JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 32, No. 6, November–December 1995

Charged-Particle Telescope Experiment on Clementine

D. N. Baker*
University of Colorado, Boulder, Colorado 80309-0590
S. Kanekal†
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
J. B. Blake‡
The Aerospace Corporation, Los Angeles, California 90009
and
J. H. Adams Jr.§
U.S. Naval Research Laboratory, Washington, DC 20375-5352

The charged-particle telescope (CPT) onboard the Clementine spacecraft measured the fluxes of energetic protons emitted in solar energetic particle events. Protons in the energy range from 10 to 80 MeV were of greatest interest for radiation effects such as total dose and single event upsets. Energetic electrons were also of interest for spacecraft charging and their contribution to total dose. The lower-energy CPT electron channels (25–500 keV) were mainly of geophysical interest. While orbiting the moon, the CPT observed the wake created by the moon when it blocked the flow of energetic particles in the magnetotail region. The CPT provided opportunities to observe energetic electron bursts during magnetic storms and magnetospheric substorms. CPT data are particularly useful in multispacecraft studies of interplanetary disturbances and their interaction with the magnetosphere. The proton channels on the CPT provided data on solar energetic protons and storm-time protons associated with the passage of an interplanetary shock at 0903 UT on Feb. 21, 1994. Results are compared with those from GOES-7, SAMPEX, and GEOTAIL.

Introduction

AN important objective of the Clementine program has been to investigate the effects of the space radiation environment on the advanced technologies and lightweight spacecraft components that were flight-tested onboard the Clementine spacecraft and the Interstage Adapter (ISA) satellite.[1] The purpose of the CPT was to measure the fluxes of energetic electrons and protons encountered by Clementine throughout its mission.

We have found that there were many times when the very simple CPT instrument returned excellent data on the geospace environment. At other times, there were significant interference problems, which are still being investigated and evaluated. In this paper, we present initial results from the CPT obtained during a large solar energetic particle (SEP) event on Feb. 21, 1994. There were several other spacecraft operating in the near-Earth region during this event, and as a consequence we can perform a multispacecraft analysis of the SEP event and its associated interplanetary shock passage. In this initial CPT report, we focus on this interesting and significant geospace disturbance.

Table 1 Purposes of the Clementine charged-particle telescope

Engineering studies
Energetic protons (10–80 MeV)
Solar-cell damage
Sensor backgrounds
Single-event upsets
Total-dose effects
Energetic electrons (> 0.5 MeV)
Spacecraft charging
Dose and other radiation effects
Scientific objectives
Magnetotail–moon interactions
Solar-wind–moon effects
Substorm particle bursts
Solar energetic particles
Shock energetic particles
Multipoint magnetospheric measurements

Scientific and Engineering Objectives

A primary goal of the CPT investigation was to measure the fluxes of energetic protons that were emitted in solar particle events during the Clementine mission and that subsequently reach the spacecraft. Protons in the energy range from 10 to 80 MeV were of greatest interest for the radiation effects they cause—in particular, single-event upsets and total radiation dose. Energetic electrons can cause spacecraft charging and also contribute to the total radiation dose. The lower-energy electron channels were also of geophysical interest. They provide data on the interaction of the moon with the Earth's magnetotail. While orbiting the moon, the CPT observed the wake created by the moon when it blocks the flow of energetic particles in the magnetotail region.[2] The CPT provided opportunities to observe energetic electron bursts during magnetic storms and magnetospheric substorms.

The proton channels on the CPT provided data on solar energetic protons and storm-time protons associated with the passage of interplanetary shocks. Both the proton and electron channels were able to detect solar energetic particles. The CPT was also able to observe the passage of corotating interaction regions by means of the particles accelerated in these regions. The CPT provided measurements of the fluxes of electrons and ions in the interplanetary medium far removed from other spacecraft and thus has provided a valuable multipoint measurement of near-Earth space. Table 1 summarizes the CPT purposes.

Instrument Description

The CPT instrument configuration was heavily driven by the requirement that the mass of the sensor could not exceed 270 g. To meet this requirement, a single-element telescope configuration was employed. Figure 1 shows a schematic diagram of the very simple

Received Sept. 2, 1994; revision received Jan. 9, 1995; accepted for publication Jan. 24, 1995.

*Director, Laboratory for Atmospheric and Space Physics, Campus Box 590.

†Principal Scientist, Hughes STX, MC 690.

‡Director, Space Sciences, M2/259, P.O. Box 92957.

§Head, Cosmic Ray Section, Space Sciences Division, Code 4154.

Table 2 CPT physical characteristics

Mass: 270 g
Power: 0.5 W
Field of view: 25 deg
$g(E) = 0.1$ cm$^2\cdot$ sr
Sensor: Si (3 mm; 100 mm^2)
Energy response:
Electrons (keV):
>25
48–90
90–115
115–220
220–500
500–3000
Protons (MeV):
3–10
10–20
>20

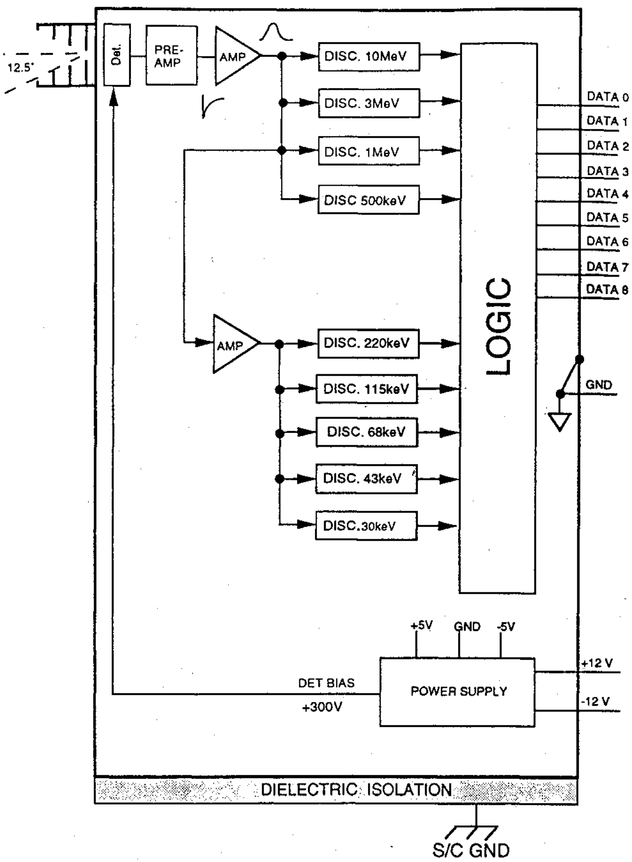

Fig. 1 Schematic diagram of the charged-particle telescope onboard Clementine.

CPT instrument. The telescope has a 12.5-deg-half-angle field of view. The detector is shielded in all other directions by sufficient mass to stop protons with incident energies below 30 MeV. The detector is a silicon surface-barrier detector with an area of 100 mm^2 and a thickness of 3 mm.

The detector is connected to preamplifier, amplifier, and discriminator electronic systems.[3] The lowest-level discriminator was set above the noise level ($\approx$15 keV), but otherwise as low as possible in order to detect electrons of low energy. The next five channels were spaced quasilogarithmically in the energy deposited. The final three discriminator levels were chosen to be substantially greater than the energy an electron could deposit in the detector. As a result, only protons and heavier ions could be detected in these channels, and background caused by electron pileup is small. The CPT was set to have nine channels covering the electron energy range from 25 keV to greater than 500 keV (six channels) and protons from 3 MeV to greater than 80 MeV (three channels). See Table 2 for detailed channel information.

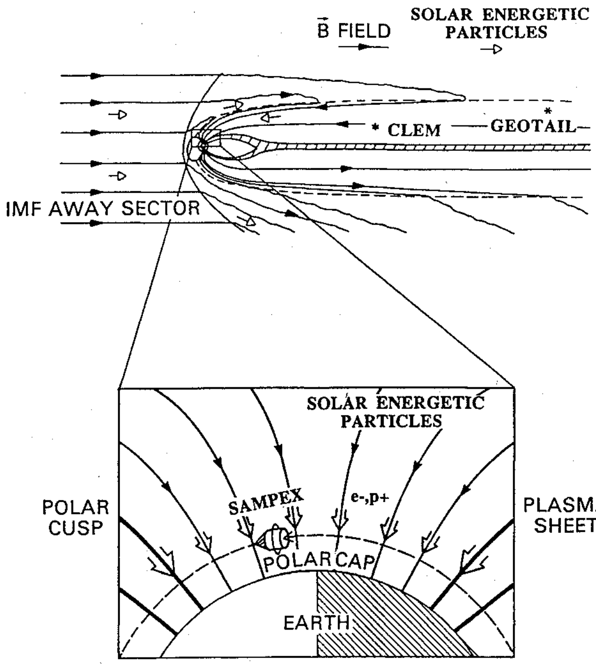

Fig. 2 Diagram of the possible multispacecraft configuration that was anticipated for the Clementine mission (see text for details).

For energies above 30 MeV, protons begin to penetrate the shielding, and thus the instrument starts to respond to protons from directions other than through the collimator. The actual thresholds depend upon the incidental shielding surrounding the CPT in the Clementine spacecraft. A shielding calculation has been performed to determine the overall energy response. The calibrated energy thresholds are shown in Table 2. Obviously, during solar particle events the electron channels respond to solar ions as well as electrons. However, under usual conditions, the contamination of the electron channels by ions was very small.

The geometric factors for the electron channels and the lowest-energy proton channel were computed using calibration data acquired from particle accelerator exposures and the geometric configuration of the collimator. Using the effective sensor area gives a geometric factor of $g = 0.1$ cm$^2\cdot$ sr. An estimate of the geometric factor for the highest-energy proton channel was also made. It is complicated in that we must allow for protons (> 30 MeV) that penetrate the collimator or the spacecraft walls. First we compute the detection efficiency of this channel, $\varepsilon(E, E_B)$, as a function of the proton energy E and the threshold energy of this integral channel, E_B (=20 MeV). This was done using proton range–energy tables and taking into account the energy lost in the complex spacecraft shielding and the path length through the detector to determine the efficiency for depositing an energy $> E_B$ in the detector. The resulting efficiency function is weighted over an assumed spectral form to obtain an effective geometry factor g. For example,

$$g \int_{E_B}^{\infty} e^{-E/E_0} = \int_{E_B}^{\infty} \varepsilon(E, E_B) e^{-E/E_0} \qquad (1)$$

gives the effective geometry factor for an assumed exponential proton energy spectrum with a characteristic energy E_0. Effective geometry factors may similarly be defined for other assumed proton spectral forms.

Results on Solar Energetic Particles

In planning for the utilization and evaluation of CPT results from Clementine, we envisioned the possibility of strong energetic-particle enhancements due to solar disturbances. It was recognized that several other spacecraft were operating in the near-Earth environment, and therefore it would be possible to use CPT data in multipoint studies of such disturbances. Figure 2 shows a schematic diagram of the kind of configuration anticipated. In general, we hoped to have Clementine in the geomagnetic tail (in orbit around

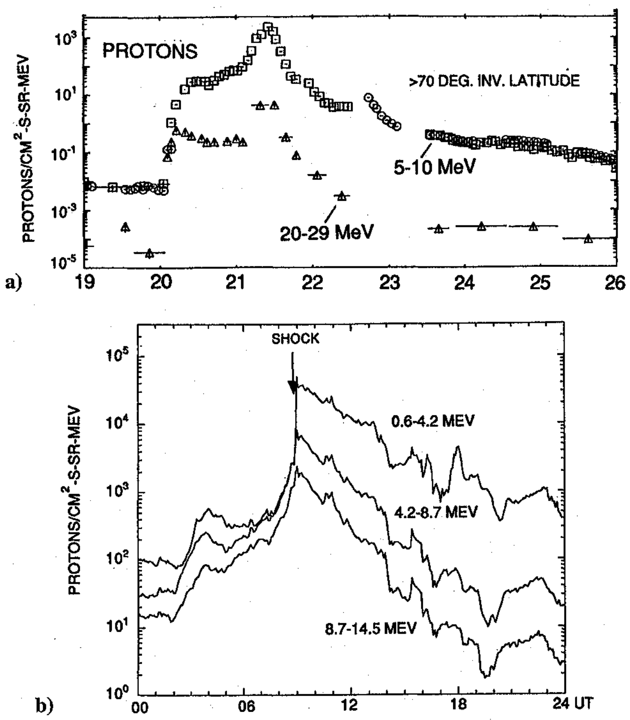

Fig. 3 a) Summary of proton fluxes for the period Feb. 19–25, 1994, as measured over the polar caps by the SAMPEX spacecraft. b) Data from GOES-7 satellite geostationary orbit for the period 00–24 UT on Feb. 21, 1994.

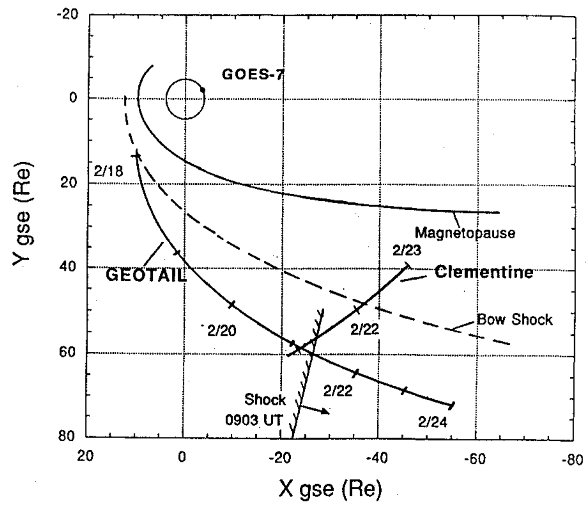

Fig. 4 Summary of spacecraft positions during the solar energetic-particle event of Feb. 1994.

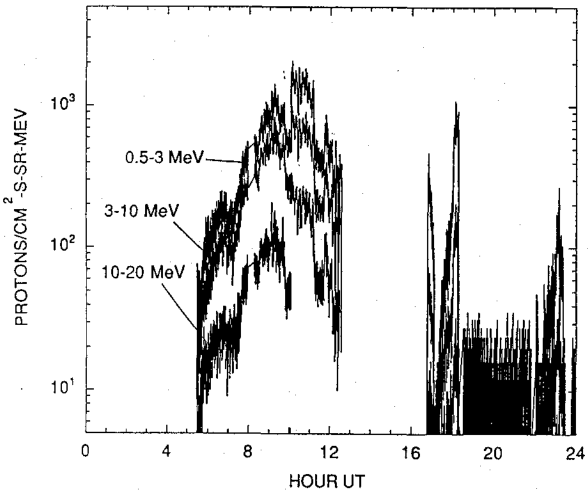

Fig. 5 Available Clementine-CPT proton fluxes in three energy ranges for Feb. 21, 1994. Other features are discussed in the text.

the moon). Concurrently we expected the joint Japanese–U.S. spacecraft GEOTAIL to be in the distant magnetotail and we hoped to have the small NASA spacecraft SAMPEX (Solar, Anomalous, and Magnetospheric Particle Explorer) in low Earth orbit over the polar cap region. As will be shown below, the details of actual events were somewhat different than shown in Fig. 2, but nonetheless a very satisfactory multispacecraft configuration was achieved.

Clementine was launched on Jan. 24, 1994, and fortuitously a large solar energetic-particle event commenced early on Feb. 20, 1994. At this time, the Clementine spacecraft had completed the second of its large phasing orbits[4] and had also undergone the lunar orbit insertion maneuver, which took place at 1251:31 UT on Feb. 19, 1994. At the beginning of Feb. 21, Clementine was on the evening side of the Earth–sun line at about $60R_E$ (Earth radii, $R_E = 6375$ km) geocentric distance. In geocentric solar ecliptic (GSE) coordinates, Clementine was at $(-24, 58, 3)R_E$. The lunar mapping program actually began at 1216 UT on Feb. 21.[5]

At ≈0200 UT on Feb. 20, the sensors onboard SAMPEX detected the sudden increase of energetic ions at energies above several MeV. SAMPEX is in an 82-deg-inclination orbit at an altitude of[6] ≈600 km. When SAMPEX is at high geomagnetic latitudes ($\gtrsim 70$ deg), it is able to see very directly solar energetic particles that move along open magnetic field lines down to the polar cap region (see Fig. 2). As shown in Fig. 3a, SAMPEX sensors observed the rapid enhancement of protons with $E > 3$ MeV, and in fact there were clear flux enhancements extending to $E > 20$ MeV. The SAMPEX data show a further gradual enhancement on Feb. 21, reaching a peak at ≈1000 UT on that day. Thereafter, fluxes decayed in an energy-dependent way, remaining well above background at least until Feb. 25.

Another spacecraft operating in the near-Earth region was the Geostationary Orbiting Environmental Satellite (GOES-7). This spacecraft monitored continuously the fluxes of protons with $E \gtrsim 0.6$ MeV at $6.6R_E$ geocentric distance.[7] Figure 3b shows the proton flux in three differential passbands for Feb. 21, 1994. The fluxes in all three GOES energy channels peaked broadly around 0900 UT on Feb. 21, but the 0.6–4.2-MeV channel, in particular, showed a very sharp rise at ≈0850 UT. As we will show below, this corresponds to the time of an interplanetary shock passage. After the peak at ≈0900 UT, the fluxes seen at GOES-7 declined substantially in an irregular fashion. The GOES sensor detected magnetospherically trapped particles in its lowest-energy channels, and thus we expect differences from Clementine measurements outside the trapping region.

The GEOTAIL spacecraft was traversing the near-Earth region in mid-Feb. 1994 on its way to a lunar-swingby maneuver[8] on Feb. 21. Thus, remarkably, both GEOTAIL and Clementine were close to the moon on Feb. 21. Figure 4 shows an X–Y projection of the GEOTAIL orbit for Feb. 18–25. Also shown is an estimate of the bow shock and magnetopause surfaces for reference. In addition to the GEOTAIL trajectory, we also show the Clementine orbit for Feb. 21, and we show the location of GOES-7 at ≈0900 UT on that day.

Detailed analysis of GEOTAIL data[9] shows that a strong interplanetary shock wave passed over the spacecraft at 0903:10 UT on Feb. 21. Using plasma, energetic-particle, and magnetic field data, GEOTAIL investigators were able also to infer the orientation of the shock front. This shock configuration is shown in Fig. 4. Quite obviously, given the proximity of Clementine to GEOTAIL, we would expect to see the shock effects nearly concurrently at the two spacecraft. On the other hand, we would have expected to see the shock effects earlier at GOES-7 (and perhaps at SAMPEX). In fact, the GOES-7 data show the shock at ≈0856 UT, nearly 7 min earlier than GEOTAIL.

A summary of available Clementine high-energy data for Feb. 21 is shown in Fig. 5. There was a data gap prior to ≈0530 UT. Between ≈1230 UT and ≈1630 UT, the CPT apparently experienced an interference problem, which is still being investigated; no data are shown for that interval until we can determine the cause of the problem. For other intervals in Fig. 5, the ≈8-s samples of CPT count-rate data have been converted to differential proton fluxes. We assume that

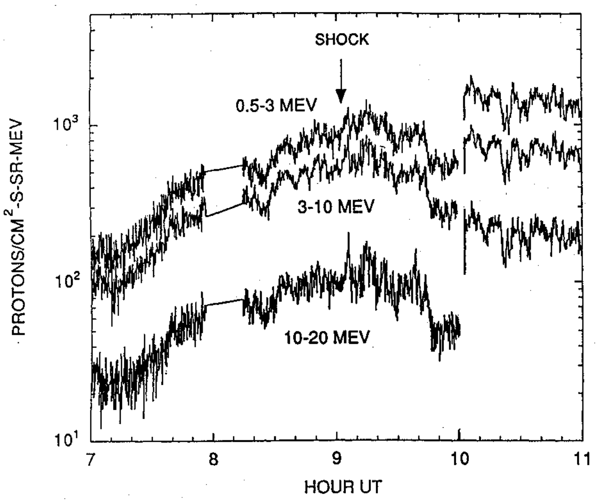

Fig. 6 Detail of CPT data for the period 0700–1100 UT on Feb. 21, 1994.

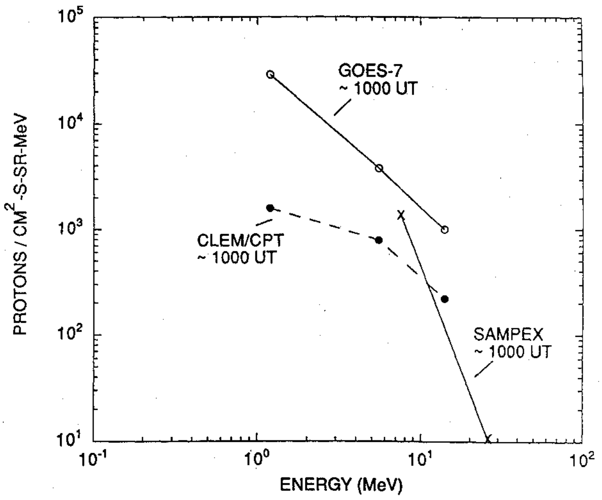

Fig. 7 Comparison of proton energy spectra measured at ≈1000 UT on Feb. 21, 1994, by GOES-7, SAMPEX, and Clementine.

the 0.5–3-MeV channel is dominated by solar protons (rather than electrons). The 3–10-MeV and 10–20-MeV channels are probably dominantly measuring protons, although He and heavier ions would also be counted.

We see several features in Fig. 5 that are similar to data in Figs. 3a and 3b. The broad flux peak around 1000 UT is evident in the Clementine data. Also, absolute intensity values at, say, ≈0600 UT are similar at Clementine and at GOES-7 (Fig. 3b). Even a deep minimum in fluxes at ≈1700 UT was seen inside the magnetosphere (GOES) and outside (Clementine).

There are, however, some very distinct differences between the CPT data and comparable channels of GOES-7. The CPT did not, for example, see the large (factor of > 10) increase in ≈0.5-MeV protons at ≈0900 UT associated with the shock passage seen at GOES-7. This was presumably due to an adiabatic compression effect inside the magnetospheric trapping region.[10] On the other hand, the CPT saw a very large decrease in particle fluxes between ≈1820 and ≈2200 UT. This was not seen by GOES-7 (or SAMPEX as far as we can tell). Thus, we have interesting observational features to untangle with the CPT relative to other observing platforms. It may be that proximity to the moon affected the ability of CPT to detect the solar protons during the period 1800–2200 UT.

Figure 6 shows a detail of CPT flux profiles for the period 0700–1100 UT on Feb. 21. Here we can see a very slight enhancement in the 10–20-MeV proton channel beginning at ≈0903 UT. This is plausibly related to the shock-wave passage seen quite clearly in the plasma and field data of GEOTAIL (Fig. 4). At these MeV energies on CPT, however, the shock signature is weak, since the overall energetic-particle enhancement is spatially very broad and not confined to the shock front itself.

Just before 1000 UT, the Clementine CPT sensor saw a large, somewhat energy-dependent flux decrease. Then, just after 1000 UT, the fluxes underwent a severalfold, very abrupt increase. Given the proximity of Clementine to the nominal bow-shock location, such flux variations may be due to magnetospheric boundary motion and the interaction of these boundaries with the moon.

As a final observational point, we can intercompare the energy spectra obtained by sensors on the several spacecraft during this event. In Fig. 7, for example, we show the proton spectrum measured by SAMPEX, by GOES-7, and by the CPT at ≈1000 UT on Feb. 21. We see reasonable agreement between the SAMPEX and CPT spectra, while the GOES-7 spectrum inside the magnetosphere is several times higher in comparable energy ranges.

Discussion and Summary

The CPT measurements of the directional energetic-particle flux are useful for characterizing the local exposure of the Clementine spacecraft to penetrating radiation. From a scientific point of view, the CPT data would have been much enhanced had there been in situ magnetic field data from Clementine as well. However, lacking such ancillary data, we must infer the physical region of the spacecraft and other changes in the environment from the energetic-particle signatures alone. This is a challenge.

We have shown in this paper that the Clementine CPT data can be quite useful in the context of multipoint measurements of the near-Earth (geospace) environment. Using data from several spacecraft—along with the CPT data—we are able to separate spatial and temporal effects. In the case presented in this paper, we were able to begin the examination of solar energetic-particle interactions with the moon. We see evidence of "shadowing" of particle fluxes due to physical occultation by the lunar surface. The high time resolution of the CPT sensor and the wide range of energies covered should allow us in the future to examine these phenomena in much greater detail. From such studies, we should get a much clearer picture of plasma interactions with the airless, weakly magnetized lunar surface.

The Clementine project is still sorting out timing, orbit, attitude, and other ephemeris information for the science investigation teams. As we get this complete data set, and as we untangle some of the interference problems in the CPT data set, we expect to obtain an interesting picture of translunar space. We have seen many examples of low-energy electron bursts of obvious magnetospheric origin. Further comparison of such data with GEOTAIL, GOES, SAMPEX, and ground-based data hold great potential for increasing substantially our understanding of global magnetospheric dynamics.

Our data plans for Clementine CPT include merging of all final orbit and attitude data with the best "clean" CPT flux information. These master data files will be available to all interested investigators. We will also produce ≈1-min average data for submission to the Planetary Data System (PDS) and to the International Solar-Terrestrial Physics (ISTP) database. We expect to compute such engineering quantities as total dose and sensor background. Last but not least, we look forward with great enthusiasm to further comparisons of CPT data with all other geomagnetic data sets available during the brief, but exciting, Clementine epoch.

Acknowledgments

The CPT team received funding support from Grant NAG5-2634 with NASA HQ. The CPT instrument was built and tested at Aerospace Corporation, and we thank the fine team of engineers there for extensive efforts. We also thank Don Horan of Naval Research Laboratory for his unflagging support. We thank Cam McCarl and the entire "Batcave" crew for excellent help and support. D.N.B. thanks Gene Shoemaker and the Clementine science team for stimulating interactions and inspiration. The team appreciates the intense efforts of P. Rustan, S. Nozette, and H. Garrett of Ballistic Missile Defense Organization and J. Rahe and B. Campbell of NASA. Thanks are extended to J. Cummings (SAMPEX), R. Zwickl and D. Wilkenson (GOES), and T. Terasawa and A. Nishida (GEOTAIL) for information used in this study.

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A. L. Vampola
Associate Editor