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Experimental Studies of Auroral Arc Generators

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). An all-sky video camera system was deployed in Eagle, Alaska at the foot of the magnetic field line that threads geosynchronous satellite 1989-046 as part of a campaign to study correlations of ground-based auroral activity with satellite-based plasma and energetic particle measurements. The overall intent of the project was to study magnetosphere-ionosphere coupling as it relates to the aurora, and, in particular, to look for signatures that may help to identify various auroral generator mechanism(s). During this study, our efforts were primarily directed towards identifying the generator mechanism(s) for pulsating aurora. Our data, though not conclusive, are found to support theories that propose a cyclotron resonance mechanism for the generation of auroral pulsations.

Background and Research Objectives

The auroral ionosphere and its corresponding magnetospheric domains have been intensively studied by both ground-based and in situ–based instrumentation for over 30 years. Despite the vast amount of knowledge that has been gained from these studies, the basic mechanisms that govern the generation of most auroral forms (in particular, discrete auroral arcs and auroral pulsations) have yet to be conclusively identified. Much of the difficulty in identifying these mechanisms relates to the fact that the generation regions and particle acceleration regions for a specific auroral form are usually far removed from, and in radically different plasma environments than, the region where precipitating auroral particles manifest themselves as visible auroral activity. This system complexity effectively precludes the possibility of using single-point measurements for the positive identification of auroral generator mechanisms.

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Over the years, there have been numerous attempts to make magnetically conjugate multi-point, multi-phenomenology observations of auroral activity in order to identify and study auroral generator mechanisms. The most promising studies have involved ground-based auroral imagery stations at locations magnetically conjugate to satellite-based plasma, particle, and magnetic/electric field instrumentation.[1-7] However, the results of most of these studies have been limited by brief or marginally conjugate satellite/ground station alignments and/or short-term ground campaigns. In this paper, we describe our efforts to field and operate a system that provides continuous, long-term monitoring of auroral activity at a ground station that is magnetically connected to a geosynchronous satellite. Our intent was to collect long-timescale data sets that can be used to address, both on a per case basis and on a statistical basis, the mapping of magnetospheric domains into their auroral counterparts, the identification of various auroral generator mechanisms, and/or the validity of existing theories of auroral generator mechanisms. Geosynchronous orbit is optimal for this type of study for two reasons: (1) since a geosynchronous satellite corotates with the earth, its magnetic footprint on the earth remains fixed, allowing for a continuous long-term monitoring of a magnetic field line with fixed, ground-based equipment, and (2) geosynchronous orbit samples several key regions of the magnetosphere that are believed to be source regions for various auroral forms: the ion and electron plasma sheets, the trough, and the plasmasphere.

Importance to LANL's Science and Technology Base and National R&D Needs

This project was important to LANL's science and technology base in that it utilized and further developed LANL's expertise and capabilities in the areas of ionospheric and magnetospheric science. Such competencies are useful in advancing basic scientific knowledge and enhancing the laboratory's reputation of excellence in carrying out quality scientific studies. In particular, it is important to maintain these competencies for programmatic purposes, in this case, to maintain our ability to measure, model and understand optical transient events in the ionosphere and magnetosphere related to atmospheric/ionospheric nuclear detonations.

Scientific Approach and Accomplishments

The campaign described in this report ran from October 1, 1994 to mid-April, 1995. The experimental setup consisted of a ground-based all-sky video camera that was fielded in Eagle, Alaska at the foot of the magnetic field line that threads geosynchronous satellite 1989-046 (Figure 1). The all-sky video camera was fielded and maintained by T. A.

Hallinan of the Geophysical Institute at the University of Alaska under contract to and in collaboration with LANL. The video camera system consisted of an intensified CCD with an unfiltered f/1.6 telecentric lens. The camera automatically began recordings in VHS format whenever the sun was below –13° elevation and the moon was below the horizon. Since 1989-046 corotates with the earth, its footpoint remains fixed in the vicinity of Eagle, allowing for routine continuous monitoring of an auroral field line both at its intersection with the ground and with geosynchronous orbit. The satellite carried two instruments, the magnetospheric plasma analyzer (MPA)[8,9] and the synchronous-orbit particle analyzer (SOPA).[10] MPA is an electrostatic analyzer that is sensitive to plasma electrons in the 1 eV to 40 keV energy range and plasma ions in the 1 eV to 40 keV energy range. The spin axis points towards the earth with six individual detectors sampling the polar angle range of +/– 66° about the spacecraft spin equator. Thus, the instrument can sample field-aligned (0° and 180°) particles and also particles looking eastward (90°) and westward (270°) along the satellite orbit. A full three-dimensional distribution is collected in one spacecraft spin period (10 seconds) and the data collection cycles once every 86 seconds. The SOPA instrument consists of three solid state detectors looking at 30°, 60°, and 90° from the earth-pointing spin-axis. It has a sampling period of 320/640 milliseconds and is sensitive to energetic electrons in the 50 keV to greater than 1.5 MeV energy range, energetic protons in the 50 keV to 50 MeV energy range, and other energetic ions in the 1 ~ 20 MeV energy range, the exact range depending on ion mass. The simultaneous operation of both the MPA and SOPA instruments provided a comprehensive survey of the geosynchronous particles (energies, densities, fluxes and temperatures) that interact with the geosynchronous environment to produce visible auroral manifestations in the ionosphere.

The ground-based video that was collected in Eagle will be studied for years to come, not only in relation to the geosynchronous satellite data and the goals of this project, but also as a stand-alone data set. As a first step in the analysis of the data set for this project, and as a means of demonstrating the overall utility of the technique developed for this study, we have completed a preliminary survey of the characteristics of the geosynchronous environment during auroral pulsation periods. A similar survey with a more limited data set and non-optimal footprint location has been presented by Nemzek et al.[7] Auroral pulsations generally occur in the post-midnight sky during the recovery phase of a substorm and are observed as intensity fluctuations of randomly located, irregularly shaped, patches or arc segments, each form having a pulsation frequency generally on the order of 0.1–3 Hz. Adjacent pulsating forms typically pulsate out of phase, have dimensions on the order of 10–200 km, and reside at predominantly e-region and lower f-region altitudes. The generation mechanism for pulsating aurorae has yet to be sufficiently described but is believed to operate at geosynchronous orbit and to rely on a periodic wave-particle resonance that scatters electrons into the loss cone. More detailed reviews of auroral pulsation phenomenology and theory can be found, for example, in papers by Johnstone,[11] Roryvik and Davis,[12] Davidson[13] and Nemzek et al.[7]

Pulsating aurorae were chosen for the first phase of this study since they typically occur when the magnetosphere is in a relatively unstretched condition (recovery phase). This condition generally results in a more accurate mapping of the magnetic footprint of the satellite to the ground. Figure 2 illustrates the magnetic field line mapping of the 1989-046 footpoint during quiet ($K_p = 0$) and moderately active ($K_p = 4$) magnetic conditions using the Tsyganenko[14] 1989 magnetic field line mapping model. The approximate field-of-view of the all-sky camera is indicated by the circle. As can be seen, the footprint mapping is more localized during quieter time periods. In addition, for a large range of magnetic conditions, the footpoint always remains well within the field-of-view of the camera. Since each of the pulsating aurora cases that were studied for this paper appeared across the entire field-of-view of the camera, we are fairly confident that for each case studied, the satellite sampled the geosynchronous environment that was magnetically connected to and responsible for the auroral pulsations as seen by the all-sky camera.

In the course of our study, there were over 70 days in which simultaneous camera and satellite observations of auroral activity were collected, most of these days exhibiting pulsation activity of some sort. For this study, 17 of the best pulsating aurora cases were analyzed. Each case produced moderately strong pulsations that covered the majority of the all-sky camera field-of-view. Figure 3 shows a typical characterization of the pulsations using both the ground-based and satellite-based data sets for the night of November 1, 1994. The bottom panel indicates the type of auroral activity as seen by the all-sky camera (NA = no activity, QA = quiet arcs, AA = active arcs, B = auroral breakup, PA = pulsating aurora). The second and third panels show the MPA electron energy spectrogram and pitch-angle, i.e. look azimuth plots (color proportional to relative energy flux) for the same time interval. The fourth panel displays the SOPA energetic electron flux as measured by the 50 keV–75 keV energy channel, and the fifth panel plots the MPA parameter "theta." Theta is the magnetic field direction angle and is referenced from the spacecraft spin axis. It is inferred by noting symmetries in the MPA particle distributions and is used here as a measure of how stretched the magnetosphere is.[15] A theta equal to 90° implies a nearly unstretched (i.e. dipolar) magnetospheric configuration.

In Figure 3, the all-sky camera was turned on at about 0620 UT at which time there was no observed auroral activity. The electron energy spectrogram for this time indicates that the satellite was in the plasmasphere (low energy electrons). At about 0700 UT, quiet and active arcs began to appear in the vicinity of the footpoint, in association with the entry of the satellite into the electron plasma sheet (electron energies increase to 1–10 keV levels). As can be seen in the theta plot, the arrival of the plasma sheet at the satellite corresponds in time to the maximum stretch of the magnetosphere. In other words, the appearance of the plasma sheet in the satellite data was likely induced more by the motion of the plasma sheet past the satellite rather than by satellite motion into the plasma sheet. This suspicion is further supported by the events immediately following the appearance of the plasma sheet. At about 0815 UT, a moderately strong injection of energetic electrons (I_1) was observed by SOPA indicating a substorm onset. This event coincides in time with an isotropic increase in MPA electron flux and with the occurrence of an auroral breakup as seen from the ground. Theta immediately dropped in value at this time as the magnetotail snapped back to a dipolar configuration. The recovery phase of the substorm began at the peak of the electron injection and is characterized in the MPA data by an anisotropization of the 8–40 keV plasma electrons (pancake distribution, flux maxima at 90° and 180°) and in the all-sky data by the appearance of strong, widespread, pulsations. Anomalous active arcs replaced the pulsations from about 0915 UT to 0930 UT, but the pulsations quickly returned and persisted until the growth phase of the next substorm. The above-mentioned anisotropization is better observed in the recovery phase of the second substorm cycle (injection peak at 1120 UT). At this point the pancake distribution was re-established after the isotropy produced by the injection, and then persisted well into the morning hours interrupted only once at about 1220 UT when yet a third substorm/injection (I_3) occurred. This third cycle was particularly interesting in that the pulsations from the recovery phase of the 1120 UT injection were "re-energized" in both brightness and frequency, just prior to, and during the growth phase of the 1220 UT substorm. This effect was seen on several occasions in the 17 cases studied.

Based on the representative results of Figure 3, we can make the following statements concerning the characterization of geosynchronous orbit during auroral pulsation activity. Pulsations (1) are observed as a recovery phase phenomenon, commencing within a few minutes of the 50 keV–75 keV injection electron flux maximum, (2) are often "re-energized" during the growth and expansion phase of subsequent substorm cycles, (3) only occur for energetic particle fluxes between 6×10^6 cm^{-2}s^{-1}sr^{-1} to 6×10^7 cm^{-2}s^{-1}sr^{-1}, i.e. between the weak and strong diffusion limits,[16,17] and (4) only occur during strong electron pitch-angle anisotropies (pancake distribution) in the 1 keV to 40 keV energy range. Of these observations, (1) has been a well-known fact since the first discovery of injection events,[18,19] (2) and (3) have been occasionally observed or reported[7,17] and are significant enough to warrant further study, and (4) represents a unique experimental confirmation of the electron pitch-angle distribution predicted by most pulsation theories. Additionally, the results (1), (2), and (3) are in agreement with the results of Nemzek et al.[7] despite the fact that the Nemzek et al.[7] footpoint was low on the horizon, making one-to-one comparisons between auroral activity and orbital data difficult.

The above results can be compared to two of the leading theories on auroral pulsation generation, the relaxation oscillator theory[13,20] and the flow cyclotron maser theory.[21,22] In the relaxation oscillator theory, a pitch-angle anisotropy near the geomagnetic equator promotes the growth of an instability that produces VLF whistler-mode waves. These waves, in turn, undergo a cyclotron resonance with counterstreaming electrons, resulting in a scattering of the electrons into a loss cone. This filling of the loss cone reduces the growth of the waves. Precipitation of the electrons into the ionosphere re-establishes the anisotropy allowing the process to repeat itself. The flow cyclotron maser model is similar to the relaxation oscillator model in that it invokes the cyclotron resonance mechanism. However, it also provides a theoretical basis for the entry of fresh injection electrons into the pulsation flux tube providing somewhat more of a physical mechanism by which to understand the process. The strength of the resonance that leads to the precipitation of these electrons is controlled not only by the flux of energetic electrons into the flux tube, but also by the cold plasma density within that flux tube. This cold plasma density must be on the order of 1 cm^{-3} for the mechanism to operate.[22]

Our results validate several aspects of the above-mentioned theories. The pitch-angle distribution plot in Figure 3, as is the case in the other 16 examples studied, shows a dominant anisotropy in pitch-angle during pulsation events. Although MPA does not have the time resolution or spatial resolution to discern the emptying and refilling of the loss cone, the confirmation that this general anisotropy is necessary for the occurrence of pulsations, lends further support to the idea of a generation process dependent upon pitch-angle diffusion into the loss cone. The pulsations were also found to occur only when the energetic electron flux was within the 6×10^6 $cm^{-2}s^{-1}sr^{-1}$ to $6 \times 10^7 cm^{-2}s^{-1}sr^{-1}$ range. This is in agreement with the requirement from the relaxation oscillator theory that the flux be less than the strong diffusion limit ($\sim 5 \times 10^7$ $cm^{-2}s^{-1}sr^{-1}$). The flow cyclotron maser theory also requires that the energetic electron density be greater than 10^{-3} times the cold plasma density. However, the cold plasma density is difficult to infer from the MPA data since the lowest energy electron signatures are generally obscured by a large background produced by penetrating, energetic charged particle fluxes. Although not shown in Figure 3, our data also show perpendicular to parallel electron temperature ratios, $T_{e,\perp}/T_{e,\parallel}$, in excess of 1 whenever pulsations occur. In fact, in the post-midnight hours, the ratio is generally seen to steadily increase from about 1 to as much as 1.6 over the duration of any one pulsation period. This measurement is in agreement with the requirements of the cyclotron maser theory although the condition also seems to be a general characteristic of the morningside magnetosphere. Finally, the observation that pulsation intensities are enhanced during the growth and expansion phase of subsequent substorms is a strong indication that the lowest energy energetic electrons that are injected into geosynchronous orbit are the same electrons that precipitate to the ground during pulsation events. The fact that pre-existing patches of pulsations are re-energized during subsequent substorms indicates that the conditions that determine patch location are independent of the existence of energetic electrons (i.e. supports the enhanced cold-plasma density flux-tube picture).

A study of discrete auroral arc generator mechanisms was also initiated but was limited by a lack of discernible discrete auroral arc signatures at geosynchronous orbit. This absence may be due to either an insufficient temporal/spatial resolution of data in orbit or a strong indicator that the fine structure of auroral arcs is developed at altitudes below geosynchronous orbit.

In summary, the data presented above gives further insight into the plasma and energetic particle conditions that exist at geosynchronous orbit particularly during auroral pulsation activity. The observed conditions are found to be in general agreement with those predicted by both the relaxation oscillator theory[13,20] and the flow cyclotron maser theory[21,22] for auroral pulsation generation. Future work with this data set under recently obtained NASA funding will include a quantification of anisotropy levels as a function of particle energy and pulsation intensity as a means of further testing observations against theory. Work will also proceed on statistically characterizing various magnetospheric domains and on studying magnetospheric boundaries and how they manifest themselves at auroral altitudes.

Publication

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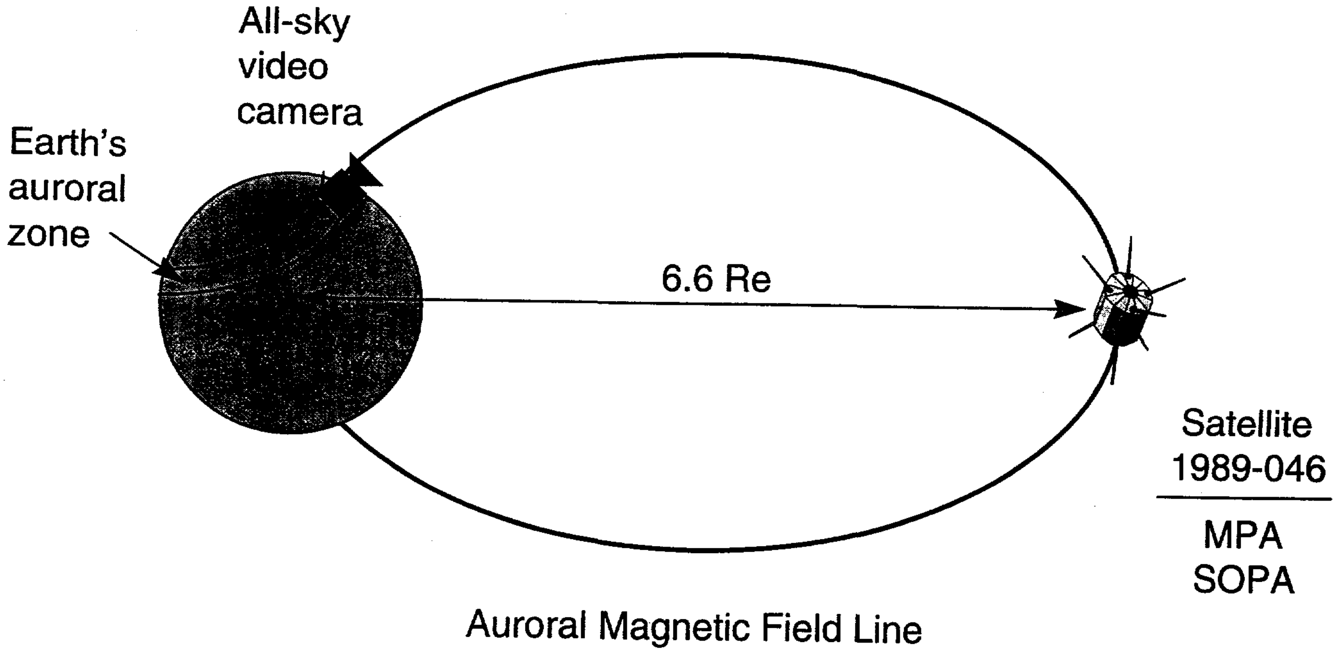

Figure 1. Experimental configuration showing the magnetic field-line connectivity of the ground-based all-sky video camera and the geosynchronous satellite 1989-046.

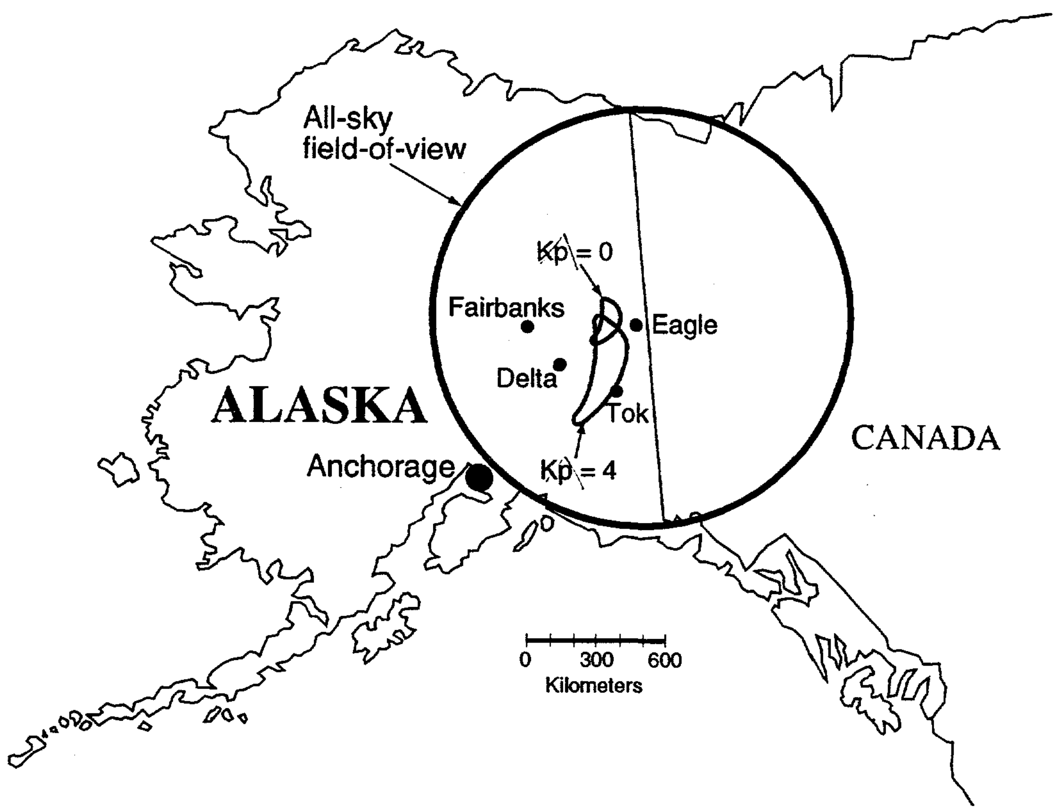

Figure 2. Location of the all-sky camera site in Eagle, Alaska. The circle represents the approximate camera field-of-view. Footprints of satellite 1989-046 are shown for quiet (K_p = 0) and moderately active (K_p = 4) magnetic conditions.

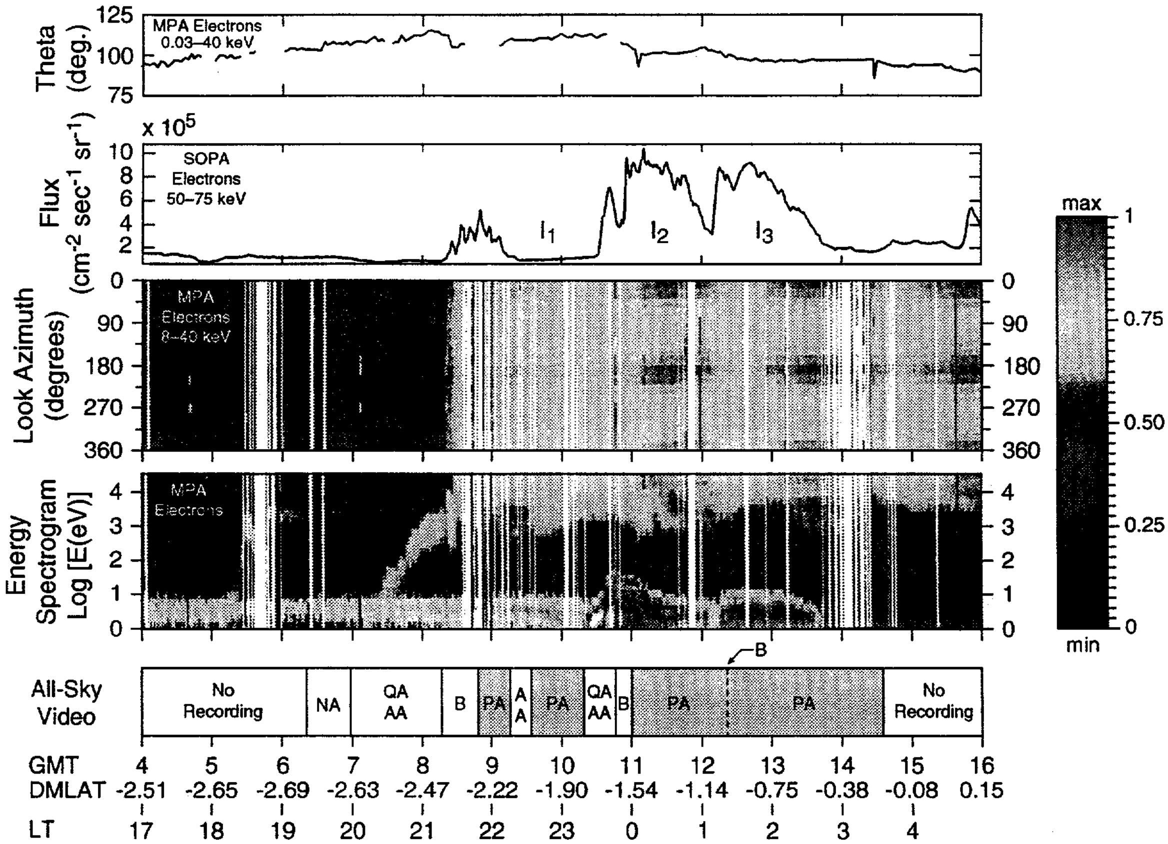

Figure 3. Data summaries as a function of time for the pulsation events of November 1, 1994. See text for description.