GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L07109, doi:10.1029/2010GL042531, 2010

The east-west effect in solar proton flux measurements in geostationary orbit: A new GOES capability

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Received 15 January 2010; revised 17 February 2010; accepted 25 February 2010; published 14 April 2010.

[1] Since 1998, the GOES system has made eastward and westward observations of multi-MeV solar proton fluxes. The gyrocenters of the fluxes observed looking westward (eastward) lie outside (inside) geostationary orbit. Due to this "east-west effect," eastward observations of 4.2–82 MeV protons vary with respect to their westward equivalents. At times of high solar wind dynamic pressure (P_{dyn} > 10 nPa), the "inside" and "outside" fluxes are approximately equal. As P_{dyn} decreases to ~1 nPa and the ring current decreases, the "inside" fluxes decrease as much as an order of magnitude with respect to the "outside" fluxes. Under low P_{dyn}, the "inside" fluxes exhibit short-lived (1–3 hr) increases, sometimes to the levels of the "outside" fluxes, during periods of enhanced *AE* index activity. This association suggests that magnetotail topologies associated with substorms enhance the access of solar protons to lower *L* shells under low P_{dyn}. **Citation:** Rodriguez, J. V., T. G. Onsager, and J. E. Mazur (2010), The east-west effect in solar proton flux measurements in geostationary orbit: A new GOES capability, *Geophys. Res. Lett.*, *37*, L07109, doi:10.1029/2010GL042531.

1. Introduction

[2] Since 1974, an Energetic Particle Sensor (EPS) has monitored solar energetic particles (SEP) on the NOAA Synchronous Meteorological Satellites (SMS) and Geostationary Operational Environmental Satellites (GOES). Starting with GOES 8, the GOES satellites have been three-axis-stabilized. The EPS on GOES 8–12 has a single, nominally westward field-of-view (FOV) [*Onsager et al.*, 1996]. However, since January 1998, the GOES 10 EPS was directed eastward. Starting with GOES 13, the successor Energetic Proton, Electron and Alpha Detector (EPEAD) instrument has both an eastward and a westward FOV, providing a new planned observational capability.

[3] On GOES 8–12, the westward EPS look direction was intended to observe solar energetic protons whose gyrocenters lie outside geostationary orbit and therefore are more likely to lie outside their geomagnetic cutoffs, or surfaces of constant cutoff rigidity (Figure 1a). The eastward GOES 10 EPS observations were of protons whose gyrocenters are inside geostationary orbit (Figure 1a). (We refer to the fluxes observed westward (eastward) as "outside" ("inside") fluxes.) In a 100 nT magnetic field characteristic of geostationary orbit, 1–100 MeV protons have gyroradii of 0.2–2 R_E (at a 90° pitch angle). The proton "east-west effect" has been used to estimate gradients in magnetospheric and solar proton fluxes [e.g., *Blake et al.*, 1974; *Walker et al.*, 1976, and references therein]. This paper evaluates the GOES east-west effect during two SEP events (22 November 2001 and 6 December 2006) with respect to solar wind bulk properties and energetic proton measurements at the L1 libration point (Advanced Composition Explorer, ACE) and in low-earth orbit (Solar, Anomalous and Magnetospheric Particle Explorer, SAMPEX). We observe that solar proton access inside geostationary orbit is enhanced by large (>10 nPa) solar wind dynamic pressures (P_{dyn}). At lower P_{dyn}, "inside" fluxes at energies <82 MeV are reduced up to an order of magnitude relative to "outside" fluxes, except in the presence of auroral electrojet activity, when repeated increases occur in the "inside" fluxes, lasting several hours.

2. Instrumentation

[4] The EPS on GOES 9 and 11 (westward FOV) and GOES 10 (eastward FOV) and the EPEAD on GOES 13 (westward and eastward FOVs) measure proton fluxes in seven channels between 0.74 and 900 MeV. The P2 (4.2–8.7 MeV) and P3 (8.7–14.5 MeV) telescope channels have a 35° half-angle FOV. The P4 (15–40 MeV) dome channel has a 45° elevation and 25° equatorial half-angles FOV, while P5 (38–82 MeV) has a 60° elevation and 30° equatorial half-angles FOV. All FOVs are centered near 90° pitch angle. The 5-minute-averaged differential proton fluxes are corrected for cosmic ray backgrounds and out-of-band protons [*Onsager et al.*, 1996].

[5] Data from the 19–28 MeV proton channel (29° half-angle FOV) in the SAMPEX Proton/Electron Telescope (PET) [*Cook et al.*, 1993] (82 degree inclination, 520 × 670 km altitude) are used to evaluate the *L* shell dependence of solar protons for comparison with GOES observations (Figure 1b). Data from the ACE Electron, Proton and Alpha Monitor (EPAM) [*Gold et al.*, 1998] are used to characterize the time variation of the solar proton fluxes at L1. We use the verified 5-minute Level 2 data in the ACE Science Center from the highest energy channel (1.9–4.8 MeV, P8') in the LEMS120 detector. The interplanetary magnetic field (IMF) and solar wind dynamic pressure (P_{dyn}) are from the 5-minute OMNI data available from the Coordinated Data Analysis Web. For these SEP events, *SYM-H* and provi-

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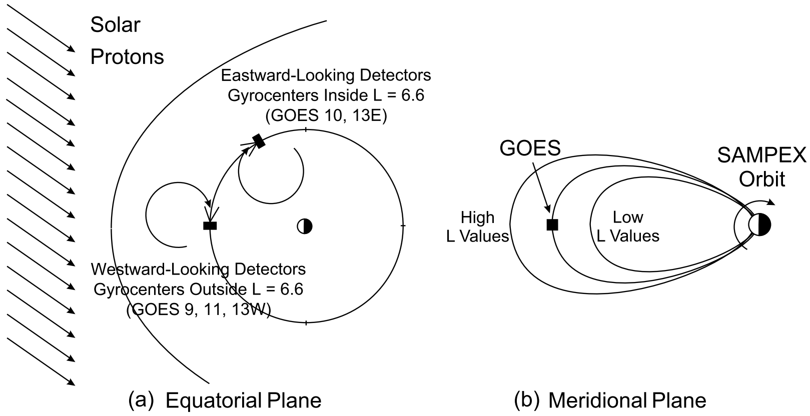

Figure 1. (a) Sketch of solar proton observations in the equatorial plane by westward-looking (GOES 9, 11, and 13) and eastward-looking (GOES 10 and 13) detectors. A westward (eastward) detector observes protons whose gyrocenters lie outside (inside) geostationary orbit. (b) Meridional plane cross-section of L shells. In low earth orbit, SAMPEX observes the GOES "inside" proton fluxes at lower L shells than the GOES "outside" proton fluxes.

sional AE indices are available from the World Data Center for Geomagnetism, Kyoto.

3. SEP Event Starting 22 November 2001

[6] The GOES EPS measurements indicated the onset of a SEP event at 2320 UT on 22 November 2001 (day 326) when the >10 MeV proton flux reached 10 protons cm^{-2} s^{-1} sr^{-1}. During the event rise (day 327–328), the GOES 10 (j_E, eastward-observed, "inside") fluxes at energies <82 MeV were generally lower in magnitude than the GOES 9 (j_W, westward-observed, "outside") fluxes and exhibited order-of-magnitude fluctuations on 1–3 hr time scales (Figure 2a). The ratio of j_E to j_W clarifies the evolution of the east-west effect (Figure 2b). In general, the magnitudes of the fluctuations in the east-west ratios (j_E/j_W) decrease with increasing energy. The "outside" fluxes exhibited a smooth increase just prior to 0600 UT on day 328, similar to that in the ACE 1.9–4.8 MeV proton fluxes. In contrast, the 4.2–8.7 MeV "inside" fluxes jumped a factor of 5 between 0545 and 0555 UT on day 328, to 10^4 cm^{-2} s^{-1} sr^{-1} MeV^{-1}. P_{dyn} increased from 3.4 nPa at 0545 UT to 34 nPa at 0600 UT, indicating the arrival of an interplanetary shock (Figure 2c).

[7] For nearly ten hours thereafter, P_{dyn} remained elevated, increasing to 85 nPa at 0725 UT and only decreasing below 10 nPa after 1535 UT. During this period of elevated P_{dyn}, j_W and j_E were similar, exhibiting the same long-term decrease and amplitude fluctuations observed in the 1.9–4.8 MeV proton fluxes at L1 (Figure 2a). The subsolar magnetopause standoff distance, r_0, estimated as a function of P_{dyn} and B_z [*Shue et al.*, 1998], was near or well inside geostationary orbit ($6.6R_E$) during this period (Figure 2d). After 1800 UT, when P_{dyn} was 0.6 nPa (following a 1 hr gap in the OMNI data) and the ring current was decreasing (Figure 2f), j_E decreased more rapidly than j_W (Figures 2a and 2b).

[8] When the interplanetary shock arrived at the magnetopause c. 0555 UT, GOES 9 and 10 were both on the night side, well with the magnetosphere (GOES 9 at 23 and GOES 10 at 21 local time). Based on the polarity of GOES 9 H_p (the magnetic field component perpendicular to the orbit plane, positive northward – not shown), GOES 9 first clearly encountered the magnetopause on the dawn side at 1344 UT. At this time, GOES 10 was still inside the magnetosphere, based on its local time and magnetometer data. These observations show that the "inside" and "outside" GOES >4.2 MeV solar proton fluxes are similar when P_{dyn} > 10 nPa (0555–1535 UT), whether the GOES satellites are inside or outside the magnetopause. Based on the conclusion from Liouville's theorem that outside its geomagnetic cutoff, the differential cosmic ray flux at a given energy and direction is equivalent to that outside the influence of Earth's magnetic field [*Lemaitre et al.*, 1935, and references therein], both the "inside" and "outside" >4.2 MeV fluxes were outside their cutoffs during this high P_{dyn} period.

[9] The decrease in j_E after 1800 UT was interrupted by an oscillation in the flux ratios between 2210 and 2255 UT on day 328, and again between 0835 and 1105 UT on day 329 (Figure 2b). These oscillations were associated with 0.3–9 nPa and 0.6–4 nPa fluctuations in P_{dyn}, respectively (Figure 2c). As with the interplanetary shock, higher pressures were associated with higher j_E/j_W. This sensitivity of j_E/j_W to P_{dyn} suggests that the decreases in j_E/j_W starting late in day 328 were related to low P_{dyn} as well as decreasing ring current, with the geomagnetic cutoffs moving outward except during the P_{dyn} fluctuations.

[10] Prior to the arrival of the shock on day 328, when there was moderate (<1000 nT) recurring AE activity (Figure 2f) during a prolonged period of fluctuating IMF B_z polarity (Figure 2e), the fluctuating j_E/j_W sometimes approached unity (Figure 2b). During the following period of high solar wind pressure and large B_z magnitudes, the auroral electrojet (AE) index far exceeded 1000 nT for several hours. In contrast, during the subsequent multi-day period of northward or very weak B_z (often <1 nT) and low P_{dyn} (<10 nPa), the AE index was very low, and j_E/j_W never approached unity after 2300 UT on day 328.

[11] The SAMPEX 19–28 MeV proton flux measurements during this SEP event confirm the radial flux gradient indicated by the "east-west" effect (Figure 3). These measurements are binned into four invariant L shell ranges and compared to the GOES 9 ("outside") and GOES 10 ("inside")

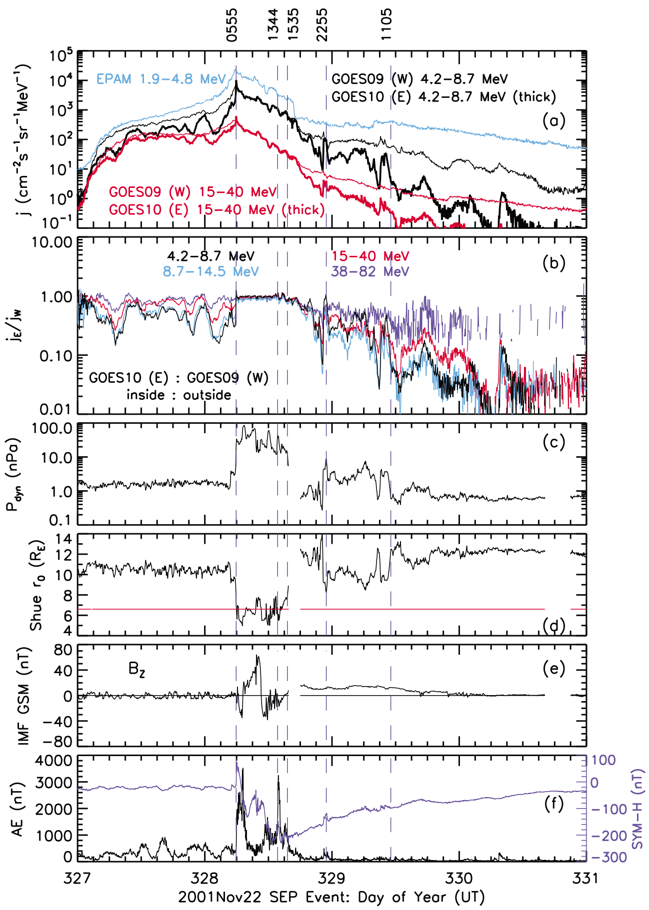

Figure 2. Solar energetic proton and solar wind observations on 23–26 November 2001 (days 327–330): (a) GOES 9 ("outside") and GOES 10 ("inside") and ACE EPAM proton fluxes, (b) east-west proton flux ratios (GOES 10 to GOES 9), (c) OMNI dynamic pressure P_{dyn} (from ACE and Geotail), (d) the *Shue et al.* [1998] magnetopause subsolar point (the red line indicates 6.6 R_E), (e) OMNI IMF B_z (GSM), and (f) *SYM-H* and provisional *AE*. Local midnight is 7 UT for GOES 9 and 9 UT for GOES 10. The east-west ratios are not plotted when either of the fluxes is less than the typical standard deviation of the instrument backgrounds (in counts). The EPAM data are not shifted to account for the travel time from L1 to Earth. The vertical guidelines refer to events discussed in the text.

15–40 MeV proton fluxes. The progression from the polar cap ($L > 10$) to $L = 4$ is striking. In the polar cap, the SAMPEX fluxes are enveloped by the GOES "outside" fluxes. (Because the energy spectrum is falling and the PET and GOES energy intervals are not the same, the PET trace falls below GOES 9.) In the L shell range closest to geostationary orbit (L = 6.0–6.5), the SAMPEX fluxes vary similarly as the "outside" fluxes but are lower on average than at $L > 10$. At L = 5.0–5.5, starting on 25 November, the SAMPEX fluxes generally lie within the "outside" and "inside" GOES fluxes. At L = 4.0–4.5, the SAMPEX fluxes differ in two major respects from the fluxes at higher L shells. First, they exhibit a much wider range of variability, except during 0555–1535 UT on 24 November (day 328) when $P_{dyn} > 10$ nPa, when they are similar to the "outside" and "inside" GOES fluxes as well as the fluxes measured by SAMPEX in the polar cap. Second, after P_{dyn} decreases on day 328 (after 1535 UT) below 10 nPa, the SAMPEX fluxes are similar to the lower "inside" GOES 10 fluxes. In summary, this comparison indicates that the gyrocenters of the GOES "inside" 15–40 MeV proton fluxes lie in the invariant L = 4.0–4.5 range, while the gyrocenters of the "outside" fluxes lie outside L = 7, and that the geomagnetic cutoff for these fluxes was inside L = 4 during the period of high P_{dyn}.

4. SEP Event Starting 6 December 2006

[12] The GOES EPS measurements indicated the onset of a SEP event at 1555 UT on 6 December 2006 (day 340). This event provided the first opportunity to compare solar proton measurements by the EPEAD instruments on GOES 13 (Figure 4a) and the previous series of EPS instruments (Figure 4c). The GOES 11 and GOES 13 j_W measurements agree well, as do the GOES 10 and GOES 13 j_E measurements. The east-west ratios from the older and newer instruments also agree well (Figures 4b and 4d) and, as in the earlier case, exhibited repeated fluctuations whose magnitudes often increased towards unity and decreased with increasing energy. The "outside" fluxes exhibited some fluctuations simultaneous with those in the "inside" fluxes, though usually smaller (for example, 1500–0300 UT on days 343–4, Figures 4a and 4c). These fluctuations did not appear in the EPAM solar proton fluxes, which decayed smoothly following the SEP event flux maximum (Figures 4a and 4c). These observations are evidence of time-varying geomagnetic cutoffs that, at times, move sufficiently outward to affect the "outside" fluxes.

[13] During this event, the solar wind properties were less extreme than during the 22 November 2001 event. During the five-day period shown in Figure 4, P_{dyn} varied between 1 and 10 nPa. Around 0430 UT on day 342, when P_{dyn} increased from 5 to 11 nPa (Figure 4e), the *Shue et al.* [1998] subsolar magnetopause distance r_0 decreased very briefly to L = 6.6 but otherwise lay outside of L = 7 (Figure 4f). Thereafter, P_{dyn} decreased gradually, reaching < 1 nPa during brief periods on days 343 and 344. Also in contrast to the earlier event, the magnitude of the *SYM-H* index was low (Figure 4h).

[14] The largest and most prolonged decrease in j_E/j_W occurred in the 4.2–8.7 MeV fluxes between 08 and 15 UT on day 343 (Figures 4b and 4d). This decrease lagged the most extended period of northward IMF (day 343, 0715–1320 UT, Figure 4g) and low *AE* index (Figure 4h). While j_E/j_W approached unity during the 11 nPa P_{dyn} pulse starting at 0430 UT on day 342, they also approached unity repeatedly when P_{dyn} was relatively low (1–3 nPa) and the level of *AE* activity was generally high. This is in stark contrast to the very low j_E/j_W and *AE* levels observed during the latter part of the 22 November 2001 event (Figures 2b and 2f). A cross-correlation of *AE* with the j_E/j_W from the P2, P3 and P4 channels for days 341–345 shows significant peak linear correlation coefficients of 0.50, 0.52 and 0.59, and at these peaks, *AE* lags the fluxes by 3, 23 and 38 minutes, respectively. These lags suggest that magnetic field

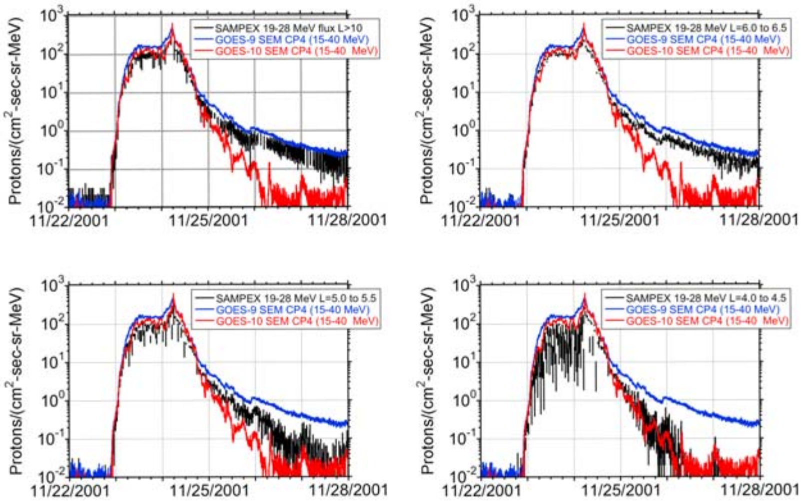

Figure 3. Comparison of GOES 9 ("outside", blue) and GOES 10 ("inside", red) EPS 15–40 MeV proton fluxes and SAMPEX PET (black) 19–28 MeV proton fluxes during the 22 November 2001 SEP event. The PET fluxes are binned in four invariant L shell ranges: $L > 10$ (polar cap), $L = 6.0$–6.5, $L = 5.0$–5.5, and $L = 4.0$–4.5. These L values are calculated in the International Geomagnetic Reference Field for the proper epoch. The scatter in the data represents the range of fluxes in individual orbits within the L shell bins.

changes during the substorm growth phase enhance solar proton access to the inner magnetosphere.

5. Summary of Observations and Discussion

[15] Based on our comparison of two SEP events, we make the following observations regarding the east-west effect in GOES solar proton measurements and the radial distribution of solar protons in the inner magnetosphere:

[16] 1. The east-west differences in solar proton fluxes are measured consistently by the combined EPS (GOES 9, 10 and 11) instruments and the new east-west observational capability of the EPEAD (GOES 13) instruments.

[17] 2. The comparison of the GOES and SAMPEX data indicates that gyrocenters of the GOES "inside" 15–40 MeV proton fluxes lie in the invariant $L = 4.0$–4.5 range, while gyrocenters of the "outside" fluxes lie outside $L = 7$.

[18] 3. In the presence of high solar wind dynamic pressure P_{dyn} (>10 nPa), the "inside" and "outside" proton fluxes are approximately equal. A large P_{dyn} increase causes the "inside" fluxes to increase to the "outside" levels, suggesting that the P_{dyn} increase has moved the geomagnetic cutoff inside $L = 4.0$–4.5.

[19] 4. As P_{dyn} drops to ~1 nPa and the ring current decreases, the "inside" fluxes below 82 MeV decrease as much as an order of magnitude with respect to the "outside" fluxes. The decrease is more pronounced at lower energies. During quiet periods, the "inside" fluxes may decay to the background level of the GOES instruments days ahead of the "outside" fluxes.

[20] 5. During times of low P_{dyn} and increased AE index activity, the "inside" fluxes increase and decay repeatedly over periods of several hours, sometimes back up to the "outside" flux levels. The relative magnitudes of the fluctuations generally decrease with increasing energy, indicating that the geomagnetic cutoffs are further inside the magnetosphere for greater energies. The association with AE suggests that magnetotail topologies associated with substorms enhance the access of solar protons to lower L shells under low P_{dyn}.

[21] During the 22 November 2001 SEP event, following a period of high P_{dyn} in which the MeV proton fluxes were nearly uniform above $L = 4$, a positive radial proton flux gradient ($dj/dr > 0$) developed rapidly as P_{dyn} and the ring current decreased (Figures 2 and 3). In contrast, in the 6 December 2006 event, some set of processes absent during the latter part of the 22 November 2001 event repeatedly caused the "inside" fluxes to increase towards the "outside" flux levels, then to decrease, thereby repeatedly reducing and increasing the radial flux gradient (Figure 4). The later event is characterized by the presence of substantial AE index activity (Figure 4h) during low P_{dyn}, while the earlier event is notable for the absence of AE activity following the event peak when P_{dyn} is low (Figure 2f). Solar proton access to the inner magnetosphere has been correlated with AE, Dst, and P_{dyn} [*Panasyuk et al.*, 2004, and references therein]. During a geomagnetically quiet period ($Kp \leq 2+$), *Paulikas and Blake* [1969] noted an association between the Kp index and the transmission coefficient of 5–21 MeV protons from the solar wind to geosynchronous orbit. The satellite-spin-averaged geosynchronous fluxes considered by *Paulikas and Blake* [1969] would be similar to an average of the GOES "inside" and "outside" fluxes. Therefore, the association of their transmission coefficients with Kp may be related to the association between j_E/j_W and AE when P_{dyn} is low.

[22] Though large P_{dyn} changes (as on 24 November 2001) can lead to the creation of trapped proton belts [*Kress et al.*, 2005, and references therein], our paper is concerned with more transient access of solar protons to the inner magnetosphere. Both large (>10 nPa) P_{dyn} and changing tail magnetic field topology associated with substorm activity may reduce geomagnetic cutoff distances. *Paulikas and Blake* [1969] suggest that a doubling of the tail field magnitude could enhance direct access to geostationary orbit on

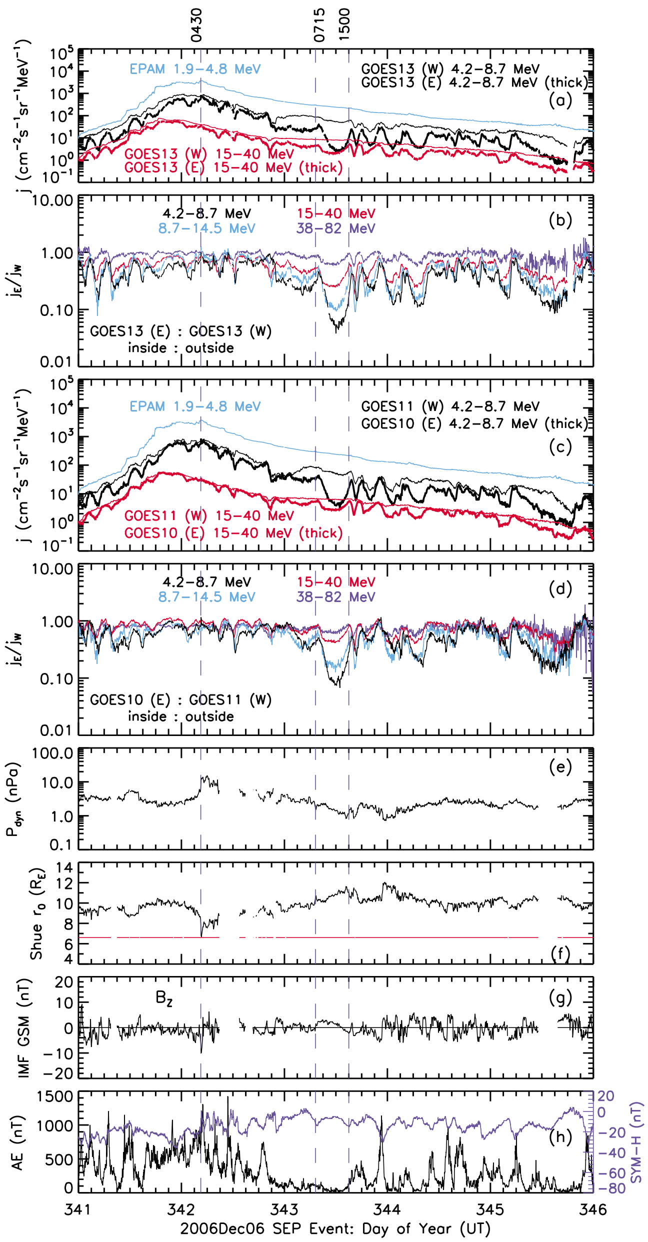

Figure 4. Solar energetic proton and solar wind observations on 7–11 December 2006 (days 341–345): (a) GOES 13 "inside" and "outside" and ACE EPAM proton fluxes, (b) east-west ratios of GOES 13 proton fluxes, (c) GOES 11 ("outside") and GOES 10 ("inside") and ACE EPAM proton fluxes, (d) east-west proton flux ratios (GOES 10 to GOES 11), (e) OMNI dynamic pressure P_{dyn} (from ACE and Wind), (f) the *Shue et al.* [1998] magnetopause subsolar point, (g) OMNI IMF B_z (GSM), and (h) *SYM-H* and provisional *AE*. Local midnight is 4 UT for GOES 10, 7 UT for GOES 13 and 9 UT for GOES 11. The data are treated as in Figure 2.

the night side. *Huang et al.* [2009] point out that, inside ~8R_E, >1 MeV proton geomagnetic cutoff distances (including their variation in local time and latitude) should depend on the magnetic field topology. Though these geomagnetic cutoff variations do not always result in the creation of new trapped populations, they affect the level of radiation hazard inside geostationary orbit during SEP events.

[23] **Acknowledgments.** We thank NOAA SWPC for the operational processing of the GOES EPS/EPEAD data, the ACE EPAM instrument team and the ACE Science Center for providing the ACE level 2 data, J. H. King and N. Papitashvili at AdnetSystems, NASA GSFC, for providing the OMNI solar wind data in CDAWeb, and the World Data Center for Geomagnetism, Kyoto, for providing the *AE* and *SYM-H* indices. We appreciate discussions with H. Singer and B. Kress. J. V. Rodriguez was supported by the GOES-R Risk Reduction program.

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