[5]Dunning, R.S., *The Orbit Mechanics of Flight Mechanics*, NASA SP-325, 1975, pp. 1-84.

[6]Soileau, K.M. and Stern, S.A., "Path-Constrained Rendezvous: Necessary and Sufficient Conditions," *Journal of Spacecraft and Rockets*, Vol. 23, Sept.-Oct. 1986, pp. 492-498.

Radiation Environment Models and the Atmospheric Cutoff

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Introduction

RADIATION environment models are widely used to predict radiation doses expected on a variety of space flight missions. In these models, omnidirectional electron and proton fluxes are stored in computer codes as functions of particle energies and the parameters B and L, where B is the local magnetic field intensity in Gauss and L is the McIlwain drift shell parameter.[1]

While trying to predict radiation doses expected at the space station orbit toward the end of this century, we discovered an artifact of the model that necessitates modifications in the standard method of their use. The following discussion explains this artifact and makes suggestions about how it can be avoided.

The most recent models are the AP-8 for protons[2] and the AE-8 for electrons. Each of these models comes in two variants that incorporate different radiation intensities observed in the atmospheric cutoff region about the 1970 solar maximum (MAX) and about the 1964 solar minimum (MIN).

During magnetically quiet periods, magnetic field models, based on the multipole expansion of the internal sources only, represent the Earth's field quiet well up to L values of about 4. Experimental evidence indicates that the Earth's magnetic field is changing: the strength of the dipole is decreasing at about 0.09%/year and geomagnetic surface features are drifting westward[3] at a rate of 0.27 deg/year. Thus, to allow a certain amount of temporal extrapolation, the models contain first-order and sometimes second-order time derivatives.

Analysis

In trying to predict the space station radiation environment using the radiation environment models, we encountered an almost exponential temporal increase of the radiation intensity. Such an unexpected and rather unrealistic result forced us to review the methodology of the calculations and the structuring of the models proper. This increase is especially noticeable in the region of the South Atlantic anomaly (SAA), which we will use here in order to illustrate the problem.

The calculations presented here will be based on the International Geomagnetic Reference Field for 1975 (IGRF 1975)[4] and fluxes of protons with energies above 30 MeV as represented by AP-8 MIN.

Figure 1 shows B and L contours in the SAA at 500 km altitude for the epochs 1965 (a), 1995 (b), and 2025 (c). In each of the plots, the minimum field region stands out clearly. Note a general westward drift of the minimum at a rate of about 0.27 deg/year and a temporal decrease of the magnetic field intensity at the center of the anomaly. This decrease is associated with an observed decay of the Earth's magnetic dipole, which currently proceeds at a rate of about 27 nT/year.[3] In addition the crosses show the location of the flux maximum for protons with energies above 30 MeV. Due to the dependence of the particle energy spectrum on L, the position of the flux maxima is somewhat offset from the magnetic field minima.

Figure 2 shows flux/altitude profiles for the years 1965, 1995, and 2025. These profiles were calculated at the locations of the flux maxima indicated in Fig. 1. Not only does the flux increase with time, but it also increases disproportionately at low altitudes and even below the Earth's surface! If real, such an increase would have implications far beyond anyone's imagination.

Discussion

Our interpretation of this phenomenon rests simply on the fact that the particle flux contained in the model as a function of B and L has built into it the atmospheric cutoff, also as a function of B and L, as of 1964 for solar minimum and as of 1970 for solar maximum. In other words, within experimental uncertainties, AP-8 MIN and MAX represent the average particle distribution as it existed for those two epochs, both deep within the magnetosphere and within the atmospheric cutoff region.

As a result of the temporal decrease in the magnitude of the geomagnetic dipole moment, locations of a fixed magnetic field intensity are found at progressively closer distances to the Earth. Consequently, flux values associated with fixed B values move to lower altitudes[5] and the models artificially move the atmospheric cutoff to lower altitudes also. Since the flux gradient within the geomagnetic cutoff is very steep, within a short time period the order of magnitude flux increases and even subterranean fluxes are predicted. Obviously, this is an artifact of the model and has no physical significance.

The above-described use of the trapped radiation environment models is also based on the assumption that B and L, being derived from the first and second adiabatic invariant, are themselves invariant. In a static magnetic field, this is certainly true and this coordinate system is very successful in ordering particle data and is, therefore, incorporated into models of the Earth's trapped radiation environment. However, since the Earth's dipole is decreasing with a characteristic time of about 1000 years, when calculating particle flux transformations, all three adiabatic invariants have to be taken into account properly.[6,7] When this is done, it is found that for a fixed point in the SAA the flux increases even more rapidly with time! The explanation for this is that, in addition to lowering of the whole B-L coordinate system, which is the cause of the flux increase when B and L are considered constant, we now also have a secular drift in the B-L space.[6]

Thus, unless the trapped radiation models are effectively decoupled from the atmospheric absorption effects and the two applied in conjunction, straightforward calculations will lead to erroneous results.

Received July 21, 1986; revision received Aug. 28, 1986.

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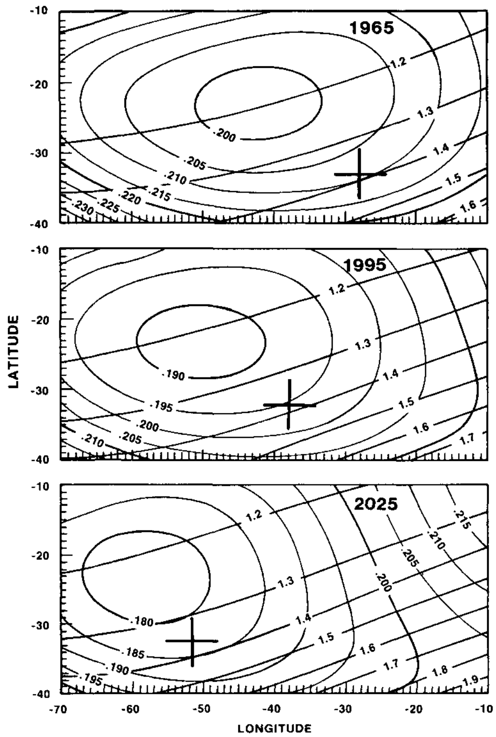

Fig. 1 SAA B-contours at 500 km for 1965, 1995, and 2025 (crosses correspond to the maxima of the 30 MeV proton fluxes).

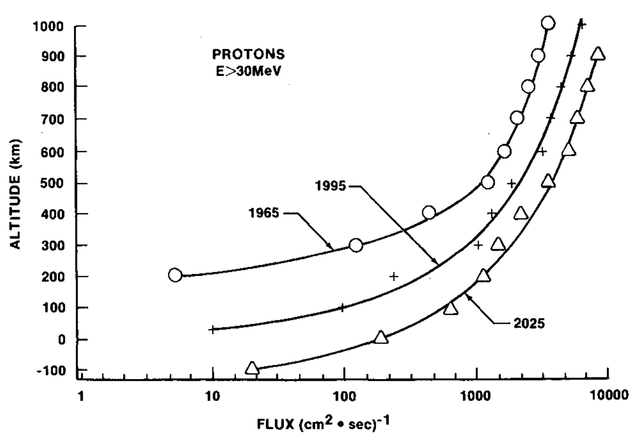

Fig. 2 Flux vs altitude profiles of protons for 1965, 1995, and 2025.

Conclusions

Pending the development of more sophisticated models that take into account the independence of the atmospheric cutoff from the magnetic field, we recommend two approaches that will produce reasonable results:

1) AP-8 and AE-8 MIN and MAX models should be used in conjunction with appropriate magnetic field models epoch 1964 and 1970, respectively, and no attempt should be made to project the radiation environment into the future. While this approach will produce reasonable predictions of exposure doses when averaged over all longitudes, it may give poor results for individual orbits because it does not take into account the westward drift of the magnetic field.

2) An alternate and operationally more accurate approach was suggested by Vette and Sawyer.[8] This involves expressing the particle flux not as a function of B and L, but rather as a function of B/B_0 and L, where B_0 is the minimum value of the magnetic field on an L shell. Both L and B/B_0 are nearly independent of the value of the magnetic dipole and thus a particle distribution tied to these parameters will show very little change with time. The trapped radiation environment models currently available from the National Space Science Data Center incorporate these changes.

Acknowledgments

The authors would like to thank Dr. E. G. Stassinopoulos for spirited and informative discussions and Dr. D.S. Nachtwey for encouraging this work.

References

[1]McIlwain, C.E., "Coordinates for Mapping the Distribution of Geomagnetically Trapped Particles," *Journal of Geophysical Research,* Vol. 66, Nov. 1961, pp. 3681–3691.

[2]Sawyer, D.M. and Vette, J.I., "AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum," National Space Science Data Center, NASA/GSFC, Greenbelt, MD, Rept. NSSDC/WDC-A-R&S-76-06, 1976.

[3]Cain, J.C., "Geomagnetic Models from Satellite Surveys," *Review of Geophysics and Space Physics,* Vol. 9, May 1971, pp. 259–273.

[4]IAGA, "International Geomagnetic Reference Field 1975," *EOS Transactions of the American Geophysical Union,* Vol. 57, No. 3, Jan. 1976, pp. 120–121.

[5]Lindstrom, P.J. and Heckman, H.H., "B-L Space and Geomagnetic Field Models," *Journal of Geophysical Research,* Vol. 73, June 1968, pp. 3441–3447.

[6]Heckman, H.H. and Lindstrom, P.J., "Response of Trapped Particles to a Collapsing Dipole Moment," *Journal of Geophysical Research,* Vol. 77, Feb. 1972, pp. 740–743.

[7]Schulz, M. and Paulikas, G.A., "Secular Magnetic Variations and the Proton Belt," *Journal of Geophysical Research,* Vol. 77, Feb. 1972, pp. 744–747.

[8]Vette, J.I. and Sawyer, D.M., "Short Report on Radiation Belt Calculations," 1986 (unpublished).