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MEMORANDUM

SUBJECT: TRAPPED-RADIATION ENVIRONMENT
PROJECT: CHANDRA X-RAY OBSERVATORY
DATE: 2006.10.31

SUMMARY

In a memorandum dated 2006.01.31, Project Science presented computations of the long-term external fluence of trapped protons in the evolving orbit of the *Chandra X-ray Observatory* through the AP8 environment. Here we respond to two questions posed by the ACIS team, regarding that memorandum:

1. What is the difference between AP8-Max and AP8-Min estimates?
2. How large are temporal variations about the AP8 environment?

DISCUSSION

This brief discussion addresses the two questions about uncertainties in the calculations of the trapped-proton (external) fluence. The previous (2006.01.31) memorandum described tools and data used for the calculations. A description of the attached supporting documents follows this Discussion (Supporting Documents).

1. The difference between AP8-Max and AP8-Min models is important only for low earth orbits (LEO). For LEO, AP8-Min actually gives a higher fluence than AP8-Max, because the expanded atmosphere during solar maximum removes magnetic-mirroring protons through enhanced atomic-collision rates. For high earth orbits such as *Chandra*'s, AP8-Max and AP8-Min give essentially the same fluence. Indeed, our SPENVIS calculations give AP8-Max and AP8-Min results (`orb-rad_models.pdf`) that are virtually indistinguishable from each other.

2. While AP8 accurately estimates the long-term-average (mean) fluence, temporal changes in the trapped-proton intensity correspond to proportionate changes in the ring current, which perturbs the earth's magnetic field during geomagnetic storms. The carriers of this ring current are primarily 10–200-keV protons, which differ on average by about a factor of two between storming and quiet conditions (`ebihara_2002.pdf`). Precipitation events result primarily from wave-induced pitch-angle scattering of the existing population into the bounce loss cone. Typically, the intensity within the loss cone remains small compared to that

outside (`walt_2003.pdf`). Consequently, an individual precipitation event rarely reduces substantially the omnidirectional proton intensity, although cumulatively these events are the primary depletion mechanism for the proton belts.

3. In addition to true temporal variations, orbit-to-orbit differences in the orbital fluence result from rotation of the Earth and its slightly asymmetric magnetic field. While the previously reported mean fluence for each epoch takes into account the evolution of *Chandra*'s orbit, it averages over orbit-to-orbit differences. Interestingly, the summed fluence for any 3 consecutive orbits changes slowly over the course of a year, because the *Chandra* (63.5-h) orbital period is very close to 8/3 days. Typically, orbit-to-orbit differences in the calculated orbital fluence are small. Large fractional orbit-to-orbit differences occur only when the trapped-proton orbital fluence is small — i.e., when the perigee is so high that the orbit does not penetrate deeply into the proton belt.

In conclusion, we estimate that temporal variations in the orbital proton fluence are about a factor of 2 (geomagnetic quiet) up to 4 (geomagnetic active). Only changes in the orbit — e.g., transiting or not transiting the most-intense region of the proton belt — would effect order-of-magnitude differences in the calculated orbital fluence. Thus, we recommend a factor-of-3 margin over the fluence estimates previously presented, in order to allow for temporal enhancements in the trapped-proton intensity.

Supporting Documents

The attached files comprise the supporting documents data products and relevant references — from this study:

1. `orb-rad.pdf` compares *Chandra*'s orbit-averaged trapped-particle spectra for different radiation-environment models, computed using SPENVIS. The spectra are 20-orbit averages at four epochs — starting on August 12 of 1999, of 2006, of 2009, and of 2012. For trapped protons, the models are AP8-Min, AP8-Max, CRRESPRO-Quiet, and CRRESPRO-Active; for trapped electrons, AE8-Min, AE8-MAX, CRRESELE-Ave, and CRRESELE-Peak. Although the mean spectrum of electrons varies with the solar cycle, that of protons does not. For these models, the mean trapped-proton intensity is stable over the solar cycle.

2. `polar_100keV.pdf` displays the temporal dependence of the proton intensity, obtained with the *Polar* Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) Imaging Proton Spectrometer (IPS), as plotted by the MSFC's Natural Environments Branch. The color plots give the dependence of 100–200-keV proton spectral intensity upon the McIlwain L value (magnetic-shell equatorial radius) and time, for the years 1996, 1997, 1998, and 1999. The black-and-white line plots record the (magnetic index) DST, driven by changes in the ring current. For these data, the trapped-proton intensity shows half-order-of magnitude temporal variations.

3. `ebihara_2002.pdf` is a paper analyzing the storm-time proton ring-current energy density, measured with the *Polar* Charge And Mass Magnetospheric Ion Composition Experiment (CAMMICE) Magnetospheric Ion Composition Sensor (MICS). This analysis (see Figure 2 therein) shows factor-of-two differences between the average storm-time proton (10–120-keV) energy density and the average quiet-time value.

4. `walt_2003.pdf` is a paper analyzing storm-time proton precipitation events, measured with the *Polar* Source/loss-cone Energetic Particle Spectrometer (SEPS). This analysis documents dramatic increases in the 155-keV proton spectral intensity within the bounce loss cone, during precipitation events. However, even during precipitation events, the proton intensity inside the nominal loss cone remains lower than that outside. This occurs because precipitation events result primarily from wave-induced pitch-angle scattering of the existing charged-particle population into the bounce loss cone. Consequently, the omnidirectional (averaged over 4π) intensity changes little, even during dramatic precipitation events.

5. The four (4) files `orb-p-fluence_1999.pdf`, `orb-p-fluence_2006.pdf`, `orb-p-fluence_2009.pdf`, and `orb-p-fluence_2012.pdf` show the accumulated proton fluence and flux and over 18 consecutive orbits starting on August 12 of 1999, of 2006, of 2009, and of 2012, respectively. The plots show (energy) integral values for protons more energetic than 150 keV, 300 keV, and 600 keV, calculated with the SPENVIS tool using the AP8 environment. Typically, rotation of the Earth's magnetic field changes the calculated orbital fluence by less than a factor of two orbit-to-orbit and much less than this for the average of 3 consecutive orbits (8 days). Larger orbit-to-orbit fractional changes in the calculated orbital fluence occur during epochs for which the *Chandra* orbit only partially penetrates the trapped-proton belt. However, in those cases, the proton orbital fluence is also very low.