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Development of a magnetospheric state-based trapped radiation database

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Abstract

At the core of any empirical trapped radiation model is a database containing energetic particle observations. The usefulness of such a database and the performance of the resulting models depend on the database flexibility to respond to queries based on differing magnetospheric conditions, and the ability to locate, select, retrieve and analyze the relevant particle data. Current empirical trapped radiation models, such as the *NASA AE-8* and *AP-8* models, are essentially flux lookup tables on (E; B/B_0, L) grids based on processed data. Such lookup tables are inherently static, non-updateable, and non-extensible. Consequently, the models constructed from them would have limited performance. As an initial effort to construct a new generation of empirical trapped radiation models, a new magnetospheric state-based trapped radiation database is being constructed in order to overcome existing model limitations. We have adopted an object-oriented database design to accommodate the complex and dynamic space radiation environment. The technique *encapsulates* the particle data, ancillary data, and metadata into abstract objects in a common framework to handle heterogeneous data sources. The new database structure will allow users to query the database using combinations of geophysical, temporal and spatial parameters. In this paper, we will focus on the implementation issues that arise in integrating heterogeneous data sets. To mitigate against early obsolescence when updated or new data become available, the models' underlying database must be updateable and extensible. In addition, to ensure high model performance, the database must be parameterizeable, so that the selection of data from the database for analysis or modeling can vary with magnetospheric conditions or states that vary with solar wind and IMF driving conditions and geomagnetic responses (see Fung, S. F. Recent development in the NASA trapped radiation models, in: Radiation Belts: Models and Standards, Geophys. Monogr. Ser., vol. 97, American Geophysical Union, Washington, DC, pp. 79–91, 1996). By following an object-oriented design, the new trapped-radiation database can be easily updated, extended and re-parameterized. Our effort in constructing a prototype particle radiation database will be applicable to the *NASA Living With a Star Program*.
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1. Introduction

The greatest deficiencies in existing space radiation models are their low accuracy and inability to model the dynamical behavior of the space radiation environment, rendering these models inadequate for use in most detailed scientific studies and engineering applications (e.g., see Gussenhoven et al., 1991; Lemaire et al., 1996 and references therein; Fung, 2004). Observations have shown for example, that radiation belt electron fluxes can increase by a few orders of magnitude during

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geomagnetic storms. The quiet-time slot region can be filled quite rapidly and would take days to recover (see, e.g., Baker et al., 1994a,b). New proton belts can also form as a result of geomagnetic activities (Blake et al., 1992; Hudson et al., 1995), which in turn may depend on solar wind and solar cycle variations. Since *Sun–Earth Connection* processes have not yet been fully understood and accounted for in physics-based radiation belt models, they can not yet be used reliably for specifying or predicting the space radiation environment.

Unlike physical models in which the time evolution of a system is simulated, empirical models *can only* provide snapshots of a system under the range of conditions associated with the data sets used to construct the models. Therefore, discrepancies will likely result when isolated observations are compare to empirical model predictions, especially when the geophysical conditions associated with the observations differ from the average conditions that defined the model. The best known empirical radiation belt models are the *NASA AP-8* and *AE-8* models (Sawyer and Vette, 1976; Vette, 1991b). Because of their comprehensiveness in data coverage (e.g., Fung, 1996) and being widely distributed, these models have been the de facto industry standards and have been used in many studies for spacecraft engineering designs, space instrument design and development, and space mission planning (e.g., Barth, 2000). Details of the *NASA* models are given in Vette (1991a).

All the existing *NASA* models are static and empirical (or statistical), constructed by using energetic particle data obtained by different types of instruments in 1959–1978 (see Fung, 1996). The data were processed, cross-calibrated and combined to yield long-term averages of differential, integral, and omni-directional fluxes as functions of L and B/B_0, with a relatively coarse and non-uniform spatial grids ($0.05 \leqslant \Delta L \leqslant 1$). The architecture and output of these models are tied to the *specific magnetic field models* used to compute the magnetic coordinates (L, B/B_0). This latter condition actually contributes much to the inflexibility of the models. Due to the lack of radiation data in the low altitude region (<1000 km) at the time, the existing models may be inaccurate in the region where low earth-orbiting spacecraft, including the space shuttles, the *International Space Station*, and many scientific missions are flown. There is now an urgent need to develop more accurate and up-to-date radiation belt models. Thus it is important to improve model accuracy at low altitudes, providing better spatial and spectral definition of the South Atlantic Anomaly and geomagnetic cutoff. The effort described in this paper is the first concerted effort to produce a new set of *NASA* space radiation models with better performance and accuracy (Fung, 1996, 2004; Fung et al., 1999).

By fully employing the flexibility and extensibility of an *object-oriented* architecture (Ambler, 1998), a new-generation trapped radiation database is being constructed such that individual data sets, written in a common data format (CDF), will remain distinct from one another and can be easily replaced or updated. The trapped particle data will be organized and queried by their associated magnetospheric states as discussed by Fung (1996, 2004) and Fung et al. (1999), so that different models appropriate for different states can be readily generated. Data will be retrieved through a friendly user interface (e.g., via the world-wide web) and analyzed by statistical analysis modules. For comparison purposes, the new, extensible database will be able to incorporate as "virtual objects" other empirical and physical models to allow semi-empirical modeling of radiation belt dynamics. We will discuss the implementation issues that arise from integrating heterogeneous data sets and servicing the needs in various space weather and space-mission engineering applications. An overview of a new generation of radiation environment models will also be presented.

2. Issues confronting empirical modeling

A number of issues confronting the development of a robust trapped-radiation database for modeling are as follows:

(1) *Heterogeneous data.* Radiation data can take on different forms, i.e., different measured quantities, such as differential and integrated fluxes, LET spectra, dose and fluence, depending on the instruments and platforms used to make the measurements. The data have to be processed into a common form so that they can be mathematically combined and manipulated as if they were a single data set in an analysis. Different data sets must be cross-calibrated.
(2) *Differences in data quality and data processing.* Different data sets can have different temporal and spatial resolutions, spectral and angular coverage, and data sources. These data must be processed or reduced into the same physically meaningful quantities (e.g., fluxes) before they can be analyzed or used in modeling. Energetic particle data are often pre-processed and organized by the very intuitive magnetic coordinates (B or B/B_0 and L) devised by McIlwain (1961, 1966). The L parameter or its dipole-field analog, L_0, has also been widely used for organizing space physics data. Since the computation of L requires the use of a model magnetic field, the L value for a specific spatial location can change as the model field changes (Heynderickx et al., 1996). Furthermore,

L actually changes along a realistic geomagnetic field line (McIlwain, 1966). Substantive effort will thus be required to pre-process the data into a common coordinate system using an appropriate magnetic field model. However, a database containing pre-processed data based only on a fixed magnetic field model would reduce the database flexibility and limit model performance (Fung, 2004).

(3) *Data corrections.* Data sets need to be corrected when there is a change in calibration or processing error. Field model updates (e.g., due to secular variations of the geomagnetic field and model improvements) will necessitate re-computation of the magnetic coordinates of pre-processed data. In order to minimize the effort needed to reprocess data already ingested in a particle database, it is best to keep particle measurements in counts or count rate and to use a coordinate system that is independent of magnetic field model for storage, such as the geographic coordinate system. In so doing, the most up-to-date calibration factors and magnetic field model can be applied when the user is ready to use the data. The database then becomes continuously *updateable*. Maintenance of data availability, accessibility and usability are the most critical issues when data sources are distributed.

(4) *Incorporation of new data.* With more satellites being flown with better instrumentation, new data are being acquired continuously. The new-generation database must be *extensible* so that it can ingest and incorporate new data sets. Moreover, simulated data from physical models can be incorporated to fill data gaps and to facilitate model validations (Fung, 2004).

(5) *Magnetospheric-state based query parameters and ancillary data.* Space physics research increasingly requires the use of data sets from multiple spacecraft and ground stations in vastly different spatial locations and times, and under different geophysical conditions. Searching and selection of appropriate data sets is key to success in correlative analyses. Despite recent advances due to the development of data services tools such as the *CDAWeb* (http://cdaweb.gsfc.nasa.gov/) and *SSCWeb* (http://sscweb.gsfc.nasa.gov/) systems at the *NASA Goddard Space Flight Center*, compilation of inter-calibrated data sets taken during similar geophysical conditions for analyses is still very cumbersome and time-consuming. Before analysis tasks can begin, a significant amount of effort has to be expended on organizing and manipulating each individual data set. Therefore, it would be useful to have data sets that can be queried by a set of common magnetospheric state parameters, or the magnetospheric-state vector, as described by Fung (1996, 2004) and Fung et al. (1999).

(6) *Data format standards.* Data sets from passed space missions tend to have different native data formats and file structures because they have not been designed for use in conjunction with other mission data. The use of multiple data sets from different data sources in a combined analysis requires that a uniform set of parameters with standard physical units be computed from the different data sets. In order to minimize the effort to access and manipulate the different data sets, it is convenient to cast all the data into a common data format, so that only one set of software will be required to access the data and be maintained. Although such data processing effort may be extensive, it is necessary to effectively support coordinated research and modeling. A few examples of data format issues associated with designing and implementing a viable database system are:
(a) What should be done about calculated values, e.g., B_{min} and L, when different missions may have used different field models to process their data? Information about the field model used is sometimes not readily available for pre-processed, legacy data.
(b) Where and how should ephemeris data be stored in the database system so that different mission data can be used simultaneously?
(c) How should instrument information and metadata be kept and made accessible from the database system?
(d) How can different data sets with different inherent temporal, spatial and angular resolutions be "synchronized"?

(7) *Model comparison.* It has been noted that there are large discrepancies between the *NASA AE-8* and *AP-8* model predications and individual observations (Gussenhoven et al., 1991). These discrepancies can be partly accounted for by the fact that the *NASA* models were constructed by combining many distinct data sets spanning a long time period. The wide range of geophysical and geomagnetic conditions under which the data sets were taken could have resulted in large statistical scattering in the data. In order to facilitate comparisons between models and data for similar geophysical conditions, the new-generation trapped radiation database must be *parameterizeable* as described above.

(8) *Multiple-user support.* It is envisioned that the new-generation trapped radiation database will support diverse user communities, such as scientists, engineers, space mission planners and operators. The database to be developed must

therefore be able to support expert and novice users. To that end, a functional, user-oriented interface must be developed and implemented. The interface must be able to accommodate different types of queries for data and analysis tools.

3. Object-oriented database system for trapped radiation modeling

Space physics data are traditionally time-ordered. Searching and selecting data for research analyses invariably involve determining the time intervals in which data sets of interest exist and are available, followed by activating the data retrieval processes to obtain the data sets for analysis. Decisions regarding data types (particle, wave, field, images, etc.), their spatial coverage and resolutions, and data sources (satellites, ground-stations, etc.) have to be made a priori and separately by the data users based on the science requirements and analyses to be performed. For that, a significant amount of effort has to be expended on organizing and manipulating each individual data set before actual analysis work can begin.

Fung (1996) proposed the development of a magnetospheric state-based trapped radiation database for constructing a new generation of trapped radiation models. Using an *object-oriented* approach (e.g., Ambler, 1998), space-mission and ancillary data can be organized and parameterized by magnetospheric states. These states represent the global magnetospheric responses to particular sets of external solar wind and interplanetary magnetic field driving conditions. Each data record as a function of observation location are then characterized by its associated magnetospheric state defined by the corresponding solar wind, interplanetary magnetic field and geomagnetic parameter values, all appropriately time-delayed to represent the magnetospheric conditions at the moment of observation. Hence, the new-generation trapped radiation database will be able to support data queries by time, location and physical condition of interest as required by a particular analysis task.

For example, recent observations have shown that trapped radiation fluxes in the earth's magnetosphere can vary significantly with geomagnetic conditions (Baker et al., 1994b, Reeves, 1998). Such variations largely reflect the changes in the earth's magnetic field caused mainly by varying solar wind and interplanetary magnetic field (IMF) conditions. Time-series measurements by ground magnetic stations provide quantitative measurements of these changes in the geomagnetic field. Therefore, the set of solar wind and IMF driver and geomagnetic response parameters can then be used to prescribe the magnetospheric state vector. The accompaniment of particle flux data by their associated magnetospheric state vectors will thus eliminate the need to pre-process the data into a specific set of magnetic coordinates (e.g., B and L) tied to a given magnetic field model. In turn, this will alleviate recurrent difficulties in constructing and using conventional empirical models and comparing their predictions with observations.

4. Magnetospheric state-based trapped radiation database

As presented in Fung (1996), the primary data for the ith particle species (electron, proton, or heavy ion) in the new trapped radiation database can be represented symbolically by $\mathbb{D}_i$, where

$$\mathbb{D}_i = \{\mathbf{\Psi}; \Phi_i\}. \tag{1}$$

where $\mathbf{\Psi}$ denotes the magnetospheric state vector and Φ_i the associated particle data. For example, $\mathbf{\Psi}$ can be represented in the form

$$\mathbf{\Psi} = [\mathbf{B}_{\mathrm{IMF}}, P_{\mathrm{SW}}, \mathrm{F10.7}; K_{\mathrm{p}}, D_{\mathrm{st}}, \mathrm{AE}, \mathrm{AL}; \boldsymbol{\tau}], \tag{2}$$

where $\mathbf{B}_{\mathrm{IMF}}$ is the interplanetary magnetic field vector, and P_{SW} is a short-hand representation for solar wind density and speed, which can be considered as two independent parameters (e.g., see Fung and Tan, 1998). These parameters and the 10.7-cm radio flux, F10.7, form a set of input drivers that "cause" the subsequent magnetospheric and ionospheric responses. Changes in magnetospheric and ionospheric configurations resulting from the varying external driving conditions are then reflected in the global geomagnetic indices, K_{p}, D_{st}, AE, AU, AL, etc. (Mayaud, 1980). These and perhaps additional magnetospheric response parameters are therefore needed for prescribing the magnetospheric state. The different response parameters also serve to account in some sense for different dominant mangetospheric processes on different time scales and in different regions. The parameters are also chosen conveniently for their "routine" availability, an important practical aspect for our database development.

Since different magnetospheric responses operate on different time scales, an explicit $\boldsymbol{\tau}$ vector is added to account for the epoch (such as in storm/substorm phases) and relative response time delays between the different state elements. To the extent that effective time delays between state parameters for defining a magnetospheric state can be determined, $\boldsymbol{\tau}$ may be suppressed from (2) by applying the appropriately time-shift parameters in the database. The magnetospheric state should thus be characterized by the driver and response parameters of the system without explicit time dependence. Consequently, the radiation environment due to the ith species is given by Φ_i with time being parameterized by the corresponding magnetospheric state elements. We then have

$$\Phi_i = \{\Phi_\Psi\}, \quad (3)$$

which is the set of all observations of species i associated with a given magnetospheric state $\tilde{\mathbf{\Psi}}$. With such organization, data from different data sources can remain distinct from one another. While lower level data, such as total counts or count rates, are stored in Φ_Ψ, higher level quantities such as particle pitch angles, directional and omnidirectional fluxes are needed in analysis or modeling tasks. These quantities can only be computed once a magnetic field model has been chosen.

For illustrative purposes, we show an example for Φ_Ψ for each particle species when a suitable magnetic field model has been chosen for the state $\mathbf{\Psi}$

$$\Phi_\Psi = [\mathbf{R}; B/B_0, L; E, \alpha, J_\alpha, J_{\mathrm{omn}}]. \quad (4)$$

Different quantities are shown explicitly to indicate the types of information that are available or can be computed as needed. Magnetic coordinates of the observation locations $\mathbf{R}$ can also be computed. It is apparent from Eq. (4) that for each magnetospheric state $\mathbf{\Psi} \approx \mathbf{\Psi}_0$, an empirical model can be constructed by selecting, retrieving and statistically analyzing all the data Φ_Ψ with $\mathbf{\Psi} \approx \mathbf{\Psi}_0$. Thus it is feasible to construct a separate model for each magnetospheric state $\mathbf{\Psi}_0$. The utility of this approach is based on the assumption that physics in the magnetosphere (including field geometry) is statistically similar under similar state conditions.

5. Trapped radiation database development

Fig. 1 shows a roadmap by which the new-generation trapped radiation database is constructed. Data processing and management are clearly two of the most important steps in the process. It is important to note that magnetic coordinates are not computed until the data are ready to be used in an analysis or modeling task. Since only data associated with the same $\mathbf{\Psi}_0$ will be used at a given time, modern computers should readily handle the computation load. One of the main advantages of the proposed structure is that the same magnetic field model will be used for analyzing all the selected data.

Depending on the specific applications, it may be convenient to use different coordinate systems to analyze the data. The most popular and intuitive system is the ($\mathbf{B}$, L) system due to McIlwain (1961, 1966). Fung and Tan (1999) have recently proposed an alternative system based on the relationship between the second adiabatic invariant of a trapped particle and the equatorial radius of the field line on which the particle is trapped. This system is useful for visualizing the drift shell structure in configuration (real) space.

6. Using the new database to develop semi-empirical trapped radiation models

It is apparent that at the present time neither purely empirical nor physical modeling alone can adequately provide accurate representation of the space radiation environment. Fung (2004) suggested a semi-empirical modeling approach by combining both empirical and physical modeling techniques. Using a magnetospheric state-based database as described in this paper, the new approach can not only accommodate new data and field models as they become available, but can also combine empirical and physical model formulations, such that the two techniques can complement one another, or they can be used independently. Unlike traditional empirical models that have fixed flux look-up tables, original information from individual data sets and magnetic field model will be stored as independent data sets in a common data format in the new model database system. The implementation of physical formulations in the model will provide physical

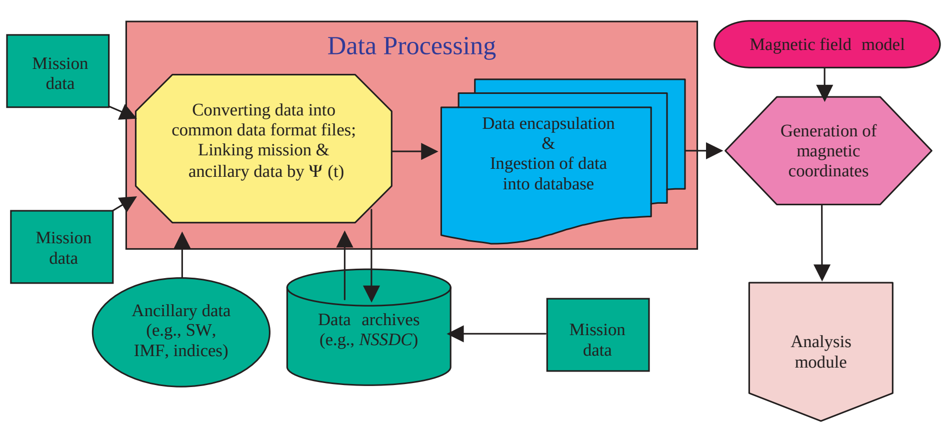

Fig. 1. A data flow diagram showing the process by which the new-generation trapped radiation database is constructed and used in analysis and modeling tasks.

understanding of the empirical model. Conversely, the use of data from the empirical model database, physical model formulations can be validated. Since there are always regions in parameter space or physical space in which pertinent observations are not readily available, physical models can also be used to generate simulated data to bridge any data gaps in the radiation database.

7. Prototype database development

The descriptions of a preliminary magnetospheric state-based trapped radiation database and examples of magnetospheric-state and particle data encapsulations have been given by Fung et al. (1999). It was pointed out that the key to having an *updateable* and *extensible* database is to store the data and associated metadata together as a unit so that each data set can be replaced without affecting the overall database structure. Thus, adding or replacing data sets in the database amounts only to resetting the appropriate pointers. When all data sets are stored in a common data structure, they can be accessed by a common interface to ensure simplicity, uniformity and maintainability of the database and its interface. There are a number of standard data formats, such as the *NASA common data format* (*CDF*), *netCDF*, *HDF*, and *UDF*, etc., that can support such a common interface. Among these formats, the self-describing and self-documenting NASA CDF has been widely adopted by the international space physics community (e.g., the *ISTP* and *IACG* communities). Several web-based data systems such as the *NASA CDAWeb* and *SSCWeb* systems are also *CDF*-based. Adopting *CDF* for our prototyping effort simplifies our interfacing with these systems.

Although Eq. (1) indicates that a complete record in the database consists of both the particle data and the associated magnetospheric state vector, all the information do not have to be co-located because accessing the data requires only the proper interface software and pointer settings. Different data sets having different native formats must be reformatted and associated with magnetospheric state information and to allow both data and metadata to be linked together. To construct a new prototype trapped radiation database, we have processed the data from the MEPHD instrument (Raben et al., 1995) aboard the *NOAA* 5-8 satellites and *HEP* on *OHZORA* (Kohno et al., 1990; Nagata et al., 1985) into *CDF* data files and included with each 1-min particle flux record information on solar wind density and bulk speed, IMF, and the concurrent AE, D_{st}, K_p, and F10.7 values. Using currently available *CDF* tools, it will be simple to include other parameters or to eliminate unneeded ones as appropriate at a later date. This will allow the concurrent values of the geomagnetic indices to eventually be replaced by the

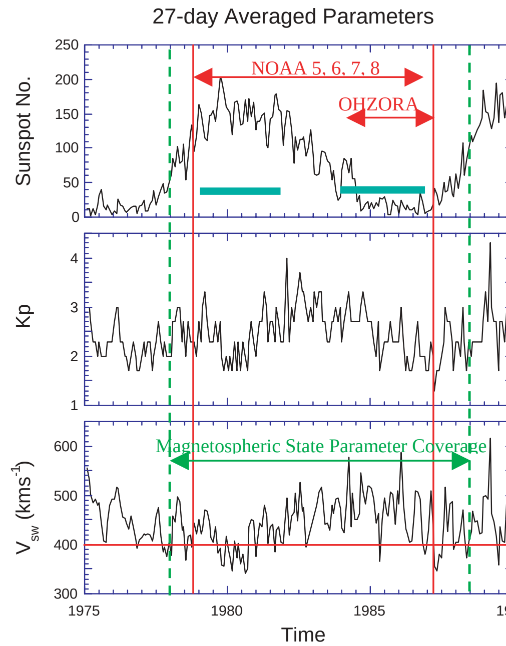

Fig. 2. Solar activity, K_p, and solar wind conditions over the time span (1978–1988) of prototype database.

appropriately delayed values. The prototype database is kept small so that it can be tested and modified quickly. Fig. 2 shows the periods in 1978–1988 when the MEPED data and magnetospheric-state parameters have nearly continuous coverage.

The *L*-profile of the inner-belt proton count rates shown in Fig. 3 turns out to be insensitive to solar cycle phase, solar wind (> and <400 km s^{-1}) and K_p (<2 and >4) variations. On the other hand, much variation in electron count rates is seen during active periods associated with high solar wind speeds and K_p, particularly at $L > 4$ during solar minimum as shown in Fig. 4. The quiet-time electron slot region, indicated by the black solid lines, is found to be located at slightly higher L (∼3) during solar maximum than at solar minimum ($L \sim 2.5$) with no apparent dependence on solar wind

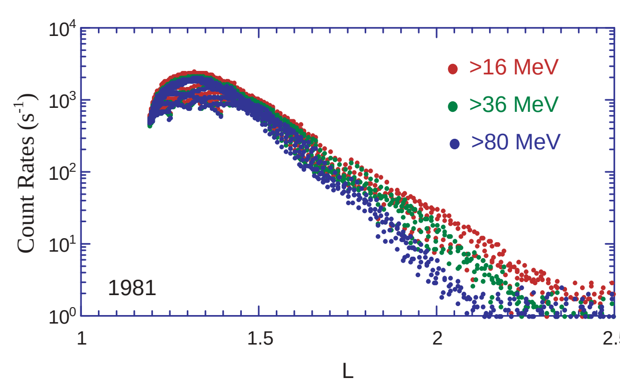

Fig. 3. Example of inner radiation belt proton measurements by MEPED in May, June and July of 1981 when $K_p < 2$ and solar wind speed >400 km s^{-1}.

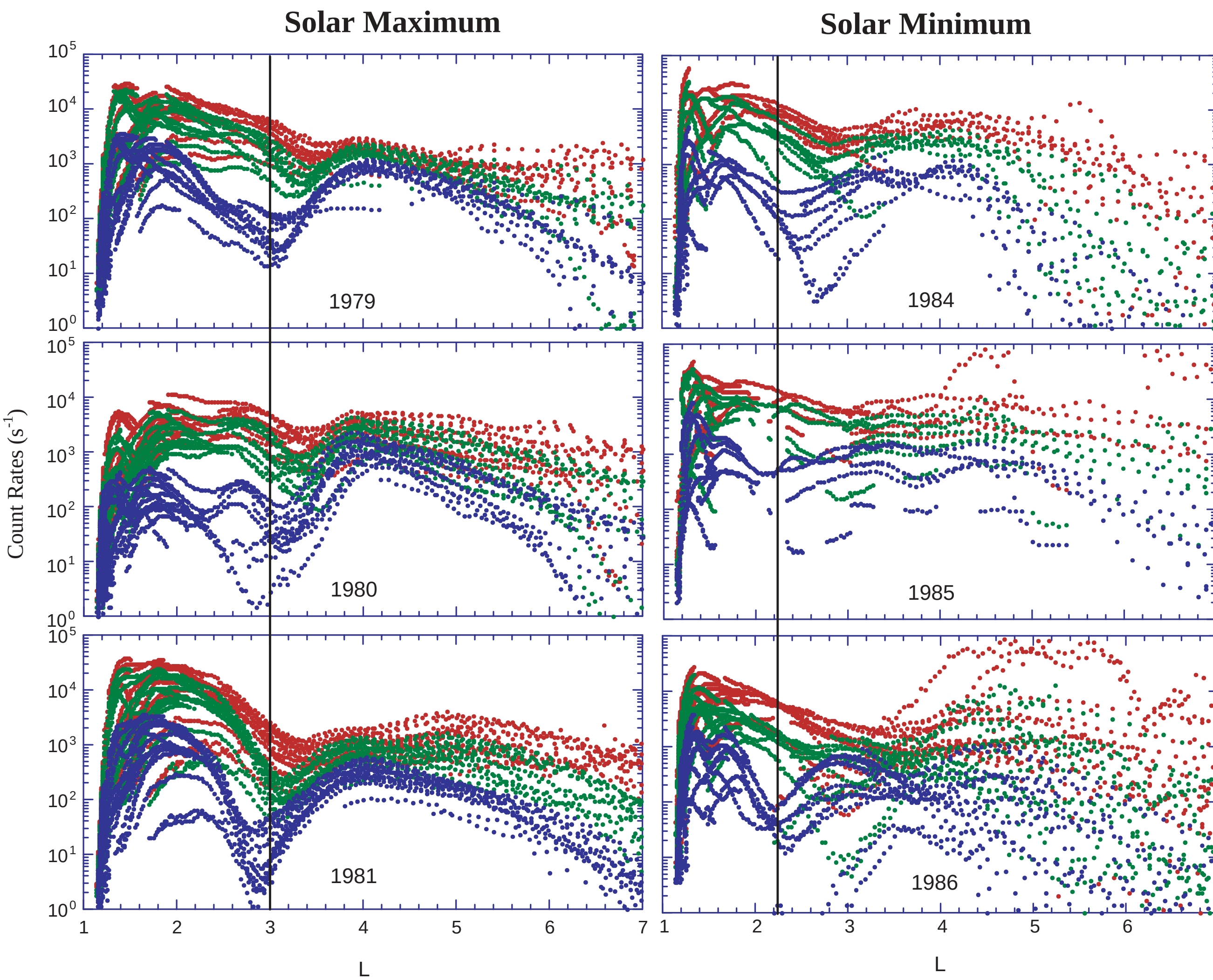

Fig. 4. Examples of count rates of >30 (red), >100 (green), and >300 (blue) keV electrons observed by MEPED at $0.55L^{3.29} < B/B_0 < 0.65L^{3.29}$ during the months of May, June and July of each year during quiet conditions ($K_p < 2$ and solar wind speeds <400 km s^{-1}) in a solar maximum (left) and active conditions ($K_p > 4$ and solar wind speeds >400 km s^{-1}) in a solar minimum (right).

speed or K_p. This appears to be consistent among the three consecutive years in both the solar maximum and minimum periods.

OHZORA and NOAA TIROS data have already been shown to be comparable so that they can be suitably combined (Fung et al., 1998) in an analysis. Additional data sets are now needed to build a more complete database.

8. Discussions

Our goal is to develop a database which could quickly respond to queries based on physical and geophysical conditions of the magnetosphere in addition to location and time, and which could incorporate new data sets and eliminate obsolete ones. A magnetospheric state-based trapped radiation database with an *object-oriented* design can be implemented to satisfy most, if not all, of these requirements.

It is well known that the geomagnetic field plays an active role in controlling the adiabatic motions of trapped particles in the magnetosphere. Thus, the state of the magnetosphere, characterized by the responses of geomagnetic field configuration to external forcing by the solar wind and IMF, can be used to specify the radiation environment as a function of position in the magnetosphere (Fung, 1996, 2004). Since the trapped radiation database is heterogeneous, it is important for all the data to be accessible by the same mechanism and with the same set of tools. To this end, we have constructed a prototype database by casting trapped radiation data taken by the NOAA MEPED and OHZORA HEP instruments by converting them into uniform *CDF* files. The prototype database will allow trapped radiation data as well as metadata and ancillary data to be queried by specifying solar wind, IMF and geomagnetic conditions as well as position and time, and to be accessed by one set of tools.

There remain some outstanding issues that need to be resolved before the new trapped-radiation database can become operational. These include: (1) determining the parameter ranges of different magnetospheric states; (2) determining the appropriate coordinate and modeling grid systems; (3) designing and implementing a user-friendly interface to support both scientific and operational requirements; (4) ensuring the availability of continuous solar wind, IMF and geomagnetic indices data; (5) ensuring the availability of long-term high-quality energetic particle data with good spatial and spectral coverage.

As indicated earlier, one of the strengths of the existing NASA trapped radiation models is the extensive data coverage (see Fung, 1996). Although some of these previous data are still available from various data archives, they may not be readily usable in conjunction with more recent data sets. The availability of long-term data sets covering different spatial regions (in altitude, latitude, and longitude) during different magnetospheric states remains critical for the construction of the new-generation trapped radiation database. Upon completion, the new database will be an important tool for space radiation modeling for both scientific research and space weather applications, such as in the. *NASA Living With A Star Program* and the world-wide space weather initiatives.

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