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A BATSE Investigation of Radiation Belt Electrons Precipitated by VLF Waves

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Final Report

For the Compton Gamma Ray Guest Investigation Program

NASA Goddard Space Flight Center

Contract Number

NAS5-32608

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Final Report to Contract NAS5-32608
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ABSTRACT

The Compton Observatory commonly encounters fluxes of energetic electrons which have been scattered from the inner radiation belt to the path of the satellite by resonant interactions with VLF waves from powerful man-made transmitters. The present investigation was motivated by the fact that in the Fall of 1993, the Gamma Ray Observatory was boosted from a 350 km altitude circular orbit to a 450 km altitude circular orbit. This was an opportunity, for the first time, to make observations at two different altitudes using the same instrument. We have examined DISCLA data from the BATSE experiment from 1-September-1993 to 29-Jaunary-1994. During the period of study we identified 48 instances of the satellite encountering a cloud of energetic electrons which had been scattered by VLF transmitters. We find that boosting the altitude of the circular orbit from 350 km to 450 km increased the intensity of cyclotron resonance scattered electrons by a factor of two. To search for long term changes in the cyclotron resonance precipitation, we have compared the ~450 km altitude data from 106 days at the end of 1993 with data at the same altitudes and time of year in 1991. The cyclotron resonance events in 1991 were three times more frequent and 25% of those cases were more intense than any seen in the 1993 data. We attribute this difference to increased level of geomagnetic activity in 1991 near the Solar Maximum.

Introduction

The resonant interaction of electromagnetic waves and trapped electrons in the Earth's magnetosphere produces wave amplification and pitch angle scattering of the electrons [*Helliwell,* 1965]. In the Earth's inner radiation belt, the cyclotron resonance mode of interaction is excited by certain large VLF broadcast transmitters. [*Inan et al,* 1984] The trapped electrons may be scattered to pitch angles that correspond to motions such that they will collide with the atmosphere and be absorbed. At some locations this process is the dominant source of electron precipitation from the inner radiation belt [*Imhof et al.,* 1981]. The process is important for satellites which seek to minimize charged particle backgrounds by choosing a low altitude, since they will see electrons scattered by a VLF transmitter as a localized source of unwanted interference. Soon after the Compton Gamma Ray Observatory(CGRO) launch in 1991, the Burst and Transient Source Experiment (BATSE) found that these intense localized regions were producing false burst triggers [*Horack and Fishman*, 1991]. Operational procedures were modified to disable triggering in regions where the electron fluxes are most often encountered. A careful study of transmitter induced electron precipitation is important for minimizing the interference with sensitive astronomical observations.

In a study completed under the Phase 2 Guest Investigator Program, *Datlowe and Imhof* [1994] studied BATSE data from the first eleven months of the Gamma Ray Observatory mission. They used counting rates above a threshold of 50 keV to identify 563 instances in which CGRO passed through a cloud of energetic electrons which had been resonantly scattered by powerful VLF transmitters. By mapping the locations of the instances, they identified two communications transmitters as the source of the VLF waves responsible for the scattering. One of the transmitters is located in Australia and has the call letters NWC, and the second is located in Russia and has the call letters UMS. There was no unambiguous evidence for contributions from other stations.

The ionospheric electron density profile strongly influences the occurrence of resonantly scattered energetic electrons. Time variations in the ionospheric electron density profile are reflected in time variations in the occurrence of resonantly scattered electrons. Data from earlier satellites [*Datlowe and Imhof*, 1993] had revealed a seasonal variation, such that events were 2.5 times more frequent in the summer than in the winter. In a study completed under the phase 2 CGRO guest investigator program, *Datlowe et al.* [1995] found a similar seasonal variation in the first year of BATSE data. They also studied the diurnal variations in the occurrence of resonant electron scattering. Due to the continuous data coverage of the CGRO and the precession of the orbit through all local times, the Phase 2 data set provided the first opportunity to study, on an hour by hour basis, the diurnal variation of coupling of VLF waves to the interaction region. The result of the study was that the VLF transmitters are most effective in scattering electrons when the local time at the station is between 2 AM and 6 AM.

The 11 year solar cycle is a time scale of interest for understanding both the ionospheric and trapped radiation environments. The first year of the CGRO mission was a time of intense solar activity: one of the largest solar flares ever recorded occurred on 6 June 1991 (JD8413), slightly more than one month after BATSE was turned on. Since the phase 2 guest investigation covered a time span of only 11 months, no information about solar cycle related time variations can be developed. By coincidence, the previous satellite measurements of cyclotron resonance scattering were also acquired near solar maximum -- P72-1 in 1972, OV1-19 in 1972, P78-1 in 1979, S81-1 in 1982, and CGRO in 1991. However, as the time of solar activity minimum approaches, CGRO data continues to be archived. Comparisons of BATSE data from the postlaunch solar maximum epoch can be compared with data closer to solar minimum to search for changes in the character of cyclotron resonance precipitation.

The present investigation was motivated by the fact that in the Fall of 1993, the Gamma Ray Observatory was boosted from a 350 km altitude circular orbit to a 450 km altitude circular orbit. This was an opportunity, for the first time, to make observations at two different altitudes using the same instrument. The *quid pro quo* of this opportunity was that seasonal variations must be corrected, as the period of study covered nearly half a year. During the period of study we identified 48 instances of the satellite encountering a cloud of energetic electrons which had been scattered by VLF transmitters, about half at ~350 km and about half at ~450 km.

The Investigation

The foundation of this investigation is a BATSE data product labelled with the acronym DISCLA for large area discriminator data. The data consists of counting rates above thresholds of 25, 50, 100, and 300 keV for all 8 BATSE large area detectors, with one second time resolution. DISCLA data, housekeeping data, and orbital data from JD 9224 to JD 9385 (25-August-1993 to 2 February-1994) were provided in the form of 8mm tape by Dr. Mark Finger at the Marshall Space Flight Center.

In a cosmic x-ray burst, at most four faces of the BATSE instrument are illuminated at one time. The experiment also commonly observes events in which all eight faces are recording counts and opposite faces have the same counting rates. Electrons which are trapped in the geomagnetic field spiral about magnetic field lines. If their mirror point is comparable to the altitude of the satellite, the fluxes in opposite directions will be equal Although electrons with energies below 300 keV cannot penetrate windows over the scintillation counters, they produce x-rays as they stop in the window material. The X-ray production above a given pulse-height threshold depends strongly on the electron spectrum, but the efficiency is of the order $\sim 10^{-3}$ [*Berger and Seltzer,* 1964]. With a collecting area over 10^4 cm^2, the geometric factor for electrons is of order of 1 cm^2 sr^{-1}. Thus we infer that events seen simultaneously in all eight Large Area Detectors are due to fluxes of locally trapped electrons.

The first step in the reduction of the data was to generate plots of DISCLA counting rates versus geographic longitude. Due to the motion of the satellite, 3.6 degrees of longitude per minute, the plots are equivalent to time history plots, but exploit the fact that events associated with transmitters occur consistently at the same longitudes. A typical plot is displayed in Figure 1, generated from data acquired on 5 January, 1994. The upper trace in the Figure shows the sum of the counting rates in the 8 Large Area Detectors above 50 keV. The lower trace is a measure of the directionality of the recorded counts: small values of this trace indicate isotropic counting rates. A complete description of how the directionality parameter is calculated is provided in the Final Report from the Phase 2 study *[Datlowe and Imhof*, 1994].

The significant feature in Figure 1 is the impulsive counting rate increase at 118°E longitude. The minimum in the lower trace indicates omnidirectional counts, which is characteristic of locally trapped electron fluxes. When the Gamma-Ray Observatory encounters clouds of resonantly scattered electrons, it is often at this longitude, which on this orbit is the point of closest approach to the large 22.3Khz VLF transmitter NWC in Australia. At the time of these counting rate increases the satellite was at an altitude of 450 km, and the geomagnetic coordinate L was 1.86.

The core task in this investigation was to survey DISCLA data from 25-August-1993 to 2 February-1994 for events of this type. We found 48 events which form the basic data for this investigation. The events are listed in Table I.

The geographic distribution of the BATSE encounters with clouds of scattered electrons is displayed in Figure 2. The Figure shows as a gray scale the number of events recorded in each bin of 5° longitude by 5° latitude. For reference the locations of major VLF communications transmitters are indicated with the symbol "•"; the locations and call letters of the stations are listed in Table II. The figure also shows the contours of geomagnetic "L-value" of 1.65 at the altitude of the satellite, because the occurrence of these events tends to track those two contours. The geographic distribution of these events in late 1993 is the same as the distribution of events during the first year of operations, as shown in Figure 7 of the Phase 2 final report [*Datlowe and Imhof*, 1994].

Examination of the list shows that there were no events recorded between JD 9329 and JD 9352, or 8 December to 31 December on the calendar. The rarity of events in the month of December has been reported previously [*Datlowe and Imhof*, 1993] and is characteristic of the data from low altitude satellites.

The time interval covered in this investigation was deliberately chosen to coincide with the orbit adjustment from a ~350 km circular orbit to a ~450 km circular orbit. The primary focus of this report is to compare the observations at "low-altitude" with the observations in the "high-altitude" regime. The data listed in Table I, which is sorted by time, can divided into two altitude groups -- before JD 9270 and after JD 9275. We can then ask if there is a statistically significant difference in the frequency of occurrence of events or in the size distribution of the events.

The data is divided into two groups as follows:

17 Events in 39 days from 1-September to 10-October 1993

31 Events in 106 days from 15-October to 29-January 1994

The normalized event size distributions are shown in Figure 3. This pre-boost size distribution is plotted as a dashed line, and the post-boost size distribution is plotted with a solid line. It is clear from the Figure the the lower altitude corresponds to smaller peak fluxes, a difference of a factor of two at the median (fraction=0.5). Although this behavior is expected qualitatively from pitch angle distribution considerations, this data give a quantitative estimate of the benefit of the lower altitude for reducing electron interference with astronomical observations: a ~100 km reduction in mean altitude reduces the background by a factor of two.

The frequency of occurrence statistics depend on two competing effects. First there is minimum detectable event size due to a "background" of about 10,000 counts per second. In this context the diffuse cosmic X-ray flux is the dominant source of the "background". Because of the threshold we expect fewer events at low altitudes where the events are typically smaller. There is also an annual cycle in the occurrence of these events -- they are less frequent in December and January on a satellite at constant circular altitude *[Datlowe and Imhof,* 1993]. The seasonal effect leads to the expectation of fewer events per day in the second half of the data coverage. The BATSE observations gave a frequency of occurrence of 0.44 (17/39) events per day in the first observing period and 0.3 (31/106) events per day in the latter observing period. Clearly the time-of-year variation is more important than the intensity increase related to a 100 km increase in altitude.

A much more significant change in the intensity of electron interference is related to the level of solar activity. The data used in the previous Phase Two study came from the first year of CGRO operations, a time of intense solar activity. During this time interval the average satellite altitude was 425 km, and ranged from 450 km right after launch to 400 km at the end of the 11 months. After the reboost in late 1993 the satellite was restored to the same ~450km altitude as the initial postlaunch orbit.

Figure 4 compares the size distribution of the after the reboost with events identified from the same time of year in 1991. In the 106 days from 15-October-1991 to 29-January-1992 there were 99 events recorded, as compared with the 31 events in the present data. The data was selected to best match the time of year and the satellite altitude ranges. Figure 4 shows clearly the 1991-1992 data is strongly weighted toward large events, events of the type seen in conjunction with geomagnetic storms. The same result is obtained if we plot all 561 electron resonance events recorded in the first 11 months of CGRO operations, May 1991-April 1992. The significant difference between the two observing periods was the level of solar activity and the frequency of large geomagnetic storms.

Hopefully continued operations throughout this solar cycle will permit BATSE to be the first experiment to continuously record the solar cycle variations of the cyclotron resonance precipitation process.

Conclusions

The conclusions of this study can be summarized as follows:

1. Boosting the altitude of the circular orbit from 450 km to 450 km increased the intensity of cyclotron resonance scattered electrons by a factor of two, but the frequency of occurrence of the events was dominated by time-of-year effects.

2. In 1991 the fluxes of electrons from cyclotron resonance precipitation were more intense than in late 1993. Some very large events occurred in the initial interval. We attribute this difference to the level of solar activity and the resulting frequency of large geomagnetic storms.

Acknowledgments

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TABLE I

Day	UT seconds	Latitude °E	Longitude °E	Altitude Km	MLT* Hours	L	Pitch† Deg	>50keV‡ Counts	BATSE Trigger
9231	63193.8	-28.37	120.59	354.4	1.72	1.764	19.84	26037	
9236	52397.7	-28.18	120.36	351.2	22.61	1.752	20.06	29322	
9236	58226.3	-27.14	122.11	352.3	0.42	1.690	21.39	30955	
9238	49186.5	-28.20	117.61	349.3	21.51	1.756	19.97	47881	2517
9238	54982.3	-27.43	117.10	351.0	23.12	1.712	20.89	24218	
9240	40361.6	-27.24	128.35	347.2	19.89	1.685	21.53	23823	
9240	40271.5	-26.21	122.19	346.7	19.40	1.637	22.56	23872	
9241	47342.2	-28.00	119.11	347.7	21.13	1.742	20.24	24357	
9243	38273.7	-27.44	113.78	345.7	18.25	1.713	20.83	85633	2524
9243	49855.1	-24.96	111.69	346.9	21.29	1.581	23.98	25318	
9243	51698.3	24.05	218.60	345.6	4.57	1.306	40.53	22758	2526
9243	57719.4	28.32	233.19	344.1	7.21	1.491	29.95	26283	
9245	48829.1	28.25	241.33	344.6	5.28	1.545	27.63	30920	2531
9266	80066.2	-28.44	122.81	357.8	6.65	1.766	19.83	28861	
9267	81576.6	-27.30	124.16	357.5	7.16	1.698	21.27	24103	
9268	77233.8	-28.29	123.24	360.1	5.91	1.757	20.02	25350	
9270	68945.6	-28.36	131.07	373.5	4.24	1.750	20.32	31705	2577
9270	74583.7	-28.27	118.21	371.7	4.81	1.766	19.90	36675	
9275	54880.9	-27.30	136.90	423.2	0.81	1.689	22.05	26550	
9279	52214.4	-27.99	122.54	444.2	23.03	1.762	20.38	29181	
9283	44145.3	-27.34	118.09	403.3	20.53	1.720	21.04	27886	2601
9285	56888.0	28.12	235.62	407.0	7.36	1.515	29.47	29112	2604
9285	57062.0	28.36	247.72	396.9	8.26	1.614	25.64	49787	
9302	23629.5	-24.44	35.39	438.9	8.95	1.572	34.30	43587	2624
9306	82179.7	-28.11	136.59	450.3	8.13	1.742	21.04	34553	2637

Day	UT seconds	Latitude °E	Longitude °E	Altitude Km	MLT* Hours	L	Pitch† Deg	>50keV‡ Counts	BATSE Trigger
9307	78678.7	-27.63	138.15	449.6	7.29	1.711	21.75	26492	
9308	14278.3	-26.33	35.47	447.2	6.11	1.642	32.02	41174	2639
9311	76319.4	-28.36	125.55	444.0	5.70	1.781	20.05	71587	2650
9313	70050.5	-28.09	131.43	438.2	4.46	1.751	20.68	31791	2653
9316	67198.6	-27.98	118.34	441.4	2.70	1.766	20.27	31294	2659
9318	61755.0	-28.40	133.54	436.3	2.41	1.763	20.45	24586	
9324	56827.5	-22.88	148.79	424.8	2.14	1.460	29.23	20918	2673
9324	58574.5	23.73	246.92	449.4	8.60	1.455	32.12	39071	
9324	64319.1	26.32	234.17	449.0	9.18	1.457	32.42	25683	
9324	66959.0	-24.14	32.77	412.2	20.46	1.565	34.53	44325	2674
9324	78980.8	-25.38	44.48	420.5	0.40	1.576	33.01	64230	2675
9329	58725.0	-25.69	34.76	420.5	18.37	1.616	32.75	85609	
9352	79040.2	-27.96	140.98	456.8	7.29	1.722	21.63	23868	
9354	79840.9	-27.96	121.67	456.1	6.05	1.766	20.38	27893	2734
9355	77388.4	-27.58	120.45	455.5	5.30	1.744	20.81	26074	
9356	80928.4	-28.17	122.24	456.0	6.38	1.778	20.15	32553	2739
9357	78445.2	-28.44	118.92	455.2	5.46	1.799	19.74	48041	2741
9358	70121.1	-26.97	123.08	453.6	3.56	1.706	21.65	40656	2746
9358	76123.8	-28.18	126.75	454.9	5.43	1.771	20.31	70486	
9359	73581.2	-28.47	119.42	453.8	4.20	1.799	19.71	38533	
9361	85510.8	-28.35	48.13	452.9	2.14	1.695	28.90	34414	
9363	72299.2	28.32	268.19	449.2	13.47	1.815	21.00	26055	
9372	64339.6	-25.54	29.06	455.2	19.23	1.632	32.78	37471	
9381	45939.4	28.24	251.03	444.1	5.15	1.651	24.87	26381	

* Midnight is 0.00 hours

† Pitch angle at the geomagnetic equator

‡ Counts in 2.048 seconds in all 8 Large Area Detectors

Table II

The **geomagnetic coordinates** of a satellite when it is 450 km over the stations marked in Figure 3 are as follows:

STN	FREQ kHz	POWER KW	LAT	LONG °E	L	CONJ Km
NAA	17.8	1000.	44.7°N	292.7	3.28	105.
NLK	24.8	850.	48.2°N	238.1	3.10	742.
NPM	23.4	300.	21.4°N	201.9	1.22	726.
NSS	21.4	265.	39.0°N	283.6	2.68	347.
NWC	22.3	1000.	21.8°S	114.2	1.46	573.
GBR	16.0	300.	52.3°N	0.3	2.59	-597.
UMS	16.2	1000.	56. °N	44.	2.79	62.
RPS	17.1	1000.	43. °N	135.	1.55	760.
Siple	var	3.	75.9°S	275.8	4.70	1077.

Station location, frequency and power from

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The calculation of geomagnetic coordinates based on

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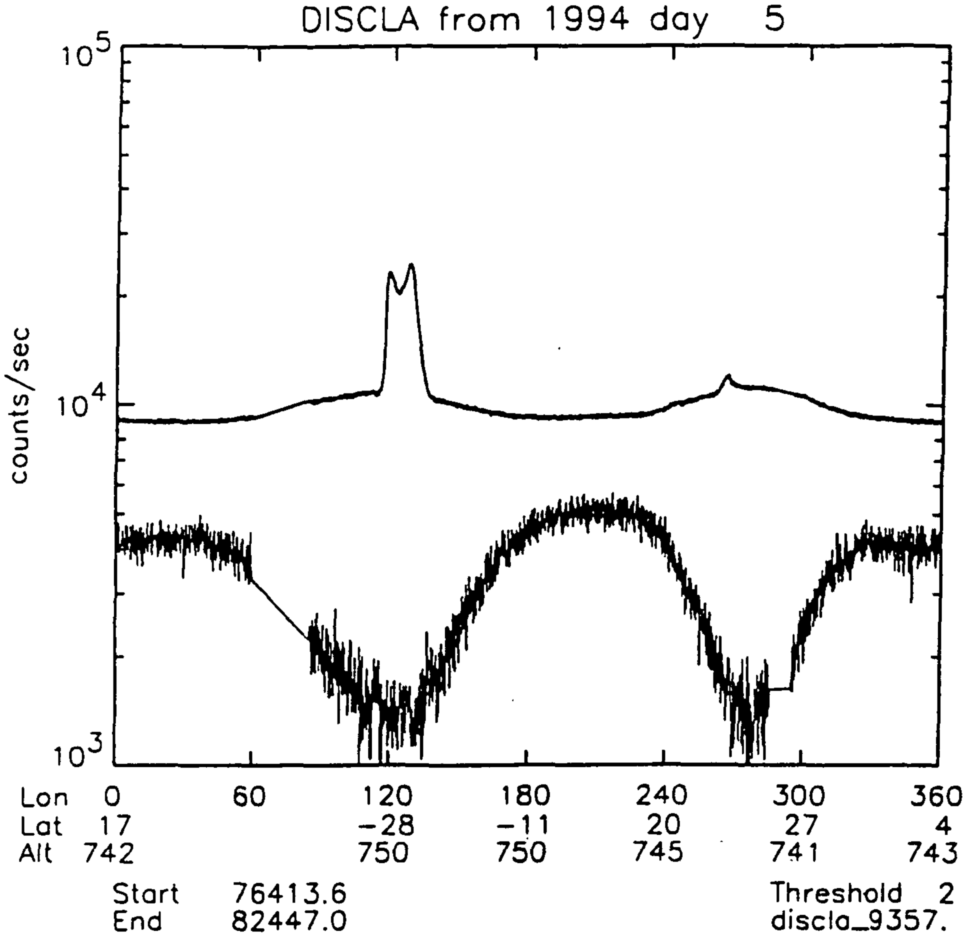
Figure Captions

Figure 1 : A plot of the DISCLA data when the satellite encounters electrons which have been scattered by waves from a large VLF transmitter. The data is from January 5, 1994.

Figure 2: A map of the frequency of occurrence of the events used in this investigation.

Figure 3: The normalized size distribution of events for 30 days before the the reboost, compared with the same distribution for the 90 days during and after the reboost.

Figure 4: The normalized size distribution of events from 15-October-1993 to 29-January-1994 compared with distribution from the same 106 days of 1991 and 1992.



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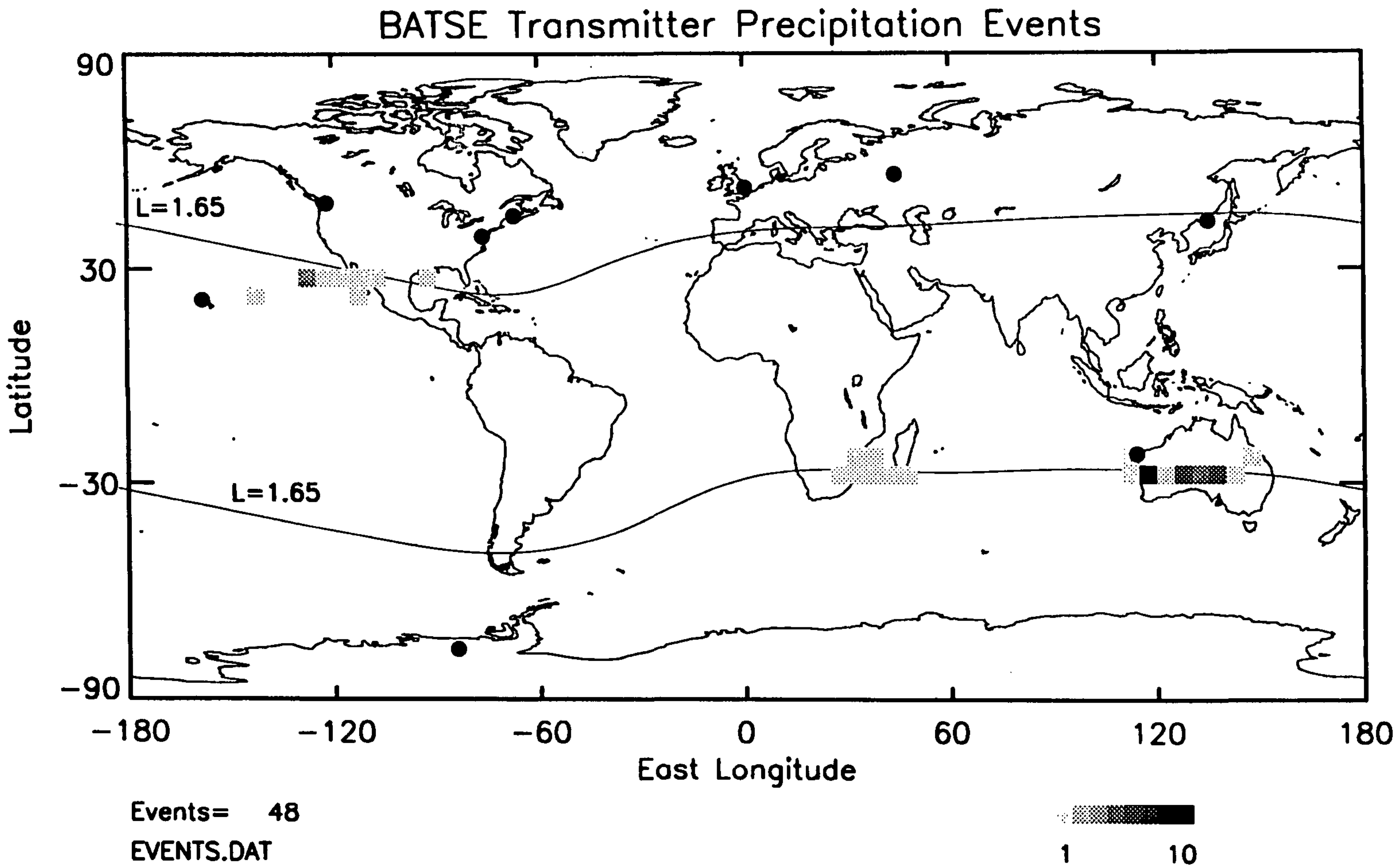

Figure 2: A map of the frequency of occurrence of the events used in this investigation.

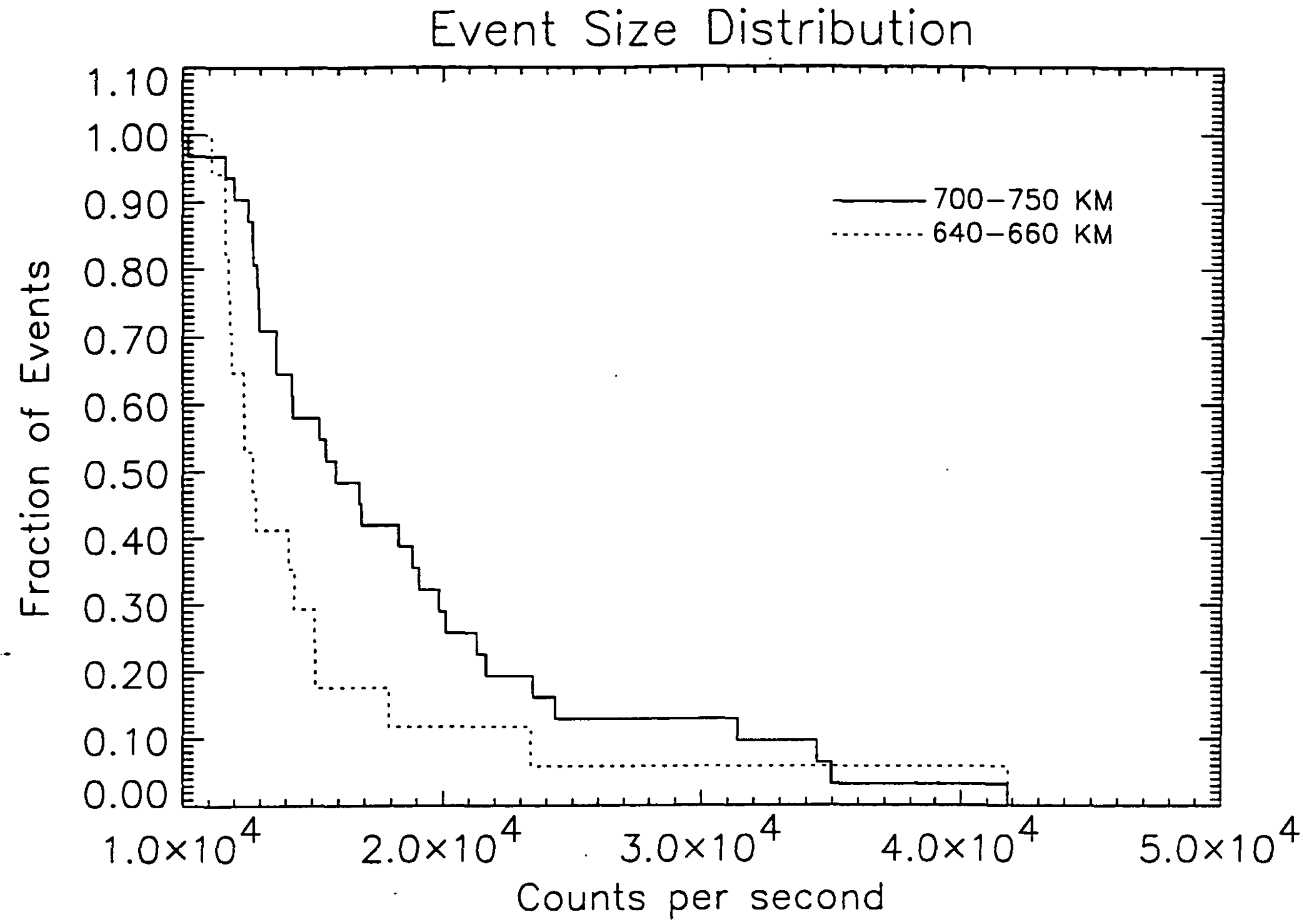

Figure 3: The normalized size distribution of events for 30 days before the the reboost, compared with the same distribution for the 90 days during and after the reboost.

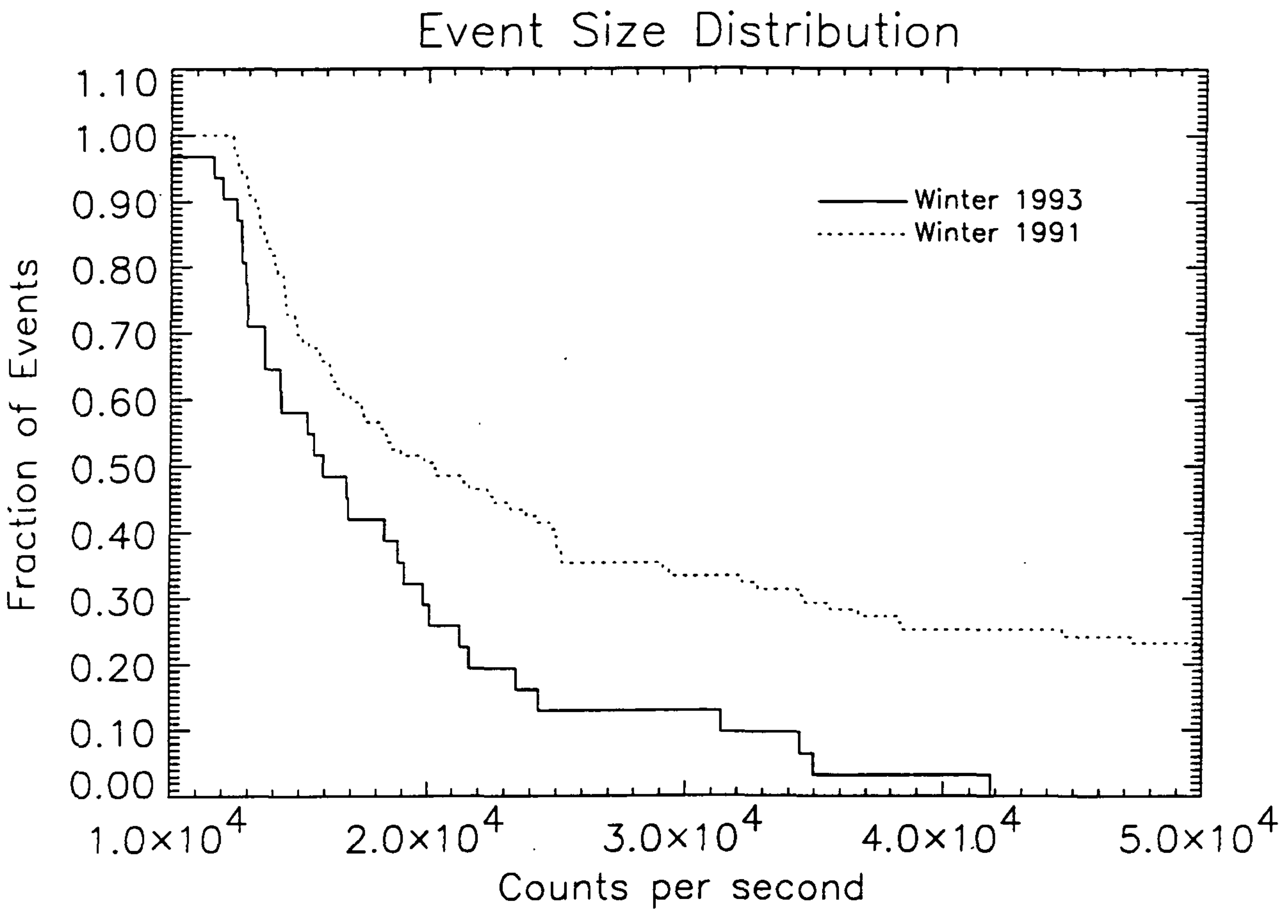

Figure 4 The normalized size distribution of events from 15-October-1993 to 29-January-1994 compared with distribution from the same 106 days of 1991 and 1992.

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The Compton Observatory commonly encounters fluxes of energetic electrons which have been scattered from the inner radiation belt to the path of the satellite by resonant interactions with VLF waves from powerful man-made transmitters. The present investigation was motivated by the fact that in the Fall of 1993, the Gamma Ray Observatory was boosted from a 350 km altitude circular orbit to a 450 km altitude circular orbit. This was an opportunity, for the first time, to make observations at two different altitudes using the same instrument. We have examined DISCLA data from the BATSE experiment from 1-September-1993 to 29-Jaunary-1994. During the period of study we identified 48 instances of the satellite encountering a cloud of energetic electrons which had been scattered by VLF transmitters. We find that boosting the altitude of the circular orbit from 350 km to 450 km increased the intensity of cyclotron resonance scattered electrons by a factor of two. To search for long term changes in the cyclotron resonance precipitation, we have compared the ~450 km altitude data from 106 days at the end of 1993 with data at the same altitudes and time of year in 1991. The cyclotron resonance events in 1991 were three times more frequent and 25% of those cases were more intense than any seen in the 1993 data. We attribute this difference to increased level of geomagnetic activity in 1991 near the Solar Maximum.

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