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NASA TM X- 71170

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AND THEIR EFFECT ON
THE LOWER MESOSPHERE

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AUGUST 1976

GODDARD SPACE FLIGHT CENTER
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On the night of May 23/24, 1975, a sequence of rocket and balloon experiments was launched from Chilca Base, Peru (12.5°S, 76.8°W, magnetic dip = -0.7°) as part of Operation Antarqui. Detailed analysis and comparisons of the data have yielded a significant and unexpected result; namely the first direct measurement of lower mesospheric response to a galactic x-ray source. This result could only have been determined at the equator, where cosmic ray background effects are minimal.

Our objective was to seek out the equatorial energetic electron belt, sporadically reported to contain fluxes near auroral levels (e.g., Heikkila, 1971; Goldberg, 1974), measure the bremsstrahlung radiation produced by this particle belt, and determine the influence of this radiation on the middle atmosphere. It was assumed that if the quasi-trapped particle belt were present, it would be subject to the nighttime downward drift forces which lower the equatorial F region ionosphere. The particle belt would therefore drop into a more dense region of the atmosphere where significant enhancement of bremsstrahlung radiation production would occur. Two high altitude rocket payloads (Nike Tomahawk 18.170 and 18.171) were launched to probe the thermosphere during and following the anticipated downward drift period. Each carried an on-axis x-ray scintillation detector with a 5 mil Be window for energetic particle rejection, and with pulse height discrimination in the energy ranges 5-10 (X1), 10-20 (X2), 20-40 (X3), and >40 keV (X4). Geiger Mueller energetic electron detectors with a multiplicity of window thicknesses and look directions were carried to monitor energetic electron fluxes above thresholds between 15 and 40 keV as a function of pitch angle. Magnetometers and lunar sensors were used to determine payload aspect.

Each Nike Tomahawk was accompanied by rocket probes to sample conductivity (σ) and ozone (O_3) below 80 km, to search for modifications in these parameters caused by the thermospherically produced x-rays. Meteorological datasondes (MET) were also used to evaluate the meteorological characteristics of the middle atmosphere and provide control data during the period of study. Finally, monitoring of cosmic rays and energetic x-rays near 40 km was made on a continuous basis during the entire night with balloon-borne instrumentation. The precise sequencing of each measurement is depicted in Figure 1.

Figure 2 compares the count rates for each of the x-ray channels during the flights of 18.170 and 18.171. The vertical line displayed at each 10 second interval represents the extremes of count rate for each second determined in the interval t ± 5 seconds. Midpoints of each range are connected to permit tracking of the mean flux through the flight. Both time and altitude are displayed for reference. The sharp rise in count rate near 50 seconds represents the sudden exposure of the x-ray detector to ambient radiation upon

nose cone deployment. Finally, the count rate enhancement on X4 for each flight above 300 km is attributed to energetic electrons (>150 keV) penetrating the Be windows. This flux is caused by the proximity of the launch site to the outer fringe of the South Atlantic anomaly.

The low energy channels show a significant enhancement in count rate between the first and second measurement of x-ray flux. It reaches a maximum ratio of 4.5 on X1, and is not present on X4, suggesting the added contribution to be caused by a relatively "soft" source. The enhancement has now been analyzed in sufficient detail to permit full accountability by x-ray galactic sources, with no need for a bremsstrahlung contribution. The absence of an equatorial energetic electron belt during this period, at the minimum of the sunspot cycle, has been further verified by near zero count rates obtained with all electron detectors aboard both flights, although each flight remained above 300 km for more than 150 seconds. Woodman (1975) has also indicated that the major portion of downward drift occurred prior to the 18.170 launch, using Jicamarca Observatory drift data. This would imply that the particle belt (if present) would have been near its lowest altitude during both measurements, thereby improving the chance of payload penetration. Finally, the spectral distribution and intensity of the x-ray flux observed aboard 18.170 has been analyzed and found to agree favorably with the diffuse galactic x-ray background.

The enhancement observed between flights can be attributed to galactic stellar x-ray sources, dominated by the presence of Sco X-1, which was at a suitable location for detection and is 10 times brighter than any other x-ray star in the 5-10 keV range. Figure 3 is a polar plot using elevation and azimuth co-ordinates relative to the 18.171 payload position. We have depicted the look direction of the payload (and x-ray detector), and the positions of the moon, Sco X-1, and galactic center in this reference system. Although the trajectory azimuth direction is nearly due west, an irregularity during nose cone deployment caused the payload to tip in the backward direction, and stabilize with a $\pm 5°$ cone centered near 125° azimuth and 60° elevation. As will be seen, this was highly fortunate, as it permitted isolation of Sco X-1 as the primary source responsible for the observed x-ray enhancement.

A power spectrum analysis, using fast Fourier transform techniques, was applied to the data of each x-ray channel on both flights. Because of the backward tip of the scintillator, the angle between detector and Sco X-1 was $46 \pm 5°$, which is sufficiently large to detect modulation effects in the lower energy channels due to coning. Figure 4 shows the spectral plot obtained from the X1 data on 18.171. A singular peak at k index (sampling interval/period) = 100 at 9 db above the RMS noise is apparent in the plot, and relates precisely to the 2.27 second coning period of the payload. Here, a unit shift in k is equivalent to about a 1% change in period. Other channels on this flight exhibited the same result, but with less definition. No periodicities could be discerned in the data of 18.170. The amplitude spike denotes the net contribution from one or more point sources (A.C. component). Further analysis of phasing data has established the point source to be within 10° azimuth of Sco X-1. Finally, in Figure 5 we show the energy spectrum for the A.C. component of x-ray flux measured on 18.171, and compare it with the average spectrum for Sco X-1 (Laros and Singer, 1976). The observed spectrum is found to be slightly harder than that of Sco X-1 and somewhat more intense. However, Holt et. al. (1976) have recently reported wide variability in the 3-6 keV intensity flux emitted from Sco X-1 for a four month period just prior to this measurement, using data from the Ariel-5 All Sky Monitor. This range is indicated on the figure to demonstrate that our extrapolated spectrum lies within the reported range. Finally, the absence of periodic data from 18.170 is consistent with Sco X-1 being low in the eastern sky and out of detector range at that time.

We now consider the stratospheric measurements which demonstrate an atmospheric response to the measured Sco X-1 radiation. Figure 6 shows the two nighttime conductivity profiles (2000 and 0153 LMT) obtained in parallel with the high altitude measurements. In addition, a daytime value on May 28 (1423 LMT) is illustrated to demonstrate measurement consistency. Below 55 km, all three profiles are nearly identical, and reflect the nearly constant influence of equatorial cosmic rays as an ionization source

in this region. The early nighttime profile continues to track the daytime value up to 65 km, above which solar Lyman a causes the daytime conductivity to grow with altitude at a far more rapid rate. Our primary concern is the enhancement of the late nighttime profile between 55 and 75 km, causing a factor of two increase near 65 km. This increase is attributed to the Sco X-1 contribution observed aboard 18.171. The height of energy deposition is consistent with the calculations of Berger et. al. (1974), which predict that 5-10 keV x-rays will be subject to maximum atmospheric absorption between 60-75 km. Finally, we note that the measurements of meteorological parameters and ozone during the period of conductivity measurement do not indicate dynamical behavior which could account for the observed conductivity enhancement.

We next turn to aeronomic considerations to establish consistency with the preceding interpretation. The time dependent continuity equation near 60 km may be written as

$$(dN/dt) = Q - a_i N^2 \qquad (1)$$

where N is total plasma density, a_i is the ion-ion recombination coefficient, and Q is the ionization source function, composed of an x-ray (Q_{XR}) and a cosmic ray (Q_{CR}) component. The steady state solution of this equation is

$$N^2 = Q/a_i \qquad (2)$$

Assuming that the first measurement (t_o) was made near equilibrium for Q_{CR} and the second (t_2) near equilibrium for $Q_{CR} + Q_{XR}$, we obtain

$$(N_2/N_0)^2 = 1 + (Q_{XR}/Q_{CR}) \qquad (3)$$

where N_2 is the steady state value at t_2 and N_0, the value at t_0. Since $N_2/N_0 = 2$, $Q_{XR}/Q_{CR} \sim 3$. The calculated Q_{XR} (65 km) = .006 ion pairs cm^{-3} s^{-1} using the date of 18.171. At first glance, the extrapolated Q_{CR} from the cosmic ray ionization chamber aboard the high altitude balloon appears to be of equivalent magnitude. However, Williamson (1976) has shown that for lower latitudes, the cosmic ray ion production rate exhibits a more rapid decrease with increasing altitude than has been assumed in the past. This empirical result is based on published data from numerous balloon flights, and implies that a value for Q_{CR} (65 km) $\sim$ .001 would be more appropriate.

The desirability for a low Q_{CR} near 65 km is even more acute when the full solution of (1) is taken into account. Under the assumption that Q and a_i remain constant between flights, we have

$$N = C(A - \exp(-Bt))/(A + \exp(-Bt)) \qquad (4)$$

where

$$C = (Q/a_i), \qquad B = 2(Qa_i)^{1/2},$$

$$A = (C - N_0)/(C + N_0),$$

and N_0 is the initial value at t = 0. We have conducted a parametric study of this solution to evaluate the conditions present during the late evening measurement (0153 LMT, t = 6 hrs) assuming that t = 0 represents the early measurement (2000 LMT). For these calculations, N_0 is 150 cm^{-3} as estimated from the blunt probe data, and a is of order 5×10^{-8} cm^3 s^{-1}. The results are shown in Table 1, where we find that N_1 6 (hrs) represents from 63 to 68% of the equilibrium value. Since the requirement that N_0 be doubled can be met during this interval, this implies that at steady state, N_2/N_0 be larger than 2, and Q_{CR} be sufficiently small to meet the criterion. The values in the table are reasonable within the experimental and theoretical guidelines of this work. Decreasing a or increasing Q will also permit the doubling effect to occur, but by exceeding limits considered reasonable for the appropriate parameters.

Table 1

a_i (cm^3 s^{-1})	Q (cm^{-3} s^{-3})	N_0 (cm^{-3})	N_1 (6 hrs) (cm^{-3})	$N_2(\infty)$ (cm^{-3})	% ($100 \times N_1/N_2$)
5×10^{-8}	7.5×10^{-3}	150	263	387	68
4	7.5	150	271	433	63
5	8.0	150	271	400	68
5	10.0	150	305	447	63
4	9.0	150	298	474	63

Finally, other experimental results have claimed observed modulation of radio waves caused by Sco X-1 nighttime enhancement of upper D region ionization (e.g., Edwards et. al., 1969; Ananthakrishnan and Ramanathan, 1969; Chilton and Crary, 1971) using limited statistical correlations. These results in turn have been discussed and disputed on theoretical grounds by Poppoff and Whitten (1969), Francey (1970), and Poppoff et. al. (1975). Although our results pertain to modifications of ion density at altitudes below which electrons can usually survive at night, it would appear that these new results show sufficient cause to reconsider the earlier theoretical arguments regarding ionospheric response to x-ray galactic sources.

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Poppoff, I. G., R. C. Whitten, and D. S. W. Willoughby, J. Atmos. Terrstr. Phys., 37, 835, 1975.

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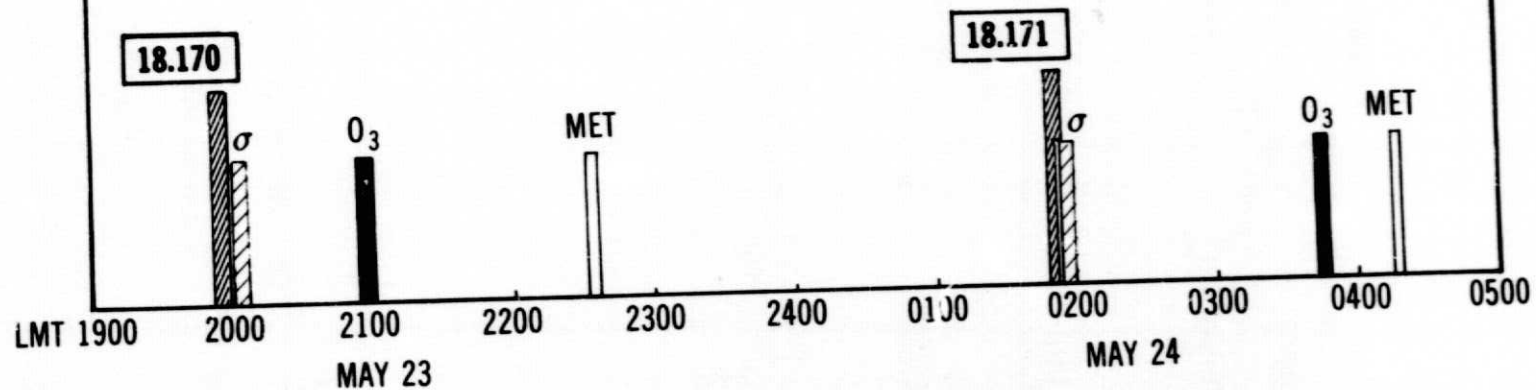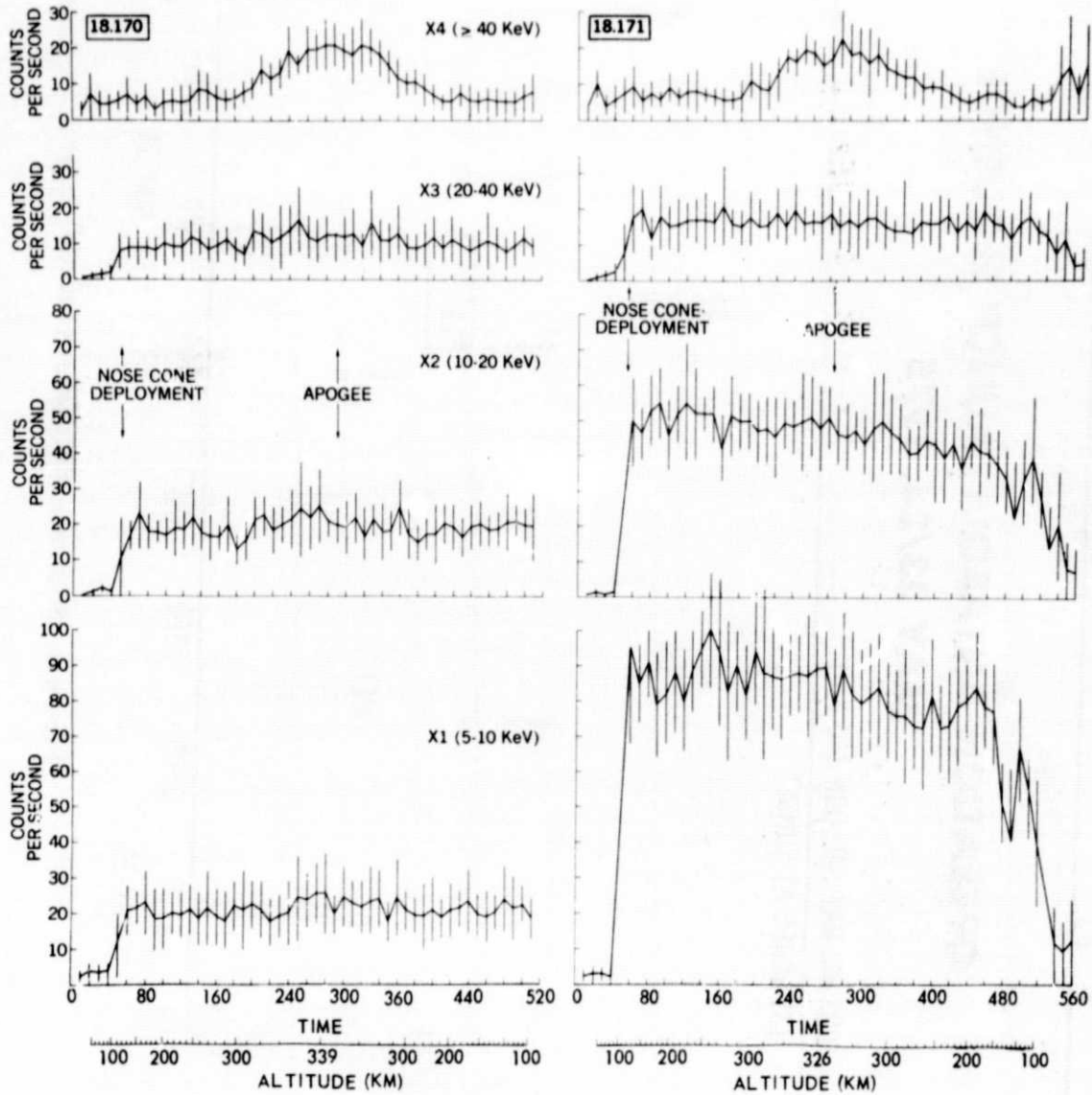Figure 1. Sequencing of Measurements
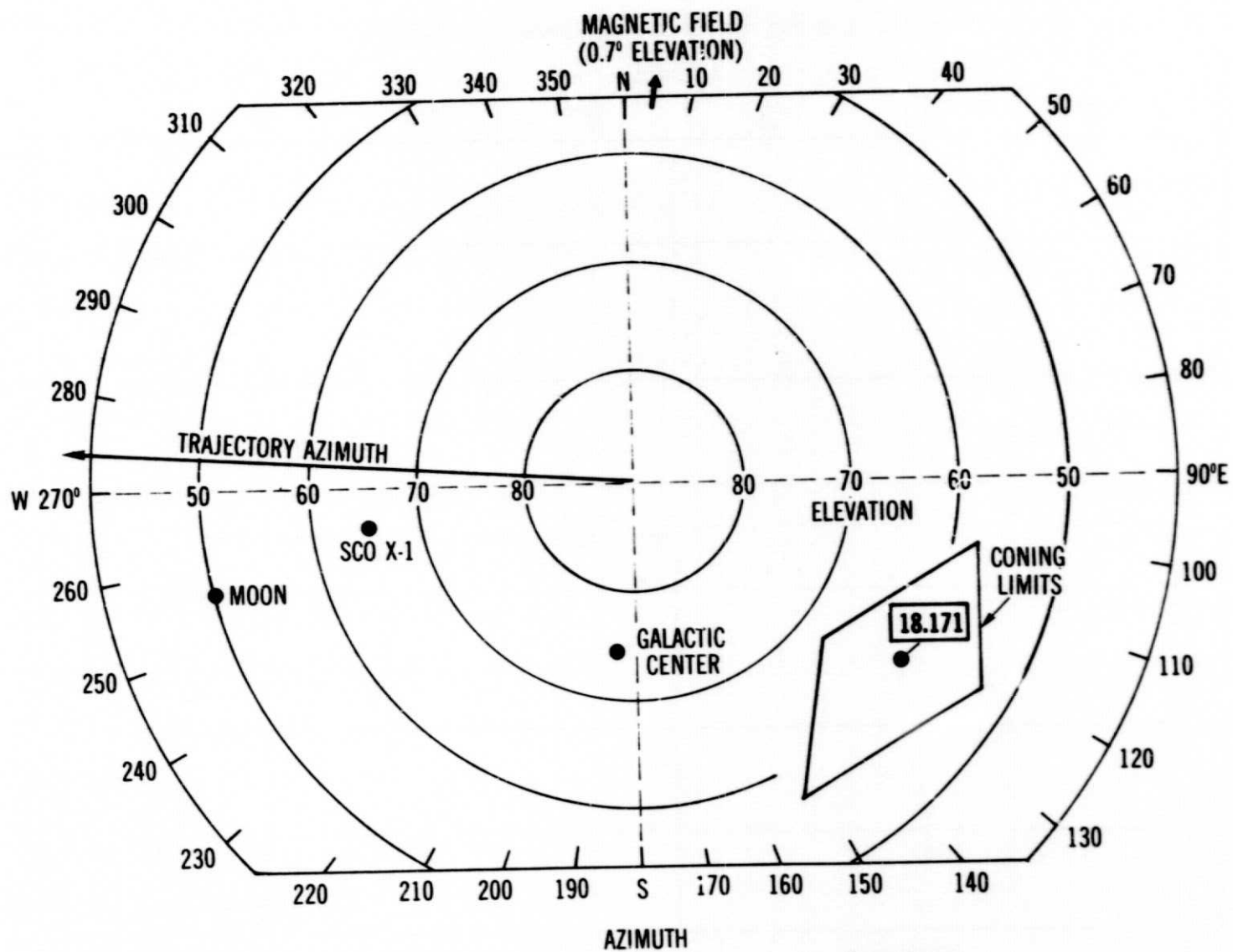
Figure 2. X-Ray Count Rates

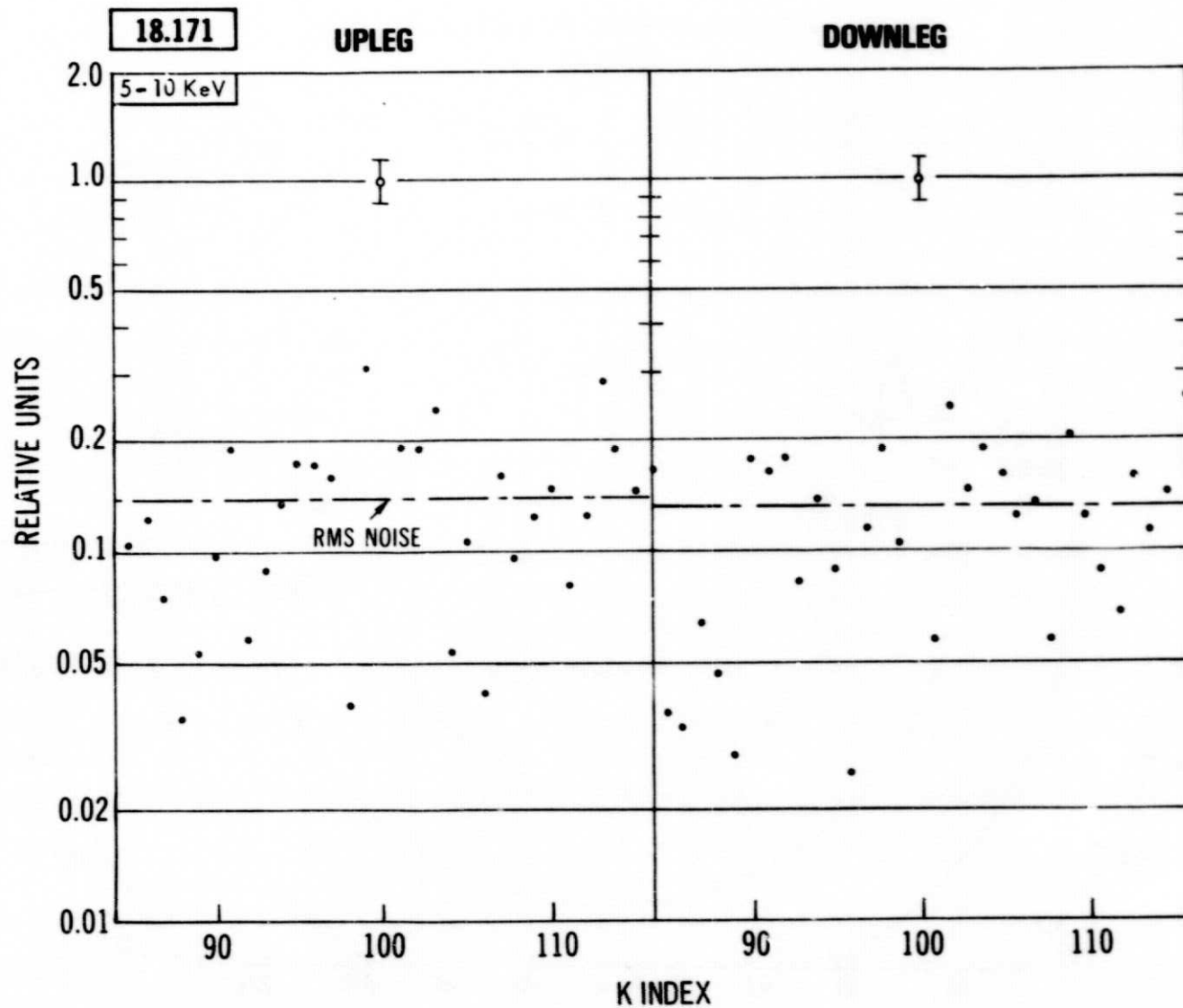Figure 3. Polar Plot Centered at 18.171 Position

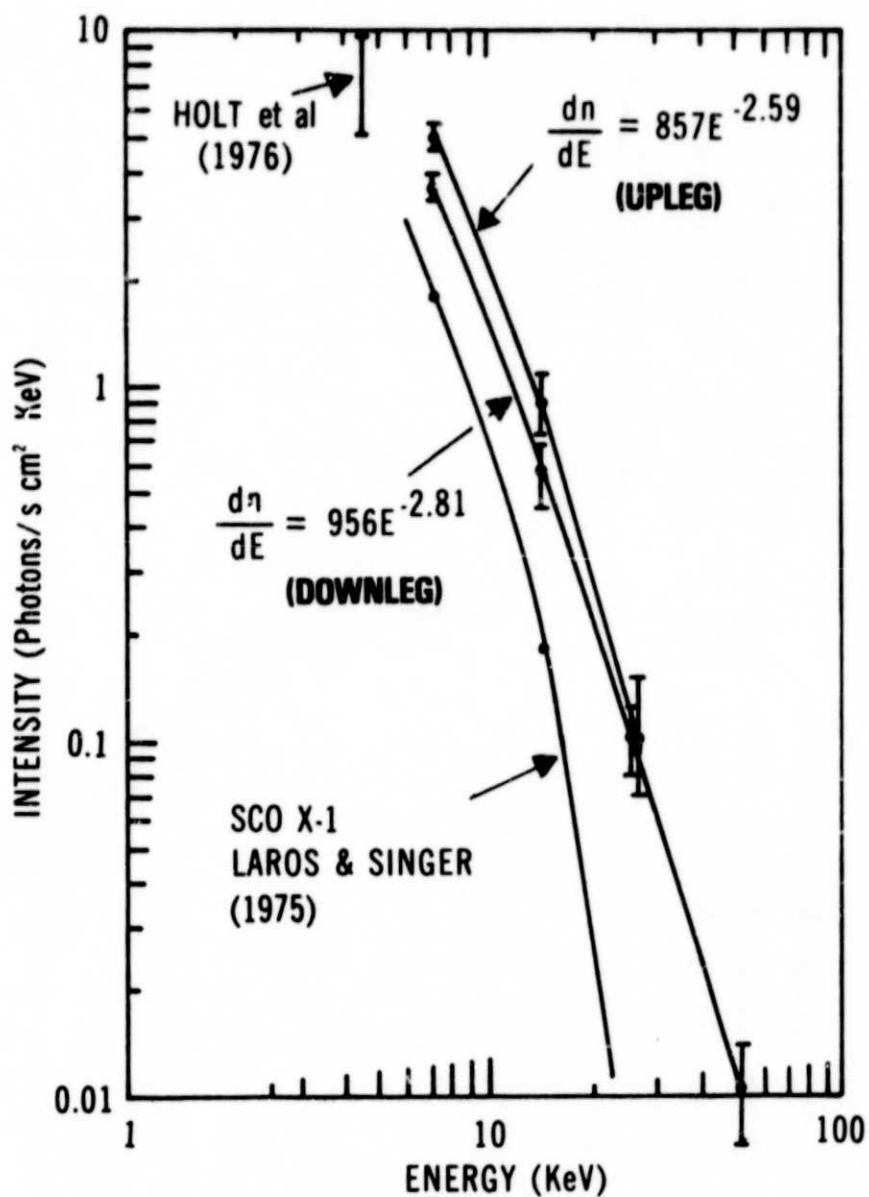Figure 4. Power Spectrum, X1 Channel, 18.171
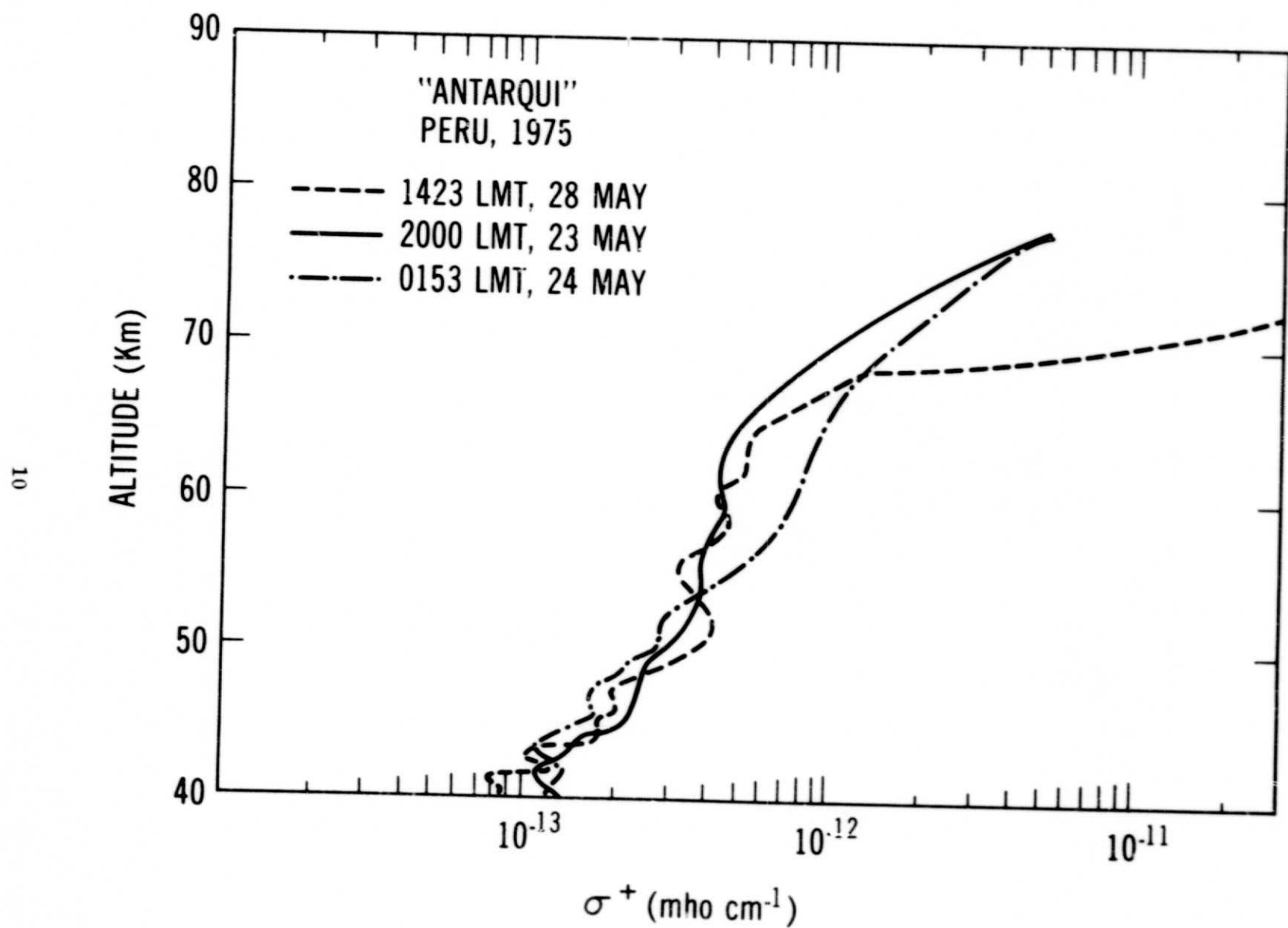
Figure 5. 18.181 X-Ray Energy Spectrum (A.C.)
Compared with Sco X-1

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Figure 6. Conductivity Profiles Measured in Peru