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Experimental Verification of Drift Shell Splitting in the Distorted Magnetosphere

K. A. Pfitzer, T. W. Lezniak,

and J. R. Winckler

School of Physics and Astronomy
University of Minnesota
Minneapolis, Minnesota

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Abstract

Data from an electron spectrometer on the synchronous orbit satellite ATS-1 and data from an electron spectrometer and ion chamber on the elliptical orbit satellite OGO-III can be used to experimentally test drift shell splitting in the non-dipolar distorted magnetosphere as proposed by Roederer. Quiet day pitch angle distributions obtained by ATS-1 at 6.6 R_e qualitatively confirm the shell splitting by showing that near noon the pitch angle distribution is nearly isotropic whereas near midnight the pitch angle distribution is peaked toward small angles (parallel to the field). Using the Mead model magnetic field for calculating the drift shells for electrons of pitch angle $\alpha = 65°$ and $\alpha = 90°$, as well as the measured pitch angle distribution and measured radial gradient for electrons at local noon, the pitch angle distribution can be calculated as a function of local time for the ATS-1 orbit. The agreement between calculated and measured fluxes is satisfactory not only in the predicting the proper noon to midnight asymmetry (25 to 1 for 500-1000 keV electrons on February 15, 1967) but also in correctly predicting the pitch angle distribution as a function of local time (isotropic at noon but non-isotropic with a 3 to 1 ratio between $\alpha = 65°$ and $\alpha = 90°$ at midnight). However, in one case (15 February, 1967) an asymmetry is observed about local midnight with minimum count rate at 2200 LT, representing a departure from the symmetric Mead model.

Introduction

Data from an electron spectrometer on the synchronous orbit satellite (Lezniak et al., 1968; Lezniak and Winckler, 1968) and data from an electron spectrometer and ion chamber on the elliptic orbit satellite OGO-III (Kane, 1967; Pfitzer, 1968; Pfitzer and Winckler, 1968) can be used to test experimentally the drift shell splitting of trapped electrons in the distorted dipolar field of the magnetosphere. Northrop and Teller (1960) pointed out that in cases where the magnetic field lacks axial symmetry, gradients of B occur in the azimuthal direction which produce radial drift motions of trapped particles and that this radial drift will vary with the equatorial pitch angle of particles found at a given point in the magnetic field. Thus, even with the conservation of the first and second adiabatic invariants of motion, particles which after drifting around the earth return to their point of origin nevertheless at intermediate points will be found on different drift shells depending on pitch angle. This is in contrast to a magnetosphere described by a pure dipole field, where all particles which initially start at the same point remain on the same drift shell independent of pitch angle or energy. Near the earth ($r < 5\ R_e$) the distortion of the earth's field is small and the drift shells of particles having different pitch angles are almost identical, a fact contained in the McIlwain L-parameter approximation which is useful for mapping particle fluxes at such low L values. However, in the vicinity of the ATS-1 orbit (6.6 R_e) the distortion of the magnetic field can be quite large due to currents on the magnetosphere boundary and currents in the tail. Theoretical studies of the motion of trapped particles in the distorted dipolar field have been carried out by Hones (1963), Fairfield (1964) and Mead (1966). This work has been extended by Roederer (1967) who has used the Mead model magnetic field (Mead, 1964; Williams and Mead, 1965; Mead, 1966) which has given reasonably good quantitative agreements with experimental measurements of the magnetic field. Roederer has followed the drift motion of particles in the model distorted magnetosphere including the effects of Chapman-Ferraro compression and a tail field parameter.

Roederer predicted among other things that "equatorial pitch angles tend to align along field lines on the night side of the magnetosphere and perpendicularly to the field on the day side". "Quiet day" pitch angle distributions of energetic electrons which have been determined on ATS-1 from a knowledge of the spectrometer look direction and the measured $\vec{B}$ field at the satellite actually qualitatively confirm this prediction by showing that near noon the pitch angle distribution is almost isotropic whereas near midnight the pitch angle distribution is strongly peaked toward smaller angles (more parallel to the field). A quantitative comparison has now been made and is reported herewith.

Procedure and Results

We have obtained from Dr. Juan Roederer a computer program which uses the Mead model magnetic field and traces the drift shells for particles having a specified pitch angle at a given location in the magnetosphere. Using this computer program as well as the radial distribution of trapped electrons measured by passes of OGO-III, the pitch angle distribution as a function of local time has been calculated and compared to the electron pitch angle distributions measured by ATS-1 on the geographic and geomagnetic equator. The input parameters for the computer program are:

1. The stand off distance, R_S, where the earth's field terminates at the sub-solar point, measured in earth radii.
2. The strength of the tail field, B_T, measured in γ's.
3. The location of the satellite.
4. The local pitch angle of the particle at the satellite.

One of the output parameters of the program is $|B|$, the Mead model total magnetic field, at the location of the satellite. Although R_S can be determined from the cutoff of the 50 keV electron flux as measured by OGO-III, the tail field, B_T, is not available. But since the total magnetic field $|B|$ is measured by ATS-1 as a function of local time, the parameters R_S and B_T can be adjusted so that the model field gives a least squares best fit to this measured magnetic field. We have chosen two quiet days when the necessary data and parameters are available. The values which give the best fit for $|B|$ vs. local time on the 15th of February, 1967 are $R_S = 9.0$ and $B_T = 20\gamma$ as well as $R_S = 9.3$ and $B_T = 18\gamma$. Similarly, $R_S = 9.5$ and $B_T = 10\gamma$ or $R_S = 9.0$ and $B_T = 14\gamma$ give least squares best fits to the observed $|B|$ values on the 7th of February, 1967. A pass of OGO-III on February 15, 1967 gives $8.5 \leq R_S \leq 9.3$ in satisfactory agreement with the above indirectly determined values. Figures 4 and 5 (lower graphs) show the measured and calculated $|B|$. We note that the agreement is quite good except that particularly on February 15, 1967 (Figure 5) a disagreement arises because the measured field is not symmetric about local midnight, an effect with which the Mead model cannot cope. This is discussed further below.

Using $R_S = 9$ and $B_T = 20\gamma$ we can now use the program to calculate the drift shells of electrons which pass through the ATS-1 satellite at $r = 6.6\ R_e$ and various local times, and for electrons having pitch angles $\alpha = 90°$ and $\alpha = 65°$ (i.e. the extremes of the pitch angle range normally covered by the spectrometer on quiet days). Figure 1 shows an example when the satellite is located at local time (LT) = 30°. In this example particles having $\alpha = 90°$ at $6.6\ R_e$ and LT = 30° cross the noon meridian (LT = 180°) at $7.97\ R_e$ with $\alpha = 90°$ and particles having $\alpha = 65°$ at $6.6\ R_e$ and LT = 30° cross the noon meridian at $7.42\ R_e$ with $\alpha = 73°$.

The OGO-III 50-120 keV electron channel covers approximately the same energy window as the ATS-1 50-150 keV electron channel and the OGO-III ion chamber (which in the outer radiation belt responds almost entirely to electrons above 600 keV (Kane, 1967)) corresponds reasonably well to the ATS-1 500-1000 keV electron channel. Since during the period December, 1966 to February, 1967 inbound passes of OGO-III are within 30° of the noon meridian and also near the equatorial plane, the trapped electron radial distributions can be determined in the vicinity of the ATS-1 orbit. Figure 2 shows such distributions for the two selected days. For the February 7 calculations an OGO-III pass at 2100 UT February 6, 1967 was available; however, for the February 15, 1967 case no suitable OGO-III data was available within two days of the calculation. An average gradient was arrived at by using the nearest four radiation belt passes and is represented on Figure 2 as the estimated gradient.

We have available also the pitch angle distributions as measured by ATS-1 at the noon meridian at 6.6 R_e (Figure 3). We must now make the assumption that the pitch angle function measured by ATS-1 at 6.6 R_e and LT = 180° is valid in the approximate range 6.6 R_e to 8 R_e. That is,

$$f(\alpha,r) = g(\alpha) \cdot h(r) \quad \text{at LT} = 180°$$

where $g(\alpha)$ is the measured pitch angle function at LT = 180° (Figure 3) and $h(r)$ is the radial dependence at LT = 180° measured by OGO-III (Figure 2). The above assumption should not be unreasonable for such a small region of space. It is now possible using the pitch angle function $g(\alpha)$ at LT = 180°, the radial function $h(r)$ at LT = 180° and the Roederer Mead model drift program to calculate the pitch angle function everywhere in the ATS-1 orbit.

For a distribution of local times in the ATS-1 orbit, the drift shells for electrons having pitch angle α = 90° and α = 65° were calculated.

The pitch angles α_1 and α_2 as well as the intercepts r_1 and r_2 of each of these drift shells at local noon were noted and $h(r_1)$ and $h(r_2)$ was determined from Figure 2. The rates $f(\alpha_1, r_1)$ and $f(\alpha_2, r_2)$ were thus determinod at noon. These directional electron fluxes are the ones that intercept the ATS-1 orbit at the specified local time where they have $\alpha = 90°$ and $\alpha = 65°$. Figures 4 and 5 show the calculated flux vs. local time curves for electrons of 50-150 keV and 500-1000 keV having pitch angles of $\alpha = 90°$ and $\alpha = 65°$ and for comparison the observed values.

We have found that the difference between the observed and calculated electron fluxes is a much stronger function of the Mead parameters, R_s and B_T than the corresponding comparison between observed and calculated magnetic field strengths. Thus, although $R_s = 9.5$ and $B_T = 10$ as well as $R_s = 9.0$ and $B_T = 14$, both gave equally good representations of the measured magnetic field data for February 7, 1967, the $R_s = 9.0$ and $B_T = 14$ parameters fit the particle data much better. Similarly, for February 15, 1967, $R_s = 9.3$ and $B_T = 18$ and $R_s = 9.0$ and $B_T = 20$ give the same best fit results to the magnetic field data, but the $R_s = 9.0$ and $B_T = 20$ parameters produce a much better agreement with the particle data.

To indicate how strongly the calculated particle fluxes depend on the input parameters of the Mead model we chose two sets of parameters for February 15, 1967 ($R_s = 9.5$, $B_T = 18$ and $R_s = 8.9$, $B_T = 25$) which cause the calculated magnetic field strengths to differ by 5% from the least square best fit magnetic field strengths (see Figure 5). In this figure we note that although the difference in the calculated magnetic field strengths is only 5%, the electron flux curves differ from the best fit curves by almost a factor of 2.

Discussion

The accuracy with which a comparison like the above can be made is obviously limited by the availability of a simultaneous pass of OGO-III on the chosen quiet day as seen on ATS-1. However, since between major magnetic storms the outer zone readjusts slowly with a decay constant of four or five days (Parks and Winckler, 1968), we regard the described procedure for obtaining the radial trapped electron distributions as satisfactory. We have observed that usually the radial gradient of 50 keV electrons is much flatter near 6.6 R_e than that for 500 keV. This is reflected directly in Figures 4 and 5 by the small difference between the $\alpha = 65°$ and $\alpha = 90°$ pitch-angle curves in the night sector for 50 keV electrons.

We note that when R_s and B_T are correctly chosen (best agreement to both the magnetic field data and particle data) the agreement between the calculated and measured electron fluxes (Figures 4 and 5) is satisfactory not only in the amount of the diurnal variation but also in the relative count rates of the $\alpha = 65°$ and $\alpha = 90°$ electrons, even when the noon to midnight flux ratios vary as much as 25:1. Thus, the observed quiet day pitch angle distributions along the ATS-1 orbit are quantitatively explained by the concept of shell splitting.

The principal discrepancy between the calculated and observed values is found on February 15, 1967 (Figure 5) where the observed values (both electrons and magnetic field) are asymmetric about local midnight with a minimum displaced westward from the Mead model minimum by about 30°. We may regard the February 15, 1967 case as an extreme example of a steady state distorted magnetosphere. This is in contrast to February 7, 1967 (Figure 4) where both the distortion and the asymmetry are less. We note that the discrepancy in the electron flux comparison is of the same order as the discrepancy in the magnetic field comparison. Therefore, we conclude that a more accurate model of the magnetic field for February 15,1967 would bring the electron fluxes into agreement.

The observed asymmetry is too large to be accounted for by the solar wind aberration angle ($\approx 7°$). Any asymmetry introduced by the interaction of the solar wind with the tilted magnetic dipole (the Mead model assumes that the dipole is perpendicular to the solar wind) cannot at present be accurately estimated. However, since February 15, 1967 is only 34 days from the equinox, the 30° asymmetry probably cannot be accounted for by the tilted dipole. The observed asymmetry can probably be caused by either an asymmetric ring current or by convective flow in the magnetosphere.

The obvious next step for "quiet day" particle motion studies is to include the proper electric fields and asymmetric magnetospheric shapes into the calculations. These calculations may then form the basis for understanding quantitatively the energizing and distribution of trapped electrons during disturbed periods.

Acknowledgments

We are greatly indebted to Dr. Juan Roederer of the University of Denver for furnishing his Mead model drift shell program for these studies, and to Paul Coleman and David Cummings of UCLA for the ATS-1 magnetic field data for selected periods in early 1967. This data study resulting from the ATS-1 and OGO programs is supported by the National Aeronautics and Space Administration under Grant NGL-24-005-008.

Figure Captions

Figure 1: Equatorial intersection of drift shells for particles having pitch angles of $\alpha = 65°$ and $\alpha = 90°$ at the location of the satellite are shown when the satellite is positioned at 6.6 R_e, 0° latitude and 30° local time. The Mead model parameters for this example are $R_s = 9.0$ and $B_T = 20\gamma$.

Figure 2: h(r), the observed electron distributions for the February 7, 1967 and the February 15, 1967 calculations are shown. The 50-120 keV distributions are obtained from the 50-120 keV energy channel of the OGO-III electron spectrometer and the >300 keV distributions are obtained from the OGO-III ion chamber. The February 7, 1967 distributions were obtained a few hours prior to the start of the ATS-1 observation; however the February 15, 1967 distributions are estimated from the nearest four OGO-III radiation belt traversals.

Figure 3: $f(\alpha)$, the pitch angle distributions at local noon measured by the ATS-1 electron spectrometer. To convert average counts/sample to directional electron flux (electrons-cm^{-2}-sec^{-1}-keV^{-1}-ster^{-1}), multiply the 50-150 keV channel by 450 and the 500-1000 keV channel by 40.3.

Figure 4: Lower: The comparison of the magnetic field on February 7, 1967 as measured by magnetometers on ATS-1 (courtesy of Paul Coleman and David Cummings of UCLA) and the best fit curve from the Mead model (a magnetic disturbance prevents comparison after 1310 UT).

Upper: The comparisons between the measured directional electron count rates at $\alpha = 65°$ and $\alpha = 90°$ with the calculated count rates obtained from the OGO-III radial gradient and drift shells based on the Mead model. To convert average counts/sample to directional electron flux (electrons-cm^{-2}-sec^{-1}-keV^{-1}-ster^{-1}) multiply the 50-150 keV channel by 450 and the 500-1000 keV channel by 40.3.

Figure 5: Lower: The comparisons between the magnetic field on February 15, 1967 as measured by magnetometers on ATS-1 (courtesy of Paul Coleman and David Cummings of UCLA) and several Mead model calculations. The solid line represents the best fit; in the dashed curves a 5% error (from the best fit) has been introduced.

Upper: The comparisons between the measured directional count rates at α = 65° and α = 90° with the calculated count rates obtained from the OGO-III radial gradient and drift shells based on the Mead model. The solid curves represent the best fit and the dashed curves represent the results when the Mead model parameters are changed such that a 5% error is introduced into the best fit magnetic field comparison. To convert average counts/sample to directional electron flux (electrons-cm^{-2}-sec^{-1}-keV^{-1}-ster^{-1}) multiply the 50-150 keV channel by 450 and the 500-1000 keV channel by 40.3.

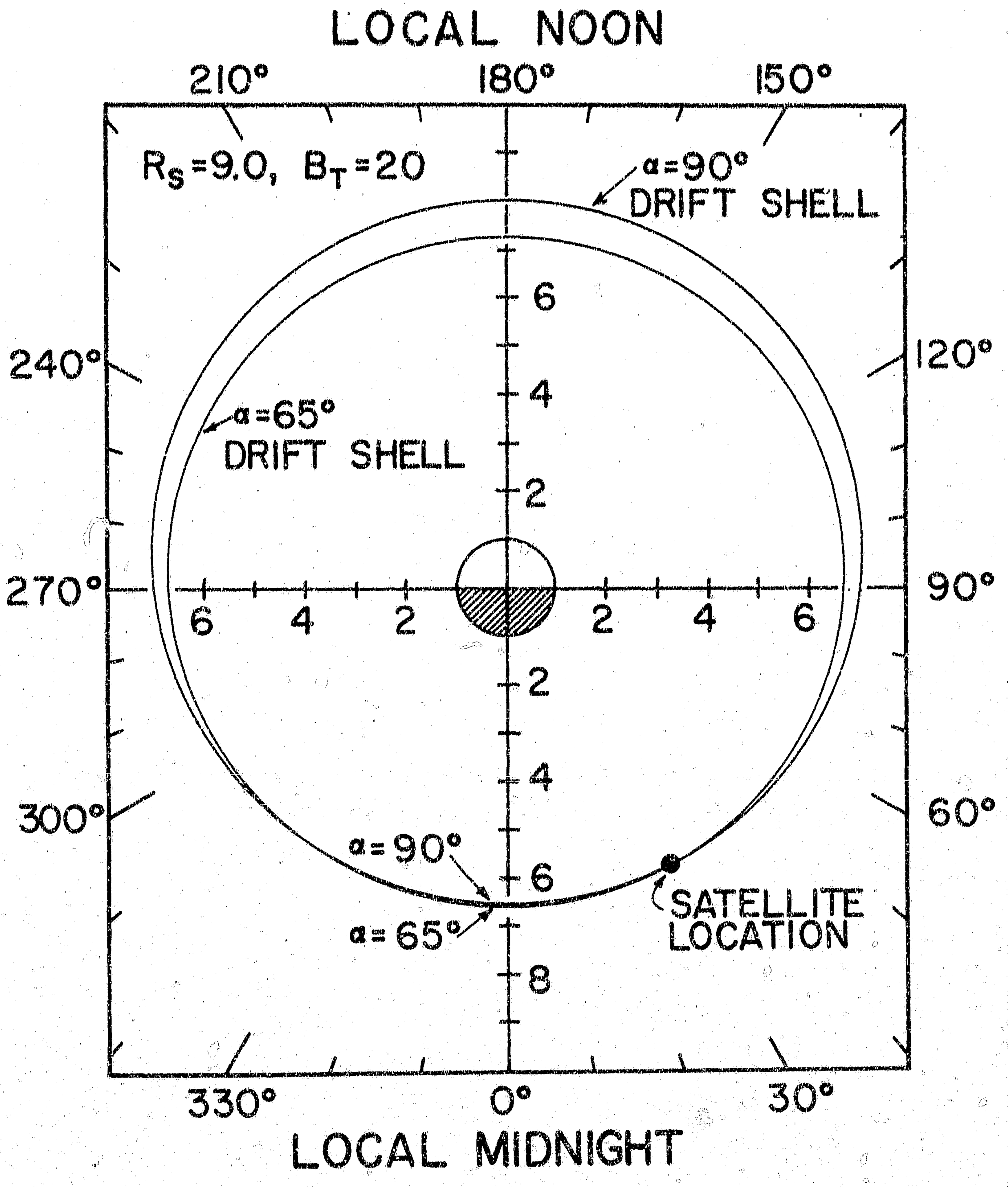

LOCAL NOON
210°
180°
150°
R_S=9.0, B_T=20
α=90°
DRIFT SHELL
6
4
2
240°
120°
α=65°
DRIFT SHELL
270°
90°
6
4
2
2
4
6
2
4
6
8
300°
60°
α=90°
α=65°
SATELLITE
LOCATION
330°
0°
30°
LOCAL MIDNIGHT

Figure 1

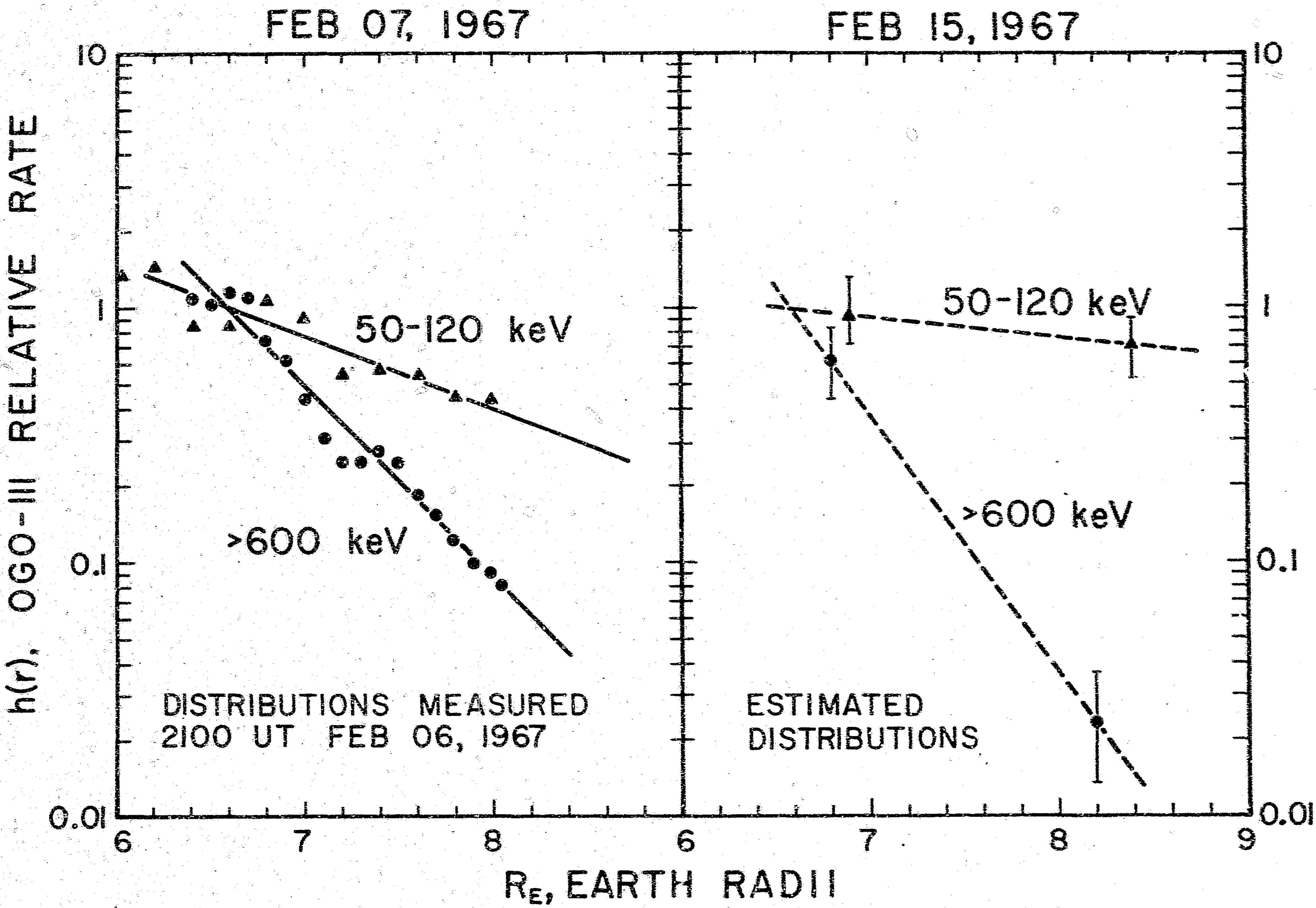
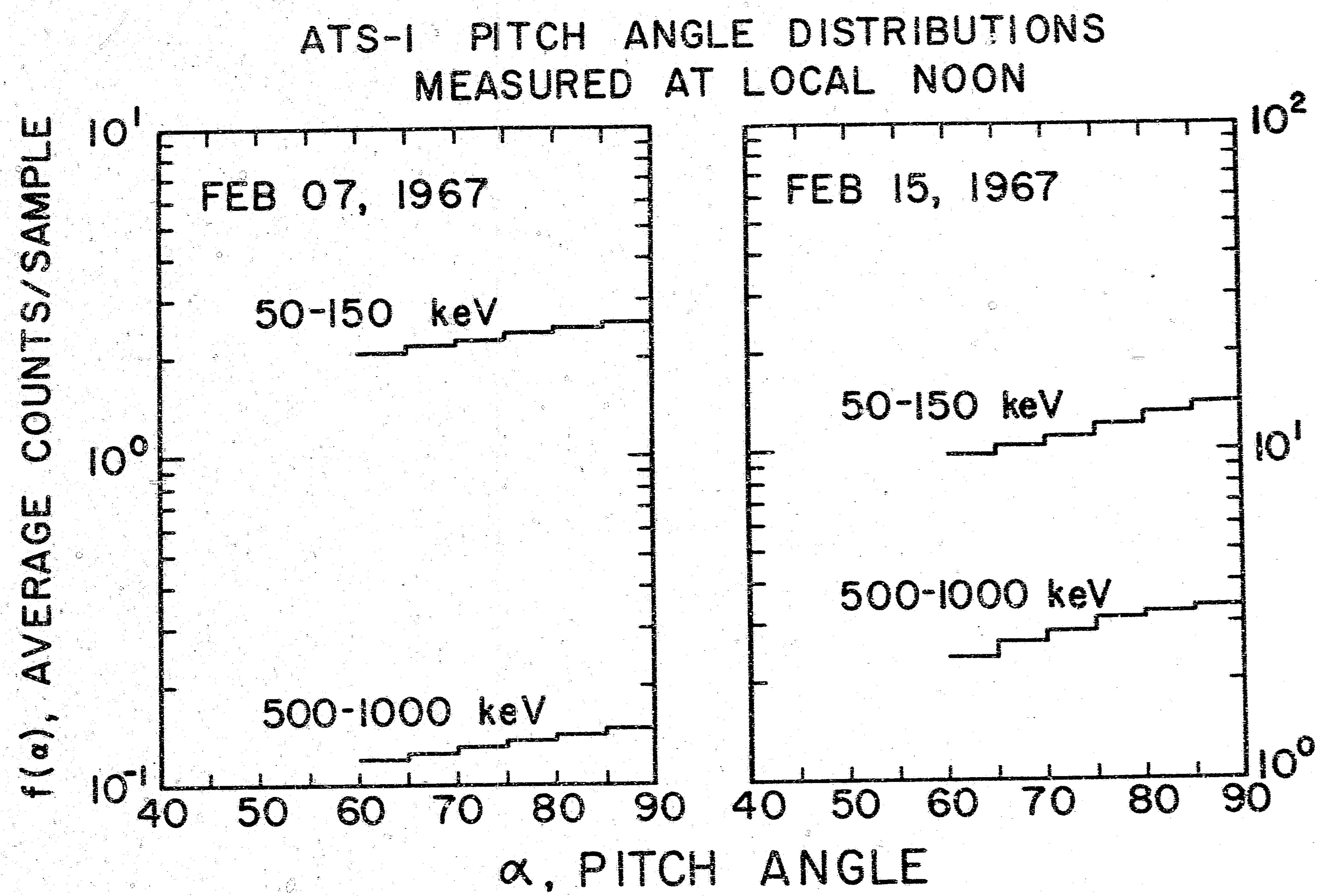
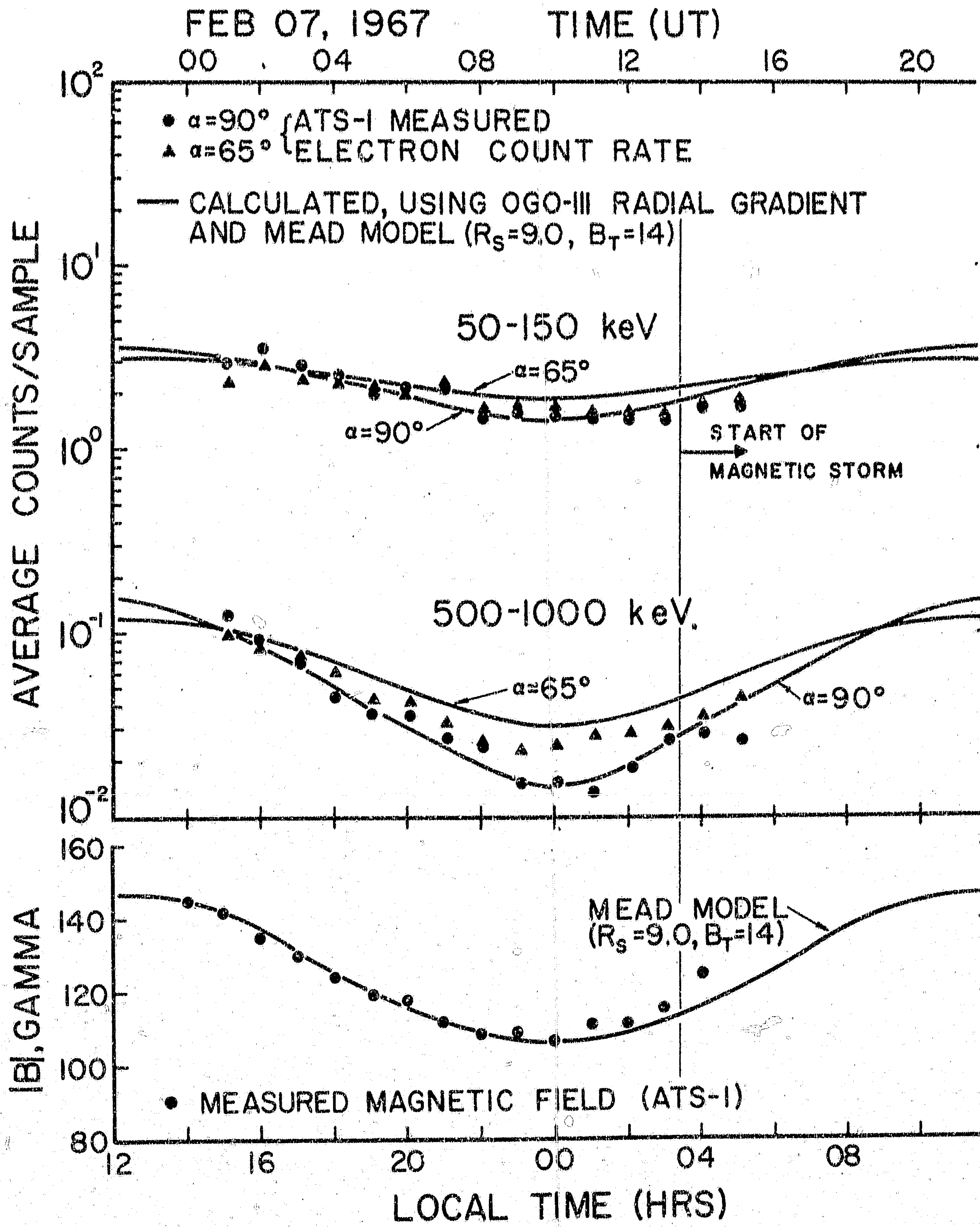

FEB 07, 1967
FEB 15, 1967
h(r), OGO-III RELATIVE RATE
10
1
0.1
0.01
50-120 keV
>600 keV
DISTRIBUTIONS MEASURED
2100 UT FEB 06, 1967
ESTIMATED
DISTRIBUTIONS
6
7
8
9
R_E, EARTH RADII

Figure 2



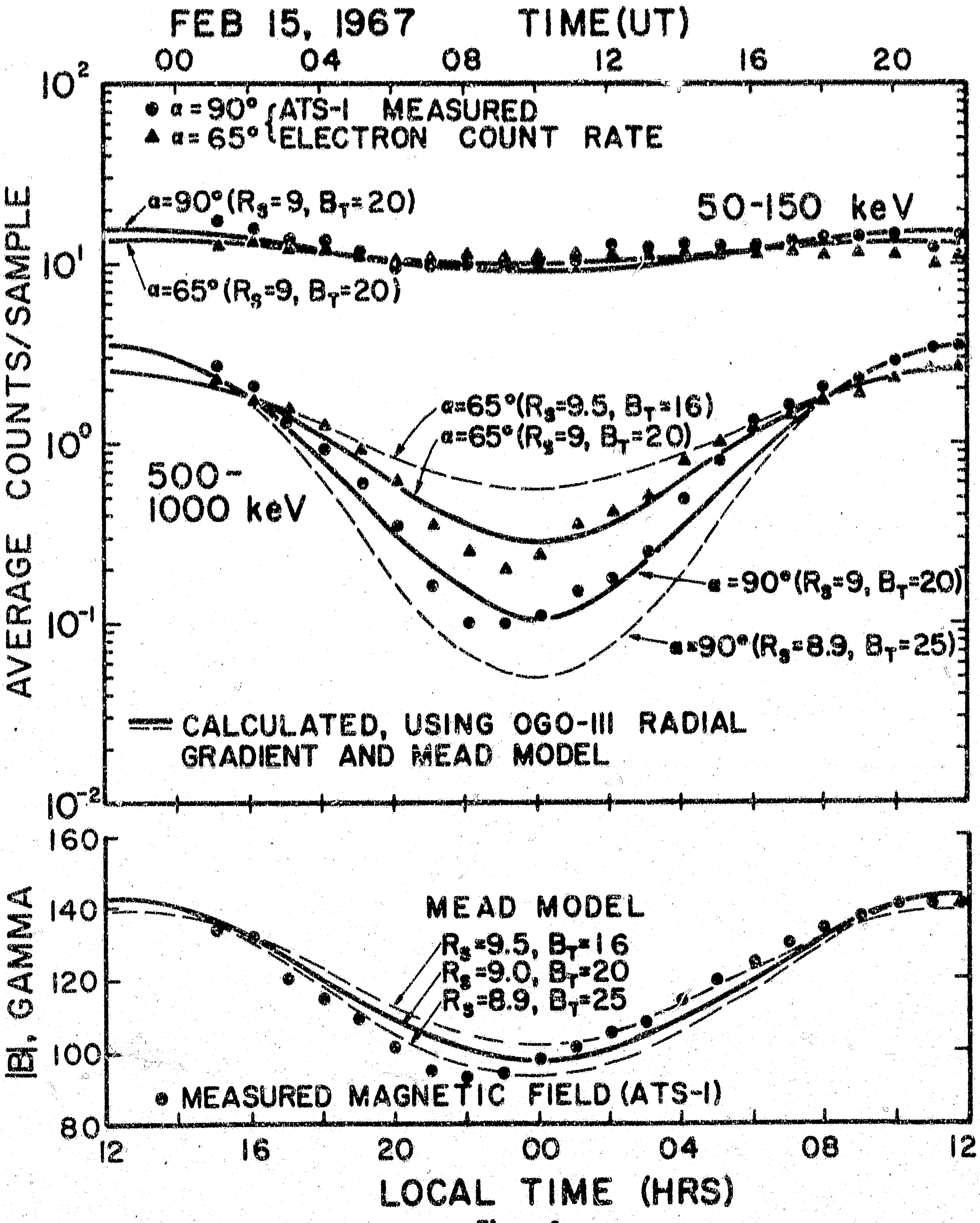
ATS-1 PITCH ANGLE DISTRIBUTIONS
MEASURED AT LOCAL NOON
FEB 07, 1967
FEB 15, 1967
50-150 keV
500-1000 keV
50-150 keV
500-1000 keV
f(α), AVERAGE COUNTS/SAMPLE
α, PITCH ANGLE

Figure 3



FEB 07, 1967 TIME (UT)
00 04 08 12 16 20
● α=90° ATS-I MEASURED
▲ α=65° ELECTRON COUNT RATE
— CALCULATED, USING OGO-III RADIAL GRADIENT AND MEAD MODEL (R_S=9.0, B_T=14)
50-150 keV
α=65°
α=90°
START OF MAGNETIC STORM
500-1000 keV
α=65°
α=90°
AVERAGE COUNTS/SAMPLE
10^2
10^1
10^0
10^{-1}
10^{-2}
160
140
120
100
80
|B|, GAMMA
MEAD MODEL (R_S=9.0, B_T=14)
● MEASURED MAGNETIC FIELD (ATS-I)
12 16 20 00 04 08
LOCAL TIME (HRS)

Figure 4



FEB 15, 1967
TIME(UT)
00
04
08
12
16
20
10^2
10^1
10^0
10^{-1}
10^{-2}
AVERAGE COUNTS/SAMPLE
● α = 90° ATS-I MEASURED
▲ α = 65° ELECTRON COUNT RATE
α=90°(R_s=9, B_T=20)
α=65°(R_s=9, B_T=20)
50-150 keV
500-1000 keV
α=65°(R_s=9.5, B_T=16)
α=65°(R_s=9, B_T=20)
α=90°(R_s=9, B_T=20)
α=90°(R_s=8.9, B_T=25)
CALCULATED, USING OGO-III RADIAL GRADIENT AND MEAD MODEL
160
140
120
100
80
|B|, GAMMA
MEAD MODEL
R_s=9.5, B_T=16
R_s=9.0, B_T=20
R_s=8.9, B_T=25
• MEASURED MAGNETIC FIELD (ATS-I)
12
16
20
00
04
08
12
LOCAL TIME (HRS)

Figure 5

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