO-5.

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Two experiments onOGO-5 are providing a fairly detailed picture of the magnetosphere: the UCLA scintillation counter experiment (six counters in fixed directions relative to the satellite) of Farley and Kivelson, and our LLL experiment. The UCLA experimenters have concentrated their efforts on wave-particle interactions and betatron acceleration and we (West et al. 1972, 1973a,b; Buck et al. 1973), have concentrated on drift-shell effects and field topology. In this paper we present a brief but unified view of our studies to date.

2. INSTRUMENTATION AND SPACECRAFT

The LLL experiment consisted of a seven-channel magnetic electron spectrometer and a seven-channel proton range-energy telescope. Our concern here is only with the electron results. Pertinent channel details are given in Table I. OGO-5 was stabilized; hence it was necessary to scan the experiment relative to the spacecraft for obtaining pitch-angle information. The scan was 3 deg/sec through excursions of ± 115 degrees. UCLA vector magnetometer data were used in determining the pitch-angle distributions.

OGO-5 was launched March 4, 1968 with its apogee of $24 R_E$ geocentric on the morning side of the earth. Its orbital inclination was initially 31 degrees and its period 62 hours. Many inbound passes during 1968 were close to the magnetic equator when OGO-5 was in the outer magnetosphere; it is data from these passes that we report here.

3. RESULTS

3.1 Survey

Here we wish to provide an overall view of PAD's of energetic electrons throughout the equatorial regions of the magnetosphere. We do not dwell on subtle pitch-angle effects, but rather, present the data in terms of three broad categories: normal, butterfly, and isotropic.

'Isotropic' means 'isotropic over the range of pitch-angles scanned'; we did not always observe at small pitch-angles, so that at times we had to use judgement in this assignment.

For the overview, we chose to concentrate on data from our lowest-energy electron channel E_1 (79 keV). Figure 1 shows the pitch-angle changes that occurred on a number of inbound orbits in 1968 whenOGO-5 was close to the geomagnetic equator or in the plasma sheet. Many of the effects are energy dependent; this is made more evident later. Note, the coordinates of Figure 1 are geocentric solar magnetospheric; this is in reference to azimuth only. To reduce some of the presentation problems the radial plots are in terms of true radial distance in R_E ; the projection of R on XY plane is usually so close to R that differences are inconsequential. Since electrons drift eastward around the earth, our discussion proceeds likewise. Our presentation here is brief; the explanation comes later.

We start in the prenoon magnetosphere. Almost without exception the normal PAD is observed (at $\sim 1000 \pm 3$ LT) from the magnetopause inwards.

In the early afternoon magnetosphere, we encounter the butterfly PAD at extended distances. Note for Day 28, 1969 we find a slight butterfly effect near the magnetopause ($j_{\perp}/j_{\parallel} \sim 0.8$); further momentary evidence is found as we approach the earth. As we proceed in azimuth towards dusk we find the butterfly PAD prevailing closer to the earth; also the depression in $j_{\perp}$ becomes greater.

In the regions past dusk ($\gtrsim 9 R_E$) we usually find large depletions of $j_{\perp}$ ($j_{\perp}/j_{\parallel}$ often < 0.01). Major magnetic storms occurred on Days 305 and 306. Days 308 and 313 show some of the after effects; the dots and dashes indicate isotropic fluxes of solar electrons but note the butterfly PADs still prevail. The disturbed day, Day 287, is interesting; isolated gusts of particles are observed early in the orbit followed by an abrupt increase at $11 R_E$.

Plus or minus a few hours from midnight we show a number of orbits with abrupt flux increases. Many of these are positively identified as substorm expansion phases by UCLA workers (Aubry et al., 1972; Russell et al., 1971). For example, note the flux increases on Day 230 at 19.2, 17.5, 14.5, and 9.2 R_E ; the first three substorms appear as flux islands. Note that closer to the earth the butterfly PAD reemerges shortly after substorm expansion.

Well past midnight the signature of the substorm is not so obvious. Although rapid flux changes are observed, the obvious substorm signatures of Days 222 and 230 are not apparent. Past midnight when we observe the butterfly PAD at $\gtrsim 9 R_E$ we find that $j_{\perp}$ is greatly enhanced relative to $j_{\parallel}$, when compared with fluxes observed in the corresponding region premidnight. Also in these extended regions, we often find evidence of the normal distribution, e.g. Day 157.

Past dawn we rapidly lose the butterfly PAD. Day 137 is interesting in that E_1 shows a normal PAD whereas the higher-energy channels $E_2 - E_6$ show the butterfly distribution at various points into $7.4 R_E$. Past ~ 0800 LT, evidence of the butterfly distribution is largely limited to momentary effects near the magnetopause and to slight depression of $j_\perp$ when nearer the earth.

3.2 Prenoon Results

Detailed results for Day 90 are presented in West et al. (1973a) and are quite representative of this region. Figures 2 and 3 present some similar data for Day 85. Note that the PAD's at extended distances show considerable energy dependence, which largely disappears in the heart of the outer belt. It is interesting to note that, in general, strong energy dependence shows in the slot (West et al., 1973a) but is mostly absent in the inner belt.

Many of the PAD's at extended distances in Figure 3 show skirts on the distributions which might be interpreted as components of isotropy. To provide the proper perspective, one should examine contours of constant equatorial B such as those measured by Fairfield (1968) and reproduced in Figure 4. Roederer (1967) has developed the framework for studying the azimuthal drift motion of particles in a distorted magnetosphere. Particles mirroring at the equator, drift at constant B as in Figure 4 (conservation of the first adiabatic invariant). Particles with small equatorial pitch-angle drift so as to keep the distance from mirror point to mirror point

about constant (conservation of the second invariant). Hence, the Day 85 PAD's that we observe at $9 R_E$ consist of equatorially-mirroring particles that came from $\sim 7 R_E$ at midnight and of particles at small pitch angles that may have been fairly deep in the magnetotail when near midnight. We later find that if these particles crossed the equator at much greater than $\sim 9 R_E$ at midnight there is a good probability that they became isotropic as a result of the strong tail fields that normally exist there. In addition to these drift-shell effects, wave-particle interactions in the region from midnight to 0900 LT probably contributed to the shape of the PAD's.

3.3 Afternoon Magnetosphere

Consider what happens to the PAD's as electrons drift through the distorted noon magnetosphere. Starting at 0900 LT we note that equatorial-mirroring particles in the pseudo trapping regions (i.e. beyond the constant-B contour that maps from the noon magnetopause to midnight of Figure 4: $\geq 9 R_E$ at 0900 LT) will drift to the magnetopause to be changed in pitch-angle or leave the magnetosphere. Because of the compressed field configuration, particles with small enough equatorial pitch angle can drift so that their drift paths are earthward of the magnetopause. In a symmetric magnetosphere, we expect the drift shells at 1500 LT to be equivalent to those at 0900 LT. Fast noon we might expect a depletion in j_1 in the pseudo-trapping regions; this is indeed what we observe as shown

by the January 7, 1969 data in Figures 5 and 6 (West et al., 1973a). This magnetopause-shadowing effect also explains the appearance of the butterfly PAD's in the afternoon regions of our survey in Figure 1.

We should mention another aspect of the picture. Shabansky (1971) shows how near-equatorially-mirroring particles, as they drift eastward, may branch north or south through minimum-B regions in the field configuration near noon so as to stay in the magnetosphere. We have considered this problem from the view point of PAD's and have shown qualitatively (Buck and West, 1973) how the PAD's of Figure 6, panels 2 and 3 showing minima at $\sim 65^\circ$, might have resulted from such drift motion. We still, however, consider the role of minimum-B regions in the high-latitude day-side field topology to be unclear.

3.4 Pre-midnight Magnetosphere

As electrons drift into the nighttime magnetosphere they encounter magnetic fields that are increasingly tail-like. Following Roederer (1967) one notes that particles drifting at constant B (90° pitch angles) move closer to the earth. Particles with large second invariant (small equatorial pitch angles) have equatorial crossings farther from the earth and their equatorial pitch angles reduced relative to that occurring earlier in their drift path (note in these considerations, that as long as adiabatic motion is occurring, Liouville's theorem holds and $j(\theta_{eq}) = \text{constant}$ with $\theta_{eq} = \sin^{-1} \sqrt{\frac{B_{eq}}{B_m}}$).

The quiet-time data of Day 295 exemplifies these effects. Radial profiles of $j_{\perp}$ and $j_{\parallel}$ are shown in Figure 7 and corresponding PAD's in Figure 8. The data at 5 to 9 R_E reflect the magnetic field configuration changes the electrons encounter in their drift from the day to night side of the earth. To appreciate this, one needs to examine the negative radial flux gradients and PAD's earlier in the drift path (e.g. Day 85 Figures 2 and 3). The data beyond $\sim 9 R_E$ in Figure 7 are due to changes both in field configuration and magnetopause shadowing.

3.5 Midnight and Substorms

As seen in the survey, Figure 1, the butterfly PAD is found in the dusk magnetosphere even during disturbed periods. Near midnight ($\sim 2300 \pm 2$ LT) the picture changes; the effects of substorms and tail-like fields caused marked changes in the particle fluxes and PAD's. OGO-5 experimenters have published a wide variety of observations in this region. We (West et al., 1973b; Buck et al., 1973) participated in a nine-paper study of substorms on August 15 (Day 228), 1965. The substorm with expansion phase at 0714 UT is especially interesting, and the PAD results are fairly general. Prior to the growth phase, the field configuration was only moderately tail-like and the butterfly PAD was observed. At 0640 UT the field at OGO-5 (at $\sim 9 R_E$) started becoming more tail-like and by 0655 UT the PAD's were isotropic. The particle fluxes then decreased several orders of magnitude until ~ 0714 UT.

With the onset of expansion and the appearance of a more dipole-like field configuration, fresh electrons showing the butterfly PAD drifted into the region of observation; the higher-energy electrons changed first in time. It is interesting to note that betatron effects (Kivelson et al., 1973) and enhanced ELF (Scarf et al., 1973) were observed during substorm recovery; both observations relate to the PAD changes that occurred.

In Figure 9 we show substorm data for Day 222 (August 9), 1968. Here we note expansions occurring at 17.8, 15.2, 12.6, and 9.8 R_E (see Russell et al., 1971 for discussion of the field data). Simultaneously with the appearance of more dipole-like fields we note the rapid increase in both electron and proton fluxes. The bottom panel marked 'scan angle' shows the pitch angles of the particles being detected at a given instance but is too compressed for that information. However, due to the orientation of the experiment the outer envelope of 'scan angle' is the field inclination and its complement and provides a descriptive picture of the field configuration: narrow when tail-like, wide when dipole-like. Note, with the possible qualification of the occasional limited range of look angles, the lack of modulation of the electron data means isotropy and the presence of modulation the butterfly PAD. An especially interesting period starts ~ 2100 UT; we see the emergence of the butterfly PAD for E_2 followed by changes in E_1 at ~ 2115 UT. The delay suggests that the drift time of the electrons from an undisturbed source is important.

At 2212 UT note the abrupt loss of modulation, indicating isotropy, as the field became more tail-like. This is the sort of thing we observed earlier in the growth phase of the 0714 UT August 15 substorm. The re-emergence of the butterfly PAD after 0130 UT in the fourth substorm of August 9 parallels the expansion phase of the 0714 UT August 15 substorm.

We consider the transition to isotropy in the growth phase as an indicator of the extent the field has become tail-like, not so much at the position of OGO-5 but farther down the tail where the field crosses the neutral sheet. Presumably when the gyro radii of the particles are comparable to the field curvature across the sheet or are of the scale of the neutral-sheet thickness, adiabatic guiding-center motion is no longer possible (Speiser, 1971). Speiser (1967), Sonnerup (1971), and Eastwood (1972) have discussed how particles can leave their guiding-center motion and become caught in a mode in which they oscillate about the field reversals they encounter on either side of the neutral sheet. Assuming this happens, electrons cannot stay in this mode for long since any finite B_z will quickly turn them towards the earth; some precipitate but many mirror and return to the interaction region. Along with these effects, magnetic noise in the neutral sheet is most certainly important in randomizing the electron motions.

We have made several observations past midnight during quiet periods that tie into this picture. OGO-5 was inbound from the north lobe of the tail. Pitch-angle isotropy was first noted followed by an abrupt

transition to the butterfly PAD asOGO-5 neared the earth. A semi-quantitative analysis of the field configuration indicates that isotropy was being observed on field lines which appeared to pass through the neutral sheet. A more careful study of these and otherOGO-5 data may allow us to make stronger statements about the field configuration in the neutral-sheet region.

3.6 Post Midnight

In terms of interpreting our PAD's, this is the least understood region of the outer magnetosphere. Clearly electrons showing the butterfly PAD can drift through midnight during substorm expansion. However, the almost complete dropout in $j_{\perp}$ seen near dusk ($> 9 R_E$) is never seen near dawn. Turbulent interactions of some sort have enhanced $j_{\perp}$ relative to $j_{\parallel}$ and the isotropic or normal PAD is often observed. At times, we have observed what we would describe as plasma sheet oscillations (in the 10 minute range) that may fit into the theories of Siscoe (1969) and McKensie (1970). In any respect, at extended distances the butterfly PAD appears to be lost as the result of randomizing processes. Nearer the earth the change in magnetic field configuration leads to the demise of the butterfly PAD so that much past dawn only the normal PAD is observed. This brings us full circle in the drift of the electrons around the earth and the description of the pitch-angle effects that occur.

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- Figure 1. Pitch-angle distribution survey for ~ 79 -keV electrons in 1968 and early 1969. Each inbound pass is annotated with the day of year and average K_p . Symbols are used to indicate the PAD form and are: wavy line, normal; period, isotropic and less than 25 electrons $\text{cm}^{-2} \text{sr}^{-1} \text{keV}^{-1} \text{s}^{-1}$; dash, isotropic and flux greater than 25; <, butterfly less than 25; and x, butterfly greater than 25. The symbol o means short isolated gusts; the cross bar, an abrupt flux increase; and s, solar particles.
- Figure 2. Radial-flux profile on the morning side of the earth.
- Figure 3. Pitch-angle distributions obtained on the morning side of the earth. See Figure 2.
- Figure 4. Contours of constant equatorial B for an average magnetosphere. After Fairfield (1968). Equatorial-mirroring particles follow such contours.
- Figure 5. Early afternoon data showing effects due to the magnetopause shadowing of drift paths.
- Figure 6. Pitch-angle distributions for Figure 5. After West et al. (1973a).
- Figure 7. Radial profile of $j_{\perp}$ and $j_{\parallel}$ for a quiet day inbound pass. $K_p = 0^+$.
- Figure 8. Pitch-angle distributions for Figure 7.
- Figure 9. Inbound data obtained near midnight on August 9 (Day 222) 1968. The data are plotted at all pitch angles reached by the experiment as it scanned. Large modulation for E_1 and E_2 means the butterfly PAD and the absence of modulation, isotropy.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5

Figure 5

Figure 7.

Oct 21 (Day 295), 1968

$\phi_{\text{GSM}} = 113.6^\circ$

132.6°

$\lambda_{\text{GSM}} = -4.4^\circ$

-16.0°

Figure 8.

Figure 9.

Table I. Electron and Proton Channel Characteristics.

	<u>E₁</u>	<u>E₂</u>	<u>E₃</u>	<u>E₄</u>	<u>E₅</u>
Energy	79 ± 23 keV	158 ± 36	266 ± 36	479 ± 52	822 ± 185
Geometry	0.18 cm ² keV sr	0.277	0.390	0.605	4.43
	<u>E₆</u>	<u>E₇</u>	<u>P₁</u>		<u>P₂</u>
Energy	1530 ± 260	2820 ± 270	100 - 150 keV		230 - 57
Geometry	8.57	3.88	2.06 x 10 ⁻³ cm ² sr		1.3 x 10 ⁻²