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Experimental Validation of Particle Model Drift Theories

M. Lauriente*
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
A. L. Vampola† and P. Inamti‡
University Research Foundation, Greenbelt, Maryland 20770
and
D. Bilitza§
Hughes STX, Greenbelt, Maryland 20771

Using a two-dimensional longitude–latitude cross-correlation technique, a database consisting of single-event effects, which were produced in the TOPEX satellite by energetic protons, is correlated with the location of the South Atlantic anomaly as predicted by the AP8MAX model. The results show that a current-epoch magnetic field model used with the AP8 particle model accurately predicts the location of the proton South Atlantic anomaly. Furthermore, the cross-correlation technique provides a means of determining the energy threshold needed to produce the single-event effects. The cross-correlation study indicates that the TOPEX single-event effects are produced by protons with a minimum proton energy of 80–90 MeV.

Introduction

THERE has been concern about the accuracy of energetic-proton flux predictions at low altitude, such as for the Shuttle or Space Station, which are obtained by using the standard NASA magnetospheric proton model, AP8.[1] AP8 was generated from data obtained in the late 1960s and is specified in terms of integral flux intensity above various energy thresholds at various L values and B/B_0 values. Changes in the magnetic field that have occurred since the AP8 model was generated result in prediction errors in location if the original magnetic field model is used, and in errors in flux intensity as a function of altitude if a current-epoch magnetic field model is used.[2] The error, in predicting present or future particle distributions, that is produced by using a trapped-particle model defined by an earlier magnetic field epoch (e.g., IGRF65, Epoch 1970 for AP8MAX) has been analyzed theoretically.[3] Experimental verification of the change in location, which is referred to as a drift, has also been attempted.[4]

In this paper, we use a large set of anomalous effects in the operation of the TOPEX satellite, which were caused by magnetospherically trapped protons, as a proxy for actual proton measurements. The change in the location of the proton belt at low altitude between the time AP8 was generated and the time of the anomalies is determined using a two-dimensional cross-correlation technique. This change is then compared with the change in the location of the proton belt predicted by AP8 solely on the basis of the change in the magnetic field during that time.

South Atlantic Anomaly

There is a local intensity minimum in the magnetic field known as the South Atlantic anomaly (SAA). It is not confined to the Earth's surface—it maps upward to high altitude also. The minimum occurs because the geomagnetic field is not a simple dipole, but has significant high-order terms (in a spherical harmonic expansion formalism), and furthermore, the magnetic axis is both offset and tilted with respect to the geographic rotational axis. The minimum is of interest because a particle that is trapped in the Earth's magnetic field and is performing bounce motion mirrors at a constant magnetic field intensity. The particle's lowest mirror altitude coincides with the location at which the geomagnetic field intensity is a minimum along the particle's drift path.

There is a secular decrease in the dipole term (and other low-order terms) of the Earth's magnetic field. As the dipole term diminishes, the centroid of the field intensity minimum at the Earth's surface changes location, or drifts. This change in the magnetic field, which was already known by seventeenth-century navigators,[5] contributes to the error in trapped-particle predictions, as noted earlier. This secular change in the field is referred to as a drift, but is not a true drift in the sense that the field configuration remains constant while rotating relative to the geographic axis of the Earth. It is a change in the location of the centroid of the field intensity minimum. In 1970 at the Earth's surface, the field intensity minimum was located at −26.2° latitude, −49.9° longitude. By mid 1993, the minimum was located at −27.4° latitude, −54.1° longitude. The total sea-level drift during this period was 4.4°, or 0.19°/year. Equivalent numbers at 1336 km were −18.8 and −45.1° in 1970, and −18.7 and −50.1° in 1993.5, for a drift of 0.21°/year. Note that neither the location of the minimum nor the drift rate was the same as at the surface of the Earth. At 0 km, the drift was primarily westward, by 4.2°, and southward, by 1.2°. At 1336 km, the drift was almost entirely westward, by 5.0°. Thus, when discussing the drift, and when attempting to confirm it, it is necessary to specify and be consistent in the use of altitude.

The SAA minimum in the field intensity is not a sharp, or well-defined, location. It actually covers a large area with a complex shape. Figure 1 is a contour map of the field intensity at 1336 km (the TOPEX altitude) in the region of the SAA as modeled by DGRF65, Epoch 1970. Epoch 1970 is used because that is the epoch that corresponds to the field model used to generate the AP8MAX particle model that we are addressing in this work. One may make various definitions of drift. In this work, we define drift as the change in location between the centroids of the field intensities at the two epochs. The drift of the centroid has been similar to the drift of the absolute minimum.

The maximum in the energetic proton flux at low altitude resulting from the SAA does not coincide in location with the exact region of the minimum in the magnetic field, since the particle maximum is a convolution of the magnetic SAA and the energy–L–B/B_0 dependence of the particle ensemble. Figure 2 shows isointensity contours for >80-MeV protons as predicted by the AP8MAX model, Epoch 1970, for the 1336-km orbit altitude of TOPEX. Note that the particle contours do not correspond in detail to the magnetic field contours

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*Manager, EnviroNET.
†Consultant. Associate Fellow AIAA.
‡Programmer.
§Member, Technical Staff.

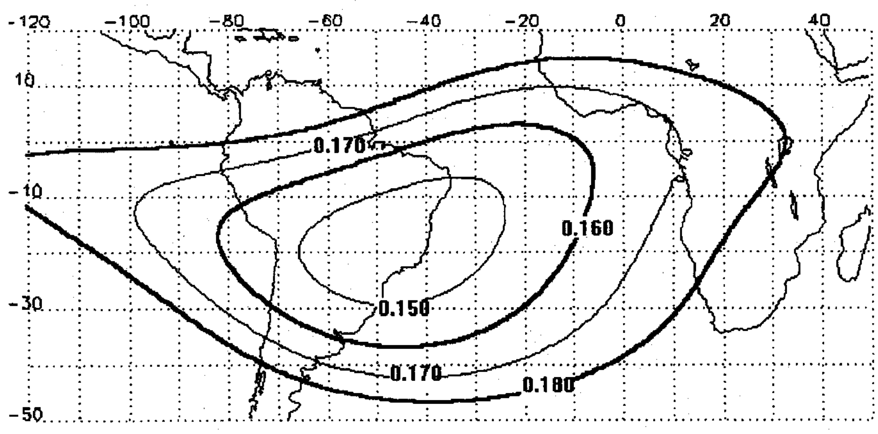

Fig. 1 DGRF65, Epoch 1970, 1336-km magnetic field contours.

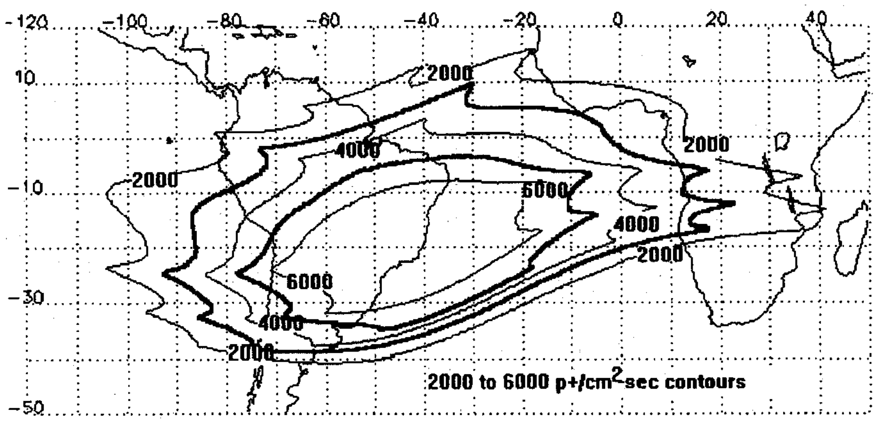

Fig. 2 AP8MAX, Epoch 1970, >80-MeV protons at 1336 km.

in Fig. 1. Other energies will produce slightly different contours (and centroid locations) for two reasons. First, higher-energy protons peak at lower L in the inner zone, which translates to a lower magnetic latitude (also closer to the geographic equator in the vicinity of the SAA). The second effect is a result of differences in flux intensity gradients as a function of altitude (or atmospheric density) and energy. This effect translates into a westward trend with increasing energy for the location of the centroid of the proton flux intensity. The interdigitation that is seen in the contours of Fig. 2 is an artifact of the AP8MAX model and its access using the NASA Goddard Space Flight Center-furnished interpolation subroutine TRARA2, which extracts flux values from the NASA particle environment models. The AP8 models are not smoothed between L values at large B/B_0. A modified version of TRARA2 that corrects this problem has been developed, but has not yet been accepted as a standard.[6]

Because the location of the peak in low-altitude energetic protons is a convolution of the proton ensemble and the magnetic field configuration, there is no requirement a priori that the proton fluxes move in unison with the magnetic field minimum. Furthermore, the change in location both in longitude and latitude will be energy-dependent for the reasons just mentioned. In this study, we use a large body of proton-induced anomaly data from the TOPEX satellite as a proxy for the present position of the particle SAA and compare it with the position of the SAA as presently predicted by an updated magnetic field model to experimentally verify the change in the location of the SAA. Additionally, we make use of the dependence on energy of the latitude and longitude of the particle SAA to estimate the energy of the particles that produce the TOPEX single-event effects (SEEs).

TOPEX SEEs

The TOPEX–Poseidon satellite, which is the orbital component of a three-year mission to constantly map the world's oceans, was launched Aug. 10, 1992, into a circular Earth orbit at an inclination of 66 deg and an altitude of 1336 km. In this orbit, the satellite traverses the SAA region approximately six times per day. In the present study, a total of 2172 Earth sensor anomalies experienced by TOPEX between launch and mid 1994 are correlated geographically with the SAA.

Two Earth-sensor assemblies are located in a module on the Earth-facing side of the TOPEX spacecraft. Each sensor consists of a sensor subassembly and an electronics subassembly. Two types of anomalies are seen in these assemblies. One is a spike in the pitch and roll error telemetry, denoted PR. The other is a switch to the wide-angle mode, denoted WA. Both of these errors occur in each of the sensors.[7] Since these anomalies are not specifically identified as upsets in digital circuitry, we use the term SEEs in this paper rather than single-event upsets, or SEUs. SEEs occur in other instruments on the spacecraft, but at a rate too low to be useful for a statistical analysis. Figure 3 is a longitude–latitude plot of the location of the TOPEX SEEs. This is a sparse data set—on average only one of six $1° \times 1°$ latitude–longitude bins in the anomaly region will have a SEE.

Correlation Analysis

General Considerations

For our comparisons, we first produced a cross-correlation between the AP8MAX/IGRF65*/Epoch 1970 (which is the magnetic field model that was used in the construction of AP8MAX, the asterisk denoting the fact that the original model actually used the pre-1960 value of 0.311653 for the dipole moment) and the AP8MAX/DGRF65/Epoch 1970, both with >80-MeV protons. This was necessary because the Epoch 1993.5 model we were going to use was internally consistent with DGRF65 but not with the original IGRF65*. The cross correlation showed an offset of 0.25° in latitude and agreement in longitude between the proton maps using the different magnetic field models. This latitudinal offset was used to correct the TOPEX-SEE–AP8MAX cross-correlation results.

The SAA particle intensity patterns that were used in these correlations were derived from the AP8MAX model. The contours were

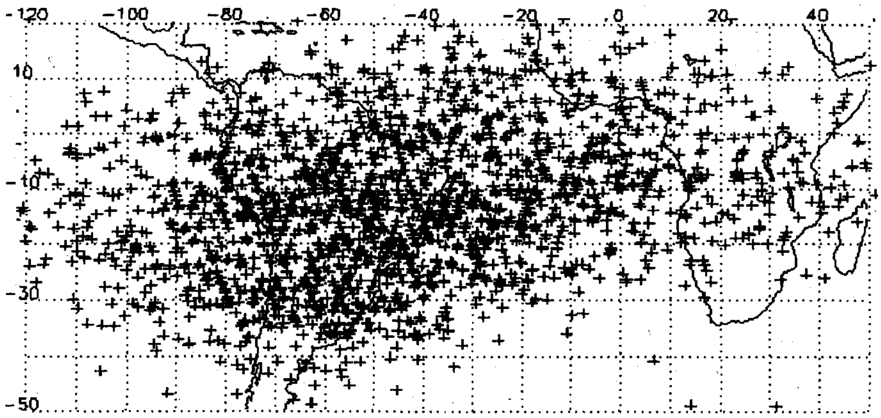

Fig. 3 TOPEX SEE geographical distribution.

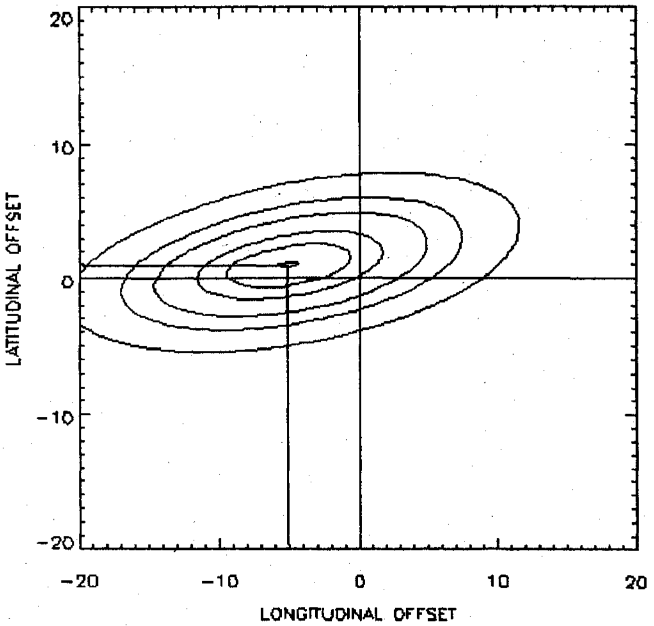

Fig. 4 Epochs 1970 and 1993.5: cross-correlation contours for > 100-MeV protons at 1336 km.

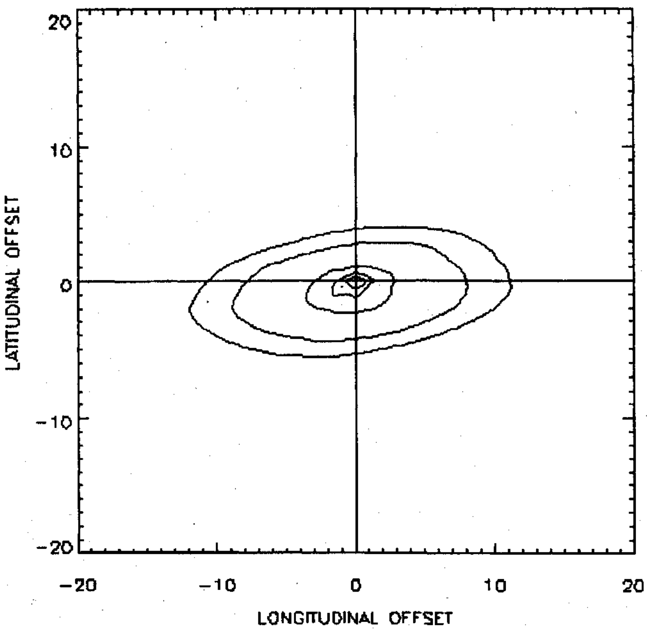

Fig. 5 TOPEX-SEE–AP8MAX >80-MeV p^+ cross-correlation contours.

derived using an Epoch of 1993.5, corresponding to the midpoint of the SEE database acquisition period. Note that these AP8MAX model intensities will not be correct, because AP8MAX was generated using a 1970 Epoch and is specified in terms of flux vs B/B_0 (Ref. 3). But unless the locations of the flux maxima in L have changed substantially, the longitude–latitude patterns should be approximately correct. A change in L will affect the latitude agreement.

Since the longitudinal agreement between IGRF65* and DGRF65 was satisfactory, the predicted westward drift between 1970 and 1993.5 was obtained by comparing proton contours from AP8MAX using DGRF65 Epoch 1970 and IGRF 1990, Epoch 1993.5 (Fig. 4). With proton >100-MeV maps, the drift was 5.1°, which is in close agreement with the drift of the magnetic field minimum at 1336 km (5.0°). The difference in latitude has been noticed previously.[8] At >30 MeV and 1336 km, the drift was 4.9°, still in quite acceptable agreement with the drift of the magnetic field. This difference shows that in testing the drift, it is essential that the comparison be made between particle maps, or between a particle map and a sensor, with the same threshold energy. The experimental verification mentioned previously[3] resulted in agreement with a 7° drift. That result was obtained for both a 450-km orbit and a 617-km orbit. Our AP8MAX correlation technique with protons >30 MeV predicts 4.3 and 4.5° for those altitudes, respectively.

TOPEX-SEE–AP8MAX Correlation

To determine the accuracy with which the AP8MAX can predict the present location of energetic particles at low altitude, e.g., for extravehicular activities on Shuttle, the sparse SEE data set was correlated with a normalized AP8MAX flux map using a two-dimensional function. AP8MAX fluxes were determined for each 0.5° × 0.5° bin from −130 to +60° longitude and −60 to +25° latitude. IRGF90 Epoch 1993.5 was used as the magnetic field model. The AP8MAX and SEE longitude–latitude maps were cross-correlated with offsets from −20° to +20° in both longitude and latitude at 0.5° increments. The resulting variational array was then normalized, and contours of constant correlation strength plotted. Figure 5 shows that the centroid of the TOPEX SEEs coincides with the AP8MAX Epoch 1993.5 predicted maximum of >80-MeV protons within the accuracy of the procedure, ≈0.2°.

The contours in Fig. 5 were obtained using the integral flux of >80-MeV protons predicted by AP8MAX. If other threshold energies are used, a slightly different correlation pattern is obtained, for the two reasons mentioned previously. First, the location of the overall flux intensity pattern in L is a function of proton energy. For higher-energy protons, the centroid of the flux intensity pattern is found at lower L. This translates to a center of the SAA flux intensity pattern at 1336-km altitude that moves northward toward the geographic equator as energy increases. The second effect is also energy related. Because of the sharper decrease in flux intensity as a function of altitude with lower-energy protons, the centroid of the proton pattern moves eastward with decreasing energy. Thus, when evaluating the motion of the SAA, the energy of the particle used in the analysis must be considered.

Since the location of the proton SAA has an energy–latitude dependence, we made use of this dependence to estimate the energy of

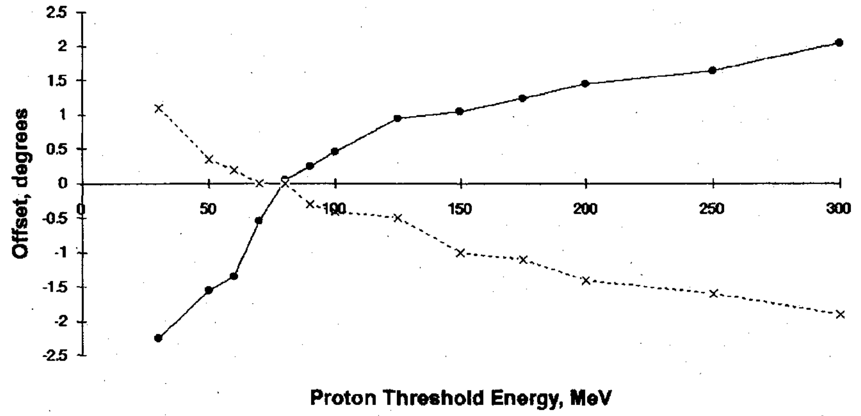

Fig. 6 TOPEX-SEE–AP8MAX cross-correlation latitude–longitude offsets vs threshold energy: •, latitude and ×, longitude.

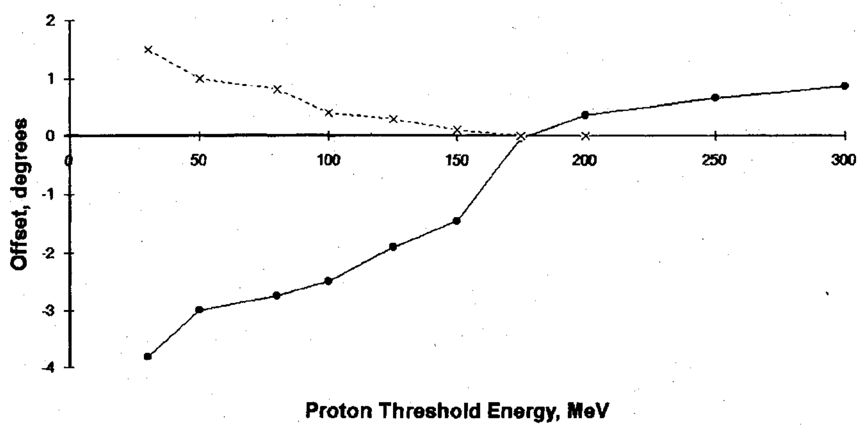

Fig. 7 TOPEX-PR-SEE–AP8MAX cross-correlation latitude–longitude offsets vs threshold energy: •, latitude and ×, longitude.

the particles that are causing the TOPEX SEEs. Figure 6 shows the latitudinal and longitudinal offsets between the SEEs and AP8MAX Epoch 1993.5 as a function of energy. Figure 6 indicates that the threshold energy for producing these SEEs is about 80 MeV. The AP8MAX energy–L profile is not quite correct for the 1990 time period (per comparison with CRRES data[9]), so the latitudinal curve may require minor correction. There is also some uncertainty because the inherent errors in AP8 may be energy dependent.

To some extent, we are engaged in a circuitous argument. We say that the drift in the magnetic field predicts a proton environment that agrees with the TOPEX SEE distribution. But this is based on a proton threshold for producing the TOPEX SEEs that is 80 MeV, a value that is derived from the SEE data. We get this 80-MeV threshold from the agreement with the AP8MAX model. The only defense against this criticism is that the latitudinal offset also agrees with the predicted energy–latitude dependence. Internally, we get consistent results. Obviously, an updated proton environment derived from in situ measurements would be a much preferred and much more reliable quantitative check against the drift value.

Figure 6 included all TOPEX SEEs. We separated the SEEs into subgroups, represented by 1, 2, WA, and PR, each of which included either all of the SEEs from assembly 1 or 2 or all of the WA or PR SEEs from both assemblies. The 1, 2, and WA subgroups provided results that were indistinguishable from the entire set. But the PR subset (Fig. 7) was definitely produced by a different particle population. There were only 337 SEEs in the PR subset. Figure 7 indicates that the threshold for production of these anomalies is around 175 MeV. The 175-MeV threshold probably indicates that the circuit elements that are involved in this type of anomaly are heavily shielded or that heavy localized ionization resulting from nuclear disruption produces them.

Discussion

The agreement between the location of the TOPEX SEEs and the Epoch-1993.5 contour confirms the validity of using the change in the magnetic field for predicting the change in the location at which SEEs can be expected to occur. It also shows that the drift in the location of the particle SAA does not coincide precisely with the drift in the magnetic field SAA (a commonly held misconception). However, because the AP8 map is organized in terms of B/B_0, the weakening of the geomagnetic field during this interval results in an artificial lowering of mirror points of the model fluxes, predicting a larger flux of protons at low altitude than is actually present. A renormalization of AP8 flux intensities is required to correct for this effect.

The agreement between the geographic location of the TOPEX SEEs and the location of energetic protons in the SAA as predicted by AP8MAX using the current magnetic field Epoch shows that a viable interim solution is available for the problem of the secular magnetic field variation on the accuracy of the AP8 model. We would propose that the intensity of proton fluxes for a given orbit be calculated using the AP8 model with 1964 (min) or 1970 (max) Epoch, but the location at which these fluxes is encountered be calculated using current Epochs. This approach, which is already in use in some establishments, avoids the unrealistically large fluxes at low altitudes that are predicted by AP8 if a current Epoch is used for intensity determinations, but retains the accuracy in location obtained by using the current Epoch.

Furthermore, the cross-correlation technique appears to offer a simple means of determining the minimum particle energy necessary for producing SEUs and other SEEs on spacecraft in low-altitude orbits. This information can then be used to get a better understanding of the SEEs. The availability of this analysis technique creates additional motivation for updating the AP8 model.

Conclusions

Comparison of the location of SEEs experienced by the TOPEX–Poseidon spacecraft in low Earth orbit shows excellent agreement with the location of the SAA using current-Epoch calculations with the AP8MAX proton model. Use of the 1970 Epoch with AP8MAX, while providing approximate flux intensities at low altitude, does not provide the proper geographic location. A combination of the two approaches, which is already in use at some facilities, is recommended as an interim solution until a new proton model is generated that can take into account the secular variation in the geomagnetic field. The pattern of occurrences of SEEs can be used to estimate the energy of the particles producing them.

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H. R. Anderson
Associate Editor