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AFTER THE FLARE OF JULY 7, 1966
OBSERVED IN THE MAGNETOTAIL
AND MAGNETOSHEATH

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135 - 1650 Kev Solar Protons After the Flare of July 7, 1966
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August 1968

Abstract

Protons with energies E > 135 Kev were observed in the tail of the magnetosphere following the flare of July 7, 1966. These protons have an isotropic pitch angle distribution. The maximum intensity of the protons reached $\sim 1.2 \times 10^4$ $(cm^2 \ sec \ ster)^{-1}$ for particles with P > 15 MV between 1000 and 1100 UT and 1400 and 1500 UT July 8, 1966. The energy spectrum of the protons expressed as an exponential in momentum indicates a monotonic softening: the characteristic rigidity, P_o, changing from about 50 to 10 MV. An hour long excursion of the satellite into the magnetosheath during the peak of the proton flux showed that the proton intensity is lower in the magnetosheath than in the magnetosphere by a factor of two. The observed pitch angle distribution is flat in both regions.

Introduction

On July 7, 1966 at 0023 UT an importance 2B flare occurred at N36, W48. The flare was accompanied by x-ray and type IV radio noise emission (Cline et al., 1968; Van Allen, 1967).

On July 8 at 0500 a sector boundary corresponding to a + to - field polarity change was observed to pass (Ness and Taylor, 1967). Electrons from tens of kev energies to relativistic were observed at 1 AU about 0058 UT (Cline and McDonald, 1967; Lin et al., 1967). Protons from 0.3 Mev to tens of Mev and 2-17 Mev α particles were observed starting at 0155 UT (Armstrong et al., 1967; Lin et al., 1967). Protons with energies greater than 15 Mev displayed a characteristic diffusive time profile with a peak at about 0700 UT July 7, while lower energy protons and electrons in the tens of Kev range exhibited a secondary peak at about 1200 UT July 8. (Fichtel and McDonald, 1967; Lin et al., 1967). This behavior of low energy protons and electrons has been interpreted as being due to the superposition of an ordinary diffusive component and the subsequest passage of co-rotating field lines onto which these particles were directly injected following the flare.

The purpose of this study is to extend observations of low energy protons down to 135 Kev, to obtain energy spectra between 135 Kev and 1.6 Mev, and to study the effect of the magnetopause on the propagation of low energy solar protons.

Instrumentation

The detector used in this study is a ZnS scintillation counter which can measure integral proton intensities in the energy range between 100 Kev and 1.6 Mev. The salient features of the detector are shown in Table 1.

TABLE I

Low Energy Cut Off (Kev)	Geometric Factor (cm^2 ster)	Super Commutation
105	3.5×10^{-5}	single
135	7.1×10^{-3}	3-fold
195	7.1×10^{-3}	2-fold
285	7.1×10^{-3}	2-fold
380	7.1×10^{-3}	single
380	4.9×10^{-4}	single
1000	7.1×10^{-3}	single
1650	7.1×10^{-3}	single

Omnidirectional penetrating protons $\sim$ 22 Mev. Look angle $\sim 11^\circ$.

The variation in low energy cut-offs is achieved by interposing various thicknesses of nickel foil absorber into the incident beam. In order to obtain measurements at various pitch angles the detector was mounted in the scanning OPEP (Orbital plane experimental package) on OGO 3. The OPEP scans through 220° every 2.46 minutes. During this interval two complete energy spectra can be obtained. In addition the > 135 Kev channel is super-commutated three fold to permit improved angular resolution.

Analysis

The orbit of OGO 3 had an apogee of 20.1 R_e, an inclination of 33° to the equatorial plane and an orbital period of 48 hours. At the beginning of July the semi-major axis was at 2000 LT so that the satellite was virtually within the geomagnetic tail. Figure 1 shows the satellite's orbit in solar magnetospheric co-ordinates in relation to a theoretical

magnetopause (Mead and Beard, 1964). At the time of the flare (F) the
satellite was past perigee, heading into the trapping region. The onset
of the second peak of the low energy protons on July 8, 1966 occurred when
the satellite was again approaching perigee and was located close to the
magnetopause. Indeed, as will be seen later, the magnetopause swept past
the satellite during the period of peak low energy proton fluxes, thus
permitting observations of solar protons in the transition region. The
sudden commencement (SC) occurred when the satellite was again past perigee
and produced no observable effects on the protons.

Figure 2 shows the time history of the solar proton event as it was
seen by the scintillation counter. The solid line represents hourly averages
of the penetrating omnidirectional proton count rate while the dashed line
shows the directional count rate for protons with $E > 135$ Kev. The four
periodic peaks in the diagram are transitions through the radiation belts.
The onset of the event occurred during the first hour of July 7, and for
penetrating protons (> 22 Mev) shows the typical behavior of solar proton
events. The low energy protons display a peak on July 8, 1966.

Figure 3 shows hourly averages of the integral proton intensities during
this peak after subtration of the penetrating background. The overall
picture is that of a slow initial rise from 1800 UT, July 7 to 0800 UT
July 8 when there is a sharp, factor of eight, increase for the low energies
which, with the exception of a drop at about 1200 UT, persists until 1600 UT
whereupon there is a sharp drop in the intensity. The level reached is
somewhat higher than before 0800 July 8. A glance at the intensities of
various energy channels indicates that the spectrum is softening with time.

Several typical spectra are shown in Figure 4. An attempt was made to find some simple parameter to describe the spectral form for the whole time period in question. A good fit, particularly for the time after 1200 UT July 8, could be obtained by an exponential in momentum.

Figure 5 shows the best fitting e-folding momentum P_0 and the integral intensity of protons above 15 Mv. (E > 120 kev) The figure clearly displays the softening of the spectrum which occurs virtually independent of changes in the integral flux. In our analysis we have lumped together all particles with different pitch angles. This procedure is justified because the pitch angle distribution is nearly isotropic. This fact is presented in Figure 6. Because of the location of the satellite we assumed that the magnetic field lines were aligned roughly along the radial direction from the sun. The diagram shows the low energy proton intensity (E > 135 Kev) averaged over the period from 0800 to 1700 UT and plotted as a function of pitch angle. From this we can see that the flux is virtually omnidirectional within the limits of angular observation.

As was shown in Figure 1 the satellite was close to the theoretical magnetopause on July 8. This raises the question of the effect of the magnetopause on the low energy protons. Figure 7 shows 10 minute averages of the proton count rate between the hours of 0600 and 1700 UT July 8. Below the proton intensities are indicated the times when the satellite was alternately within the tail and the transition region. The two regions were defined by the magnetometer flown by J. P. Heppner on OGO III. Chronologically, the satellite was in the transition region between 2300 UT July 7 and 0730 UT July 8, and between 1100 and 1230 UT July 8. The first

excursion of the satellite into the magnetosheath occurred while the proton flux was quite low and therefore it is not clear whether there was any appreciable effect of the magnetosheath on the solar proton flux. The second penetration into the magnetosheath occurred virtually at the peak of the low energy flux and coincides in time with a factor of 2 decrease in the low energy flux. It should be noted that if the depression is indeed caused by the magnetosheath, then the modulation is in effect mainly for protons with energies less than 1 Mev and is much less pronounced for greater than 1.6 Mev protons. During the penetration into the magnetosheath the pitch angle distribution remained flat.

Discussion

The low energy protons described above were observed in the tail of the magnetosphere. One can ask the question whether these protons may not be of the "island" type (Konradi, 1966; Armstrong and Krimigis, 1968) reported earlier. While the intensities of protons above 100 Kev are comparable, the spectra are quite different. Indeed, e-folding energies reported for island protons are less than 85 Kev and more like 40-20 Kev. In our case if an exponential in energy is fitted to the data, the e-folding energy is about 500 Kev (12 UT). This is a spectrum more typical of protons at $L \sim 2.5$ (Davis and Williamson, 1962; Armstrong and Krimigis, 1968). In addition, low energy protons were observed to peak at about the same time as those in interplanetary space observed on Explorer 33 and IMP 3 (Lin et al., 1967; Armstrong et al., 1967).

Additional supporting evidence can be obtained from comparison of peak proton intensities.

The peak intensities of > .5 Mev protons in IMP III and > .3 Mev

protons on Explorer 33 (Lin et al. 1967) compare quite well with our own

peak intensities of > 380 Kev protons : 8 x 10^3 (cm^2 sec ster)$^{-1}$ versus

7.3 x 10^3 (cm^2 sec ster)$^{-1}$. Low energy solar protons were also observed

by detectors on Injun IV over the polar caps. (Krimigis et al., 1967).

These protons seem to track in time those observed by the U. of I. detector

on Explorer 33 very well. However, there is no data available about the peak

proton intensities during the maximum of this event. If we apply the

observed ratio of 10 between the Explorer 33 and Injun IV count rates to the

Explorer 33 count rates we come out with intensities at 1 x 10^4 (cm^2 sec ster)$^{-1}$

for E > .5 Mev protons at the peak of the event which are also in reasonable

agreement with our data. Thus, it is very probable that we are sampling

solar protons within the tail of the magnetosphere.

In the following discussion we shall adopt the interpretation of the

low energy proton event presented by Lin et al. (1967) and consider our own

observations in the light of that interpretation.

Briefly, the interpretation given to the observed low energy flux is

that at the time of the flare and for some time afterward low energy solar

electrons and protons were injected directly onto co-rotating field lines

at the point of production and trapped on those field lines because of the

very low transverse diffusion.

Thus the observed particles present a spatial profile of the region on

the sun responsible for the injection. This profile consists of a halo

formed by 3 - 15 Mev protons and a very narrow low energy electron core

overlapped by a somewhat less narrow proton core due to ~ .3 Mev protons.

Figure 3 shown the halo and the core of the low energy protons as seen by our detector. The halo is clearly outlined by protons with $E > 1.6$ Mev and extends from 1800 UT July 7 to 0000 UT July 9. The core, composed of protons with $E \leq 1.3$ Mev., begins at about 0700 UT July 8 and extends also to 0000 UT July 9. It has a complex structure consisting of a peak from 0700 UT to 1600 UT July 8 and a wing stretching to 0000 UT July 9. As mentioned earlier, the dip in the low energy proton intensity at 1100 UT July 8 is an effect of the magnetosheath and not due to the core structure.

The low energy protons within the core exhibit a well defined softening of the spectrum. If we approximate the spectra in the core by an exponential of the form $e^{-\frac{E}{E_o}}$ we can determine the behavior of E_o as a function of time. A plot of $\frac{1}{E_o}$ vs t indicates that in the core the relationship $t - t_o = \frac{\alpha}{E_o}$ is a good approximation with $t_o = 1.9$ hours UT July 8, 1966 and $\alpha = 4900$ KeV-hrs. These results not only lead to decay times which are completely different from those in the halo (Lin et al., 1967) but also indicate that for an extrapolation to $t = t_o$ the spectrum must have been completely flat. This is most unlikely and thus we are led to the conclusion that what we are seeing is a spectrum whose hardness depends on the position of the field line within the co-rotating core. Thus the western edge of the core contains a higher ratio of high energy to low energy protons than the eastern edge. In all fairness, it must be pointed out that this argument is based on an extrapolation - a notoriously dangerous procedure. However, if other spectral forms are fitted to the data, one still arrives at spectral parameters which are unreasonable if extrapolations are carried out to the beginning of July 8, 1966.

Another possible, though less likely, explanation would be that, indeed, before July 8, 1966 the core did not exist as a separate entity but was formed on that day. In this case the softening of the spectrum could be attributed to time decay.

Two additional features of the low energy protons observed in this study are: isotropy of the incident flux both in the magnetosheath and in the tail, and a relative depression of the proton intensity in the magnetosheath. Since previously reported results (Armstrong et al. 1967) indicate very pronounced anisotropies of low energy protons in interplanetary space our observations need explanation. We shall try it by looking at models of the magnetosphere.

To see whether any field line re-connection between the interplanetary and the goemagnetic field can be expected (Dungey, 1961) we have converted the published direction of the interplanetary magnetic field (Ness and Taylor, 1967) to geomagnetic coordinates. The results indicate that the magnetic field had a northward component between 1000 UT and 2100 UT and therefore it seems impossible to establish a re-connection during that period and the magnetosphere must have been closed.

However, if we are dealing with a closed magnetosphere (Piddington, 1962,1963, Dessler, 1964, Spreiter et al., 1966, Dryer and Faye-Petersen, 1966, Alskne, 1967, Fairfield, 1967) we assume that the low energy protons must enter it through the far off tail. Disturbances in the tail field could cause the flux to become isotropic. Protons found in the transition region can follow field lines which are draped around the magnetosphere. Since the magneto-sheath is a region of disturbed magnetic field it is reasonable that scattering

out of low energy protons could take place and thus isotropize and decrease

the flux. Calculations using the observed power spectra of the magnetic

field should test the reasonableness of this hypothesis.

ACKNOWLEDGEMENTS

FIGURE CAPTIONS

1. Projection of the satellite orbit onto the solar magnetospheric
   equatorial plane. The position of the satellite during
   the flare (F) and the subsequent sudden commencement (SC) are also
   indicated. The open curve on top represents the Mead-Beard boundary.

2. Ion Electron detector response to solar protons from the flare of
   July 7, 1966. Dashed line represents protons with E > 140 Kev plus
   omnidirectional background, while the solid line corresponds to the
   omnidirectional background ($\sim$ 20 Mev) alone. The periodic peaks are
   transitions through the trapping region.

3. Hourly averages of the count rate of low energy protons after background
   subtraction.

4. Typical low energy proton spectra plotted as a function of proton rigidity.

5. Time plot of the integral proton intensity above 15 MV ($\sim$ 120 KeV) and
   the e-folding rigidity P_o.

6. Pitch angle distribution of the low energy protons as a function of the
   sun-detector angle.

7. Ten minute averages of several low energy proton channels as a function
   of time. The bars along the sides of the diagram indicate the magnitude
   of the errors due to statistics. Also shown is the position of the
   satellite with respect to the boundary of the magnetosphere as determined
   from the magnetometer data.

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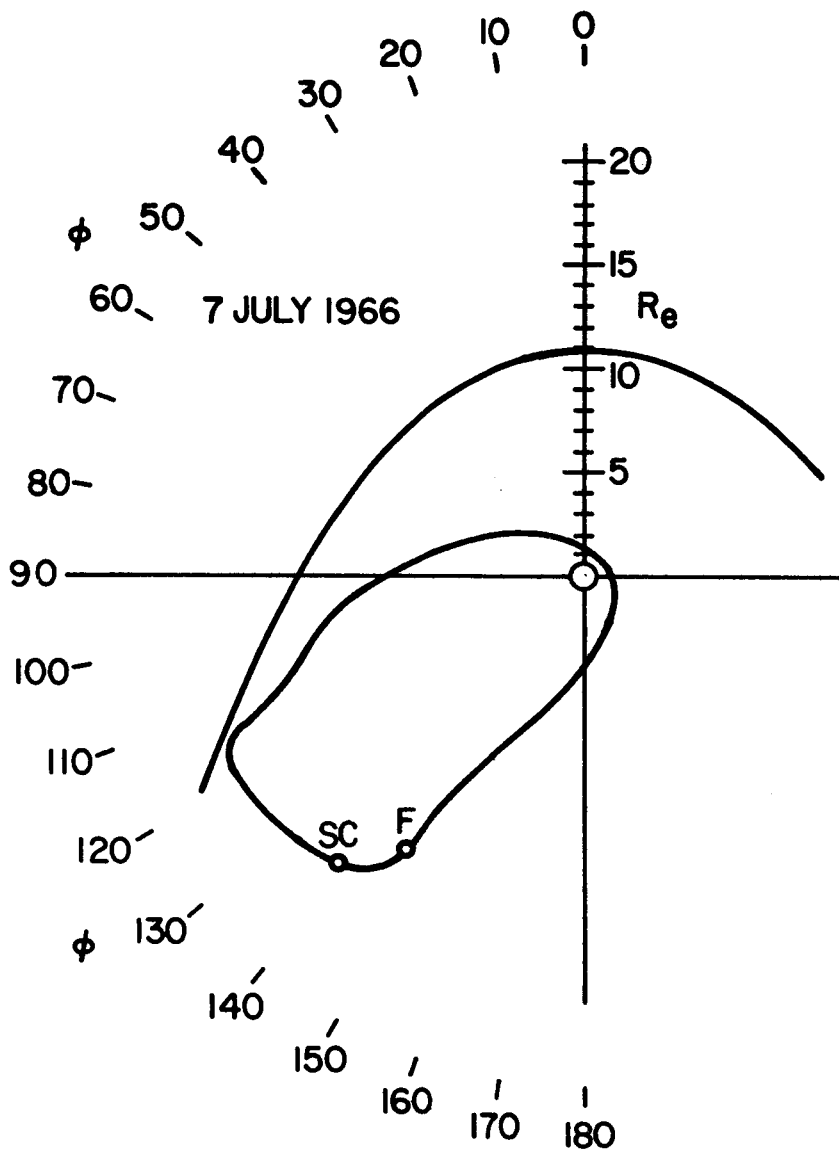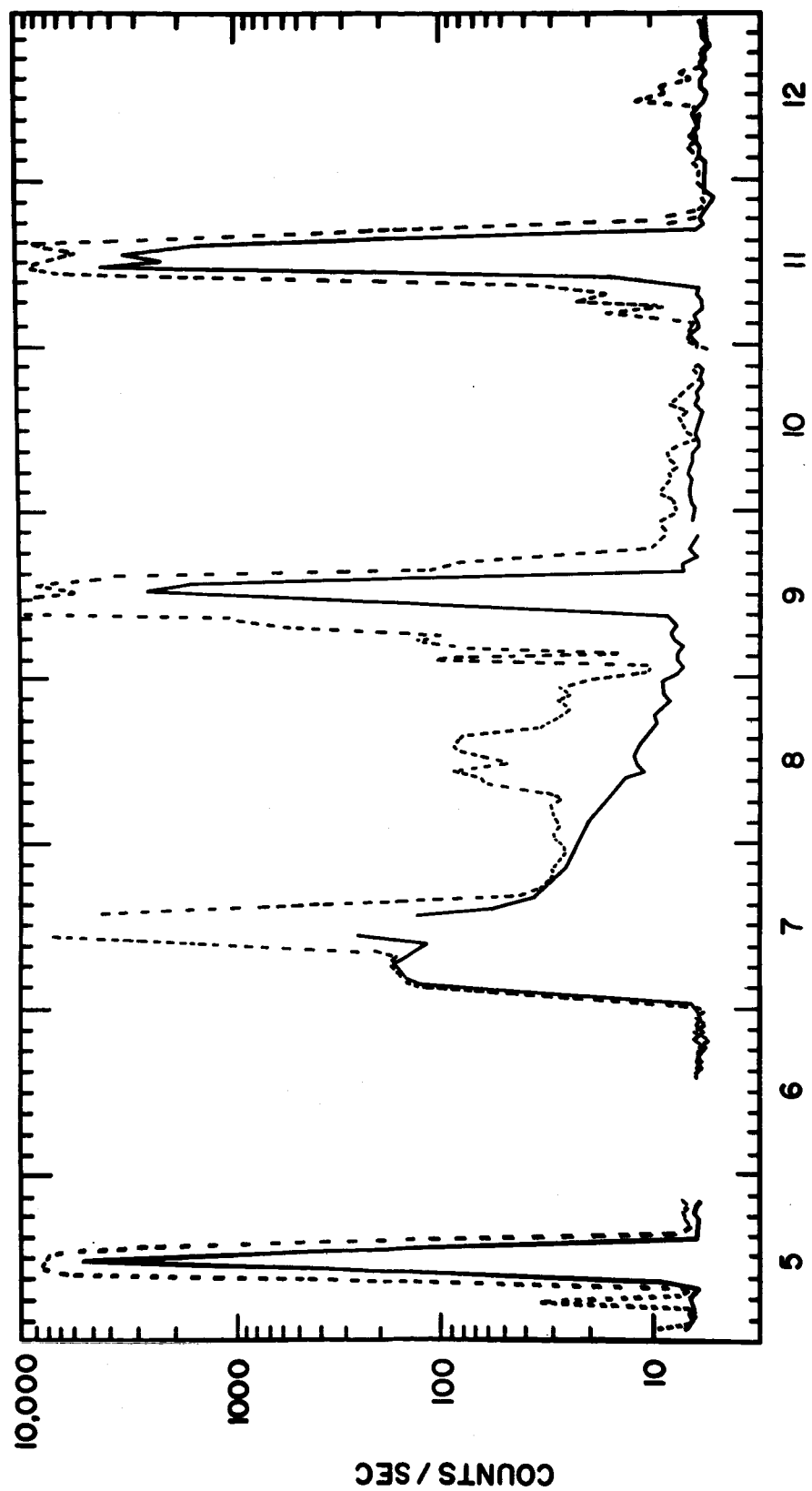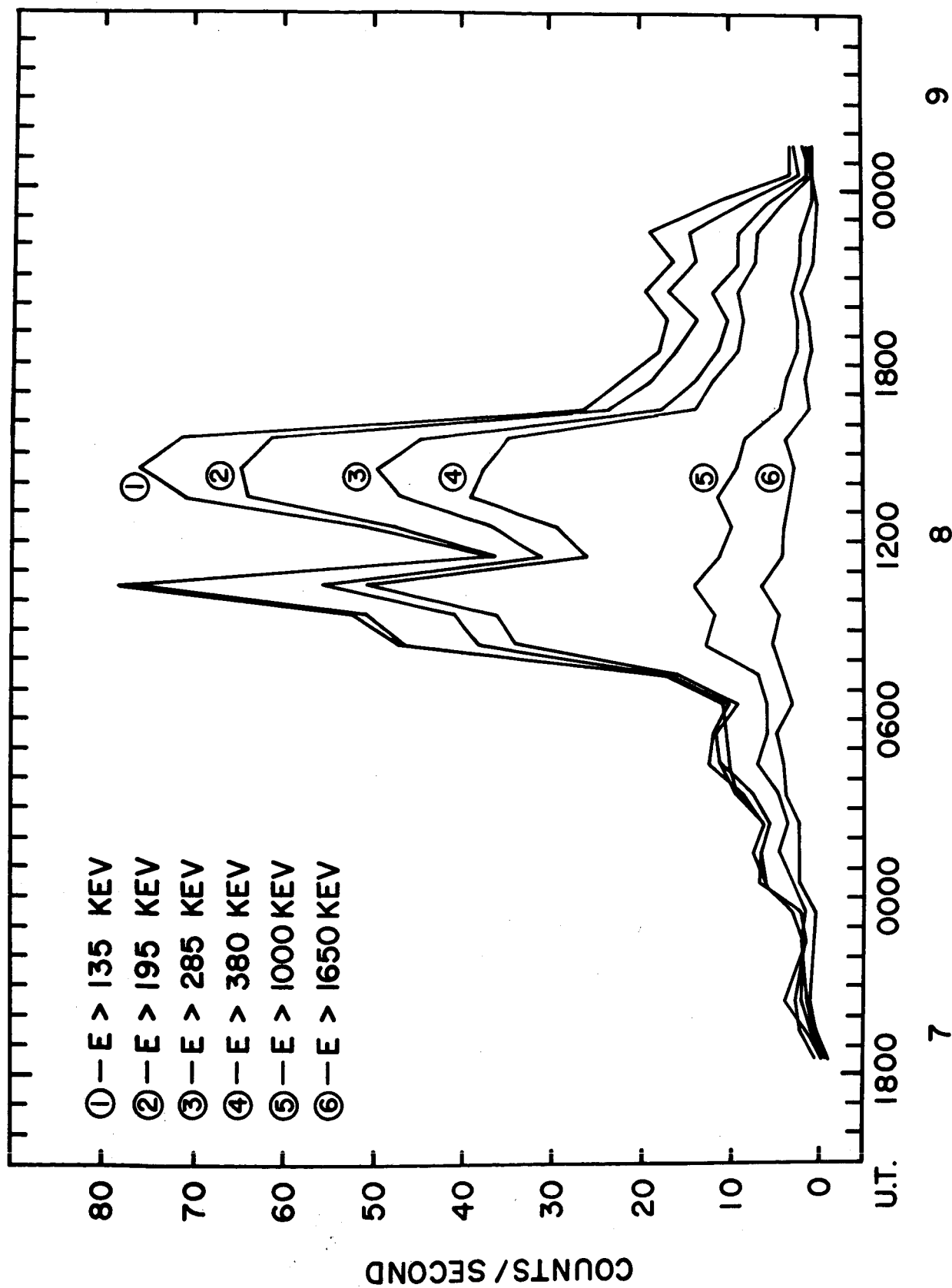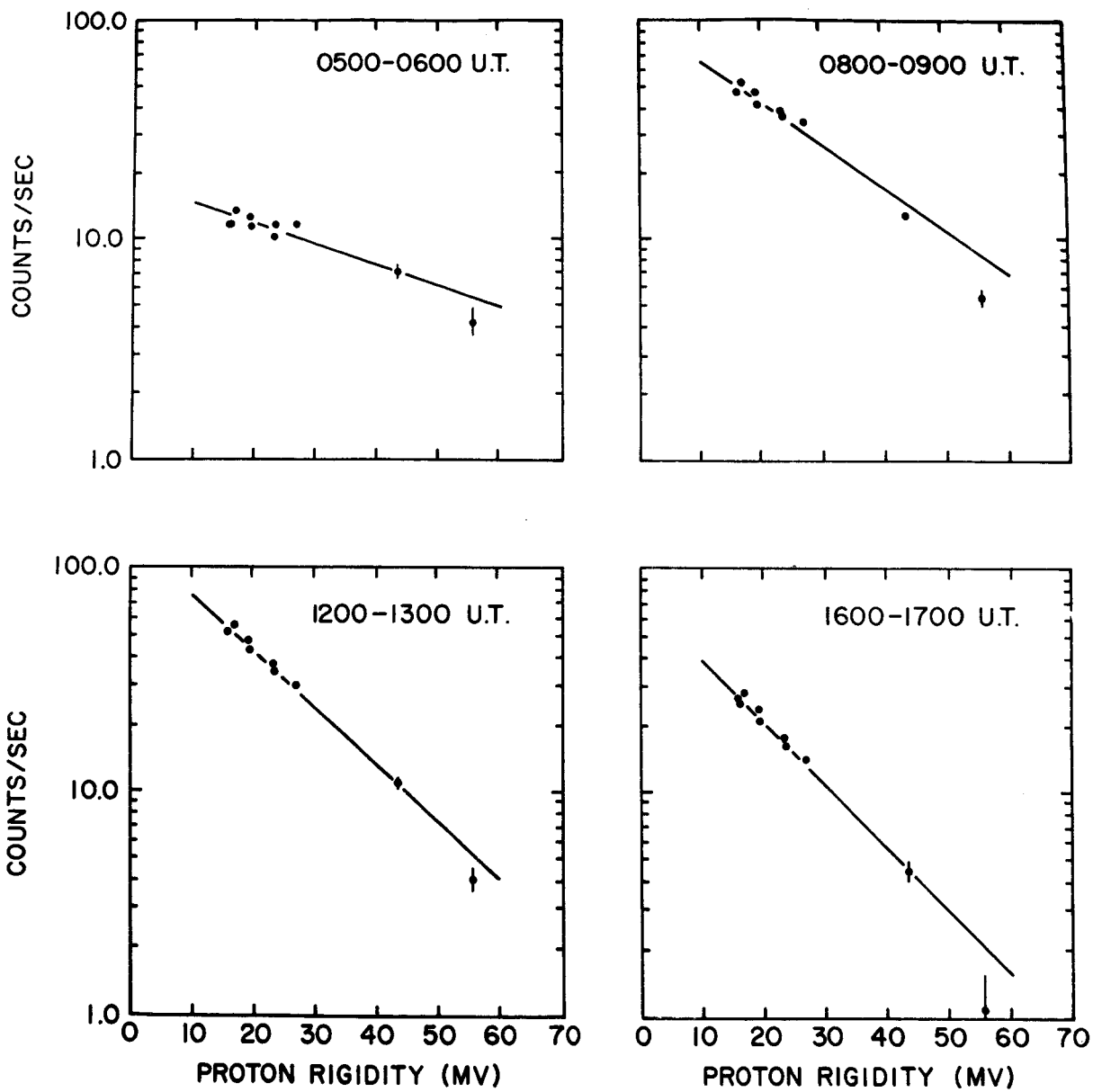
Figure 1

COUNTS / SEC

JULY 1966

Figure 2

COUNTS / SECOND

80 — 70 — 60 — 50 — 40 — 30 — 20 — 10 — 0

U.T.

① — E > 135 KEV
② — E > 195 KEV
③ — E > 285 KEV
④ — E > 380 KEV
⑤ — E > 1000 KEV
⑥ — E > 1650 KEV

1800   0000   0600   1200   1800   0000
  7   8   9
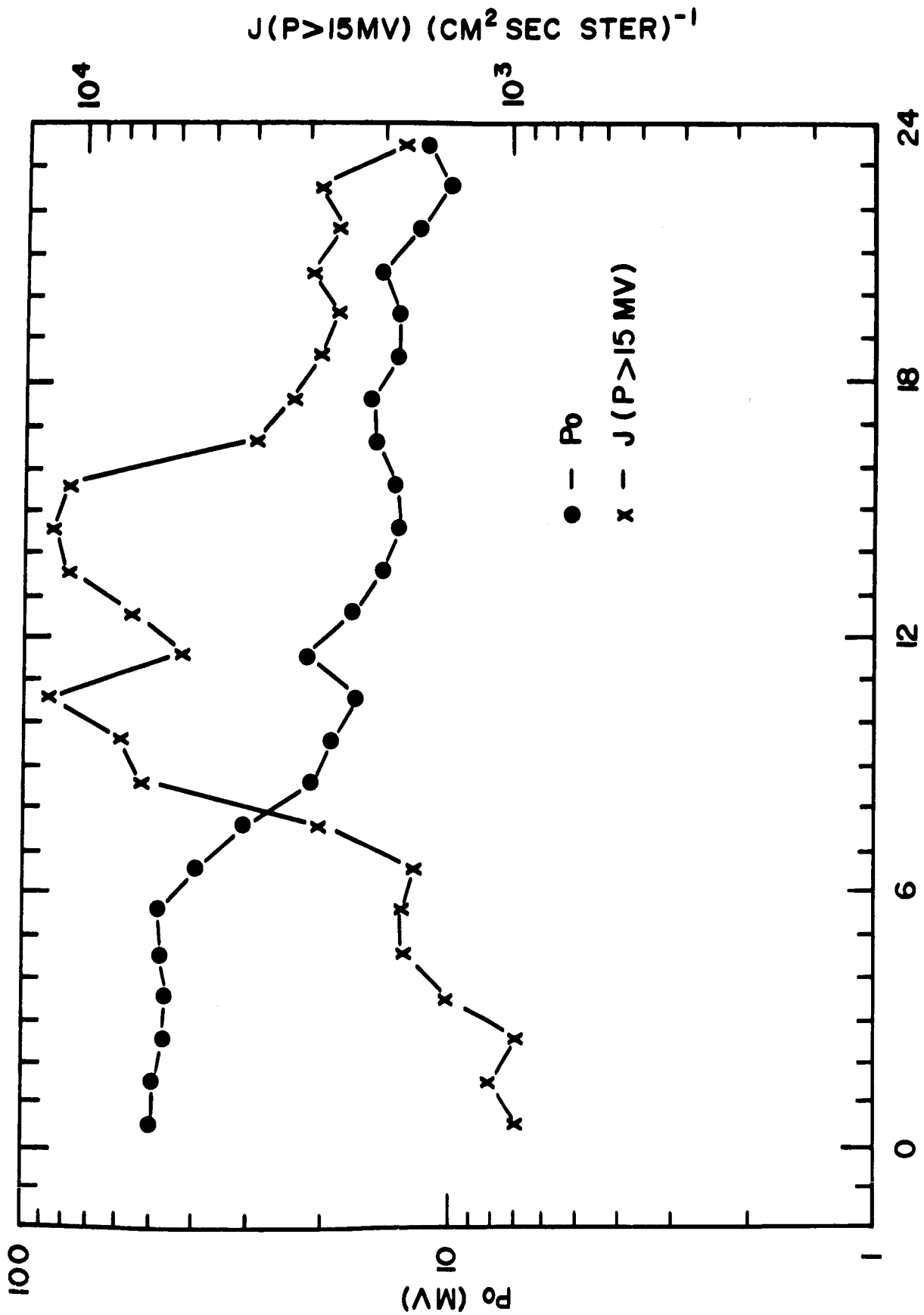
JULY, 1966
Figure 3

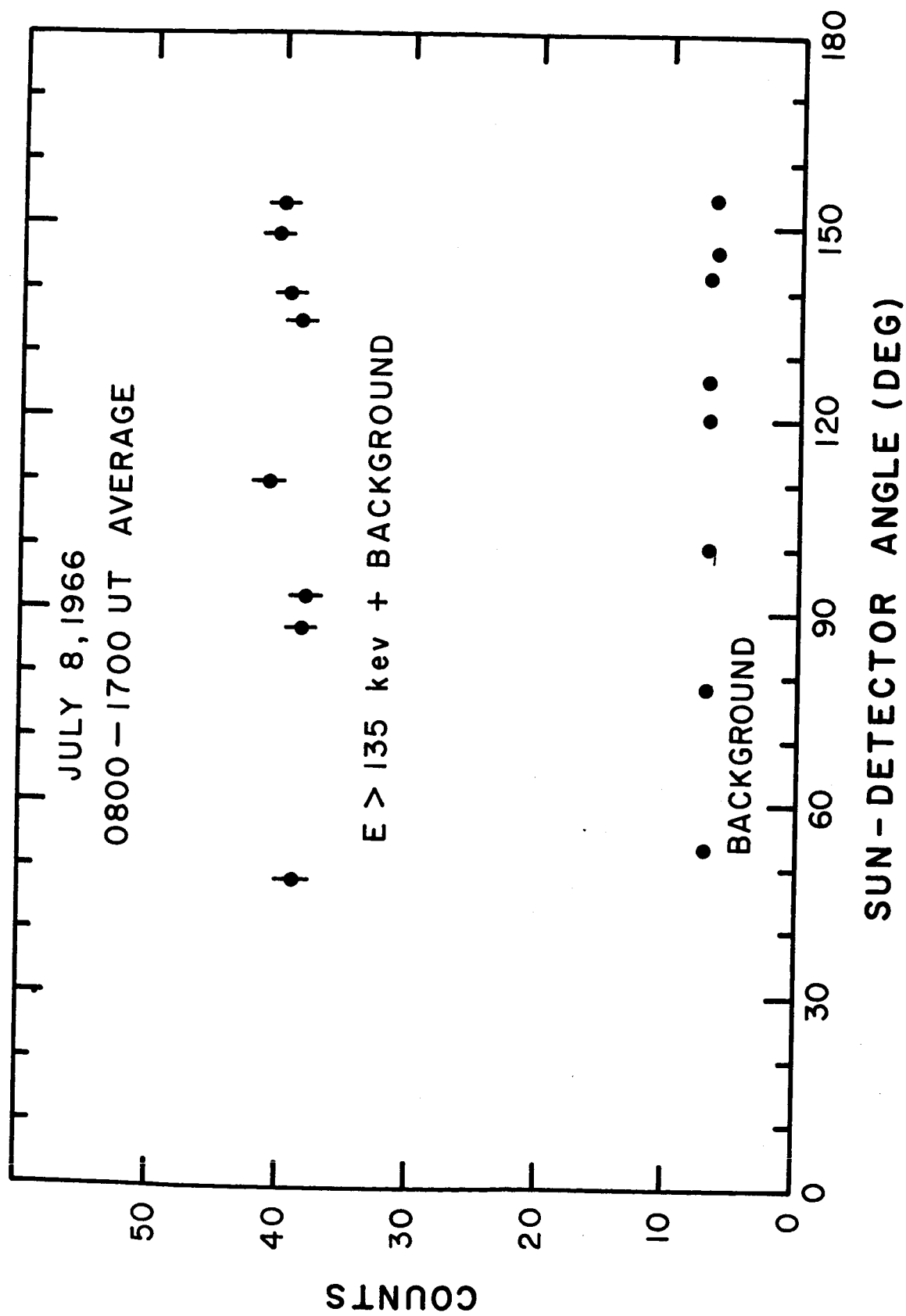JULY 8, 1966

Figure 4

JULY 8, 1966

U.T.

Figure 5

JULY 8, 1966
0800 – 1700 UT AVERAGE

E > 135 kev + BACKGROUND

BACKGROUND

COUNTS

SUN – DETECTOR ANGLE (DEG)

Figure 6

Figure 7