IMAGE analysis and modelling of substorm onsets

J. A. Wanliss and G. Rostoker

Abstract: We consider the list of substorm 'onsets' from the IMAGE satellite and use the recent Tsyganenko models (T96, T01) to map these ionospheric locations into the magnetotail. We investigate, in a statistical fashion, the source region of the auroral arc that brightens at the onset of expansive phase. This arc is usually identified as the ionospheric signature of the expansive phase onset that occurs in the magnetotail. The arc that brightens maps to a most likely downtail position of $X_{GSM} = -6.6 \pm 0.2 R_E$. Mappings during space storms are even closer to the earth; $X_{GSM} = -4.7 \pm 0.1 R_E$. These results can be interpreted in two ways. First, onsets are initiated in the near-earth magnetotail, typically within geostationary orbit. Second, the mappings are too close to the earth, so the Tsyganenko models are insufficiently stretched in these regions. Finally, we used CANOPUS data to demonstrate that the IMAGE onset list contains auroral brightenings that are not classical substorm onsets, but are actually poleward border intensifications.

Key words: Substorms, modelling, PBI.

1. Introduction

Many event studies have considered the location in the magnetotail of the substorm expansive phase ignition site or zone [14, 9, 10, 7, 3, 4, 2]. Several of these studies used satellite data and the Tsyganenko models to study various aspects related to substorms, for example to map ionospheric auroral brightenings to the distant location in the magnetotail. The statistical samples were very small; so for example, in their work Pulkkinen et al. [10] found it difficult to paint a coherent picture in mapping of individual substorm auroral arcs.

The magnetospheric location of the expansive phase onset is important since mechanisms that may be responsible for the onset of instability, for example the Kelvin-Helmholtz instability [**?**] or the kinetic ballooning instability [1], to name only two possible candidates, are strongly dependent upon spatially variable parameters such as plasma density and magnetic field strength. Frank and Sigwarth [4] and Erickson et al. [3] used the Polar and CRRES satellites, respectively, to present evidence that expansive phase is triggered as close as 4 to 7 RE from the Earth. This was consistent with earlier evidence from ground-based data presented by Samson et al. [14], which suggested expansive phase onset occurs between 6 to 10 RE. Recently, Dubyagin et al. [2] used data from the FAST satellite and ground-based instruments, along with a mapping via the Tsyganenko magnetic field model [18] to provide evidence of a near-earth breakup location. Wanliss [25] recently used data from many isolated substorms compiled over the most recent solar cycle to map onsets to about 14 R_E downtail. All indications are that the onset location is usually very close to the Earth.

In this paper we extend these studies through the use of the recently available list of substorm onsets [5] estimated from the IMAGE FUV instrument. Rather than considering detailed event studies, this paper describes the extension of mapping efforts that include multiple substorms from an ionospheric perspective. As was the case for previous small sample event studies (e.g. [14, 9, 10, 8, 3, 4, 2], we trace back from the ionosphere along the magnetic field lines to pinpoint the magnetospheric location of the ignition site. Although it is difficult to accurately map the onset location to the magnetotail, we believe that the statistical nature of the investigation will provide an average onset location consistent with reality. In addition, mapping of the onset arcs from the ionosphere to the plasma sheet was performed with several different models than those used in the studies mentioned above. We employed the empirical magnetospheric magnetic field models of Tsyganenko [15, 16, 18, 20, 21, 22], and make comparisons between mappings produced by the various models (hereinafter referred to as T87, T89, T96, T01).

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2. Models

The models of N. A. Tsyganenko and his collaborators are widely used [15, 16, 18, 20, 21, 17]. Since substorm time scales are so short, and the Tsyganenko models are averages, it is not strictly appropriate to use them to study substorms, even though they have been commonly used in this manner, as noted above by many references. During the expansive phase of substorms it is almost certainly inappropriate to use the Tsyganenko models, since this is when dramatic and highly dynamic processes such as dipolarization and particle injections occur. But the growth phase is quite different. Steady equatorward motion of the auroral oval during growth phase is associated with slow stretching of the inner magnetotail field [23]. We assume that during the growth phase stretching of the tail and plasma sheet thinning take place without a major reconfiguration of magnetic field lines. This is not an unreasonable assumption, and several studies have shown how this is consistent with observations [6, 24]. Wanliss [25] exploited this loophole to map onset locations for several hundred substorms. The important thing to note is that mapping was done during substorm growth phase when slow changes ensure that the models are most likely to provide results that are within reason. Since the IMAGE list [5] gives the location of the centre of the arc that brightens the real location of the onset, i.e. the location of the most equatorward arc that brightens, is always equatorward of the location given in the IMAGE list. We are nevertheless able to obtain an *upper limit* to the downtail location of the mapped IMAGE ionospheric brightening.

For the purposes of this work we have used T96 and T01 models. T01 is supposed to be the most realistic model, especially in mapping the inner magnetotail. We used T96 since T01 is only strictly valid earthward of 15 RE, and onset sites could be further downtail where the other models are valid. Secondly, even though T01 is ostensibly the best model, it is also the least used. It was not used in any of the event studies listed above, so the results found here could cast a cautionary or different light on previous work.

Whereas the models prior to T96 did not have a pre-defined magnetopause and were calibrated exclusively by the magnetic dipole tilt and Kp index, the T96 and T01 models explicitly include (i) the solar-wind controlled magnetopause, (ii) region 1 and 2 Birkeland currents, and (iii) the interconnection of the magnetospheric and solar wind fields at the boundary. They include further parameterization with the solar wind dynamic pressure, DST-index, and interplanetary magnetic field By and Bz.

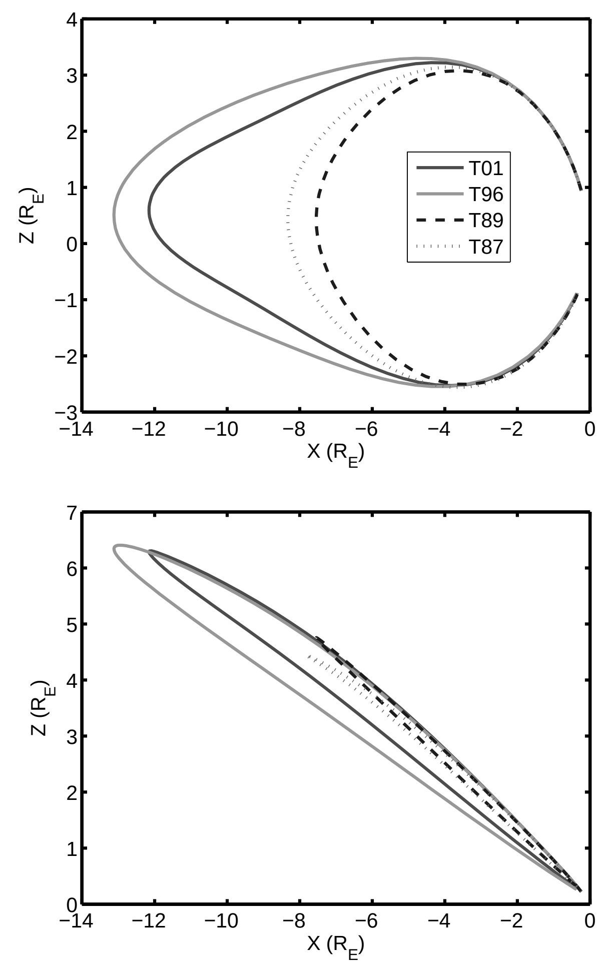

Fig. 1. Meridian plots of the model magnetic field lines mapped from the ionospheric onset location to the magnetotail for the April 30, 2002 brightening at 05:50:52 UT.

The earlier models appear to be too stretched in the inner magnetosphere as compared to in-situ observations, particularly during active times. The most recent model, namely T01, is probably the best suited to determine onset locations, since previous observations suggest that substorm onset occurs in the inner magnetotail. In fact, T01 was intended primarily to improve the description of the inner magnetospheric field ($X \geq -15R_E$), and unlike the previous models, includes in the modeling database measurements from within geostationary orbit. T01 follows the same approach as in T96, but uses an improved approximation for the ring current field [20].

Figure 1 shows two different cross-sectional views of model magnetic field lines that map from the ionospheric onset position for the April 30, 2002 image brightening that occurred at 05:50:58 UT. The magnetospheric source of the auroral precipitation is understood to map along the corresponding magnetic field line to its greatest radial distance from the Earth. The T87 and T89 model results are also shown, and these map much closer than do the T96 and T01 models. The latter two models include field-aligned currents which may be responsible for the mapping differences. Furthermore, when mappings are so close to the Earth, it has been shown that T87 and T89 require modifications to take into account the behavior of the inner magnetotail and plasma sheet, which call into question the validity of these earlier models unless suitably modified during late growth phase [9, 10, 12]. Note that the models also predict quite different flankward (Y) positions.

3. Results

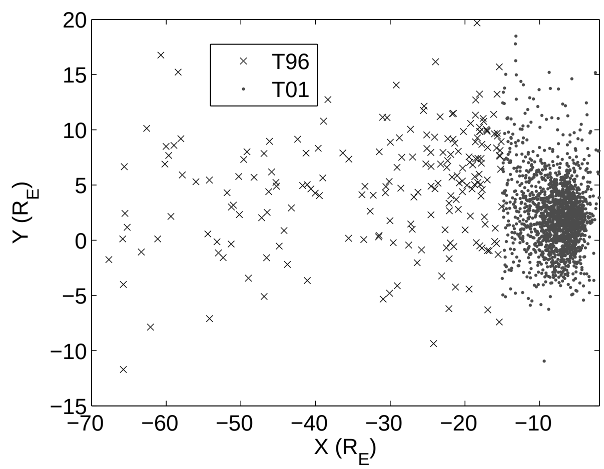

Fig. 2. Location of the model mapped brightenings in X-Y plane. T96 mappings are indicated with crosses and T01 mappings with dots.

Because the differences in the field configuration during quiet and disturbed times are large, it is essential that the effects of varying geomagnetic activity be taken into account in the mapping studies. However, the T87 and T89 models are parameterized by the Kp index which is a three-hour average. Thus the veracity of these two models is expected to be inferior to results from T96 and T01. We were able to perform mappings for 2588 events between May 2000 and April 2003.

In Figure 2 the model onset locations are projected onto the $X - Y$ plane. T01 mappings are shown by the dots. The T96 mappings (crosses) were selected for the cases where the mapping was tailward of T01 applicability (i.e. -15 R_E). As found by Wanliss [25] there is a clear preference for the auroral brightenings to map to the dusk side of the magnetotail, and each of the pre-midnight brightenings map to the dusk side.

Figure 3 shows the relationship between the mapped locations of the IMAGE brightenings as a function of Dst. The light curve (bottom) shows the results when sorted for their dates between October-March. The darker curve is the result for brightening between April-September. Since all the brighteninqs mapped were from the geographic northern hemisphere this plot seems to indicate a difference between the 'summer' (April to September) and 'winter' brightenings. The summer brightening occur at consistently less negative Dst values; i.e. the same value of the downtail mapped distance (X_{GSM}) is achieved for smaller Dst values during summer. There is also a clear change of the curves for brightenings that occur during space storms (Dst$\leq -30nT$). In this case the onset or brightening locations map much closer to the earth, within geostationary orbit.

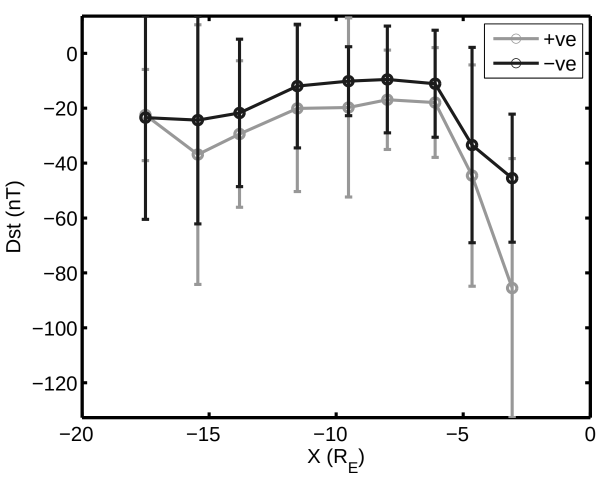

Fig. 3. Mapped locations of the IMAGE brightenings as a function of Dst. The light curve (bottom) shows the results when sorted for their dates between October-March. The darker curve is the result for brightening between April-September.

Finally, Figure 4 shows the most probable location of the downtail mapping. The dark curve shows the normalized result for all 2588 mappings, and the light curve shows the normalized result for space storm time mappings only. The most probable location of the mapped auroral brightening tends to be slightly closer to the earth during storms. For all data $X_{GSM} = -6.6 \pm 0.2 R_E$ and for storms (480 events) $X_{GSM} = -4.7 \pm 0.1 R_E$.

4. Conclusions

Taken at face value, these results suggest that enormous stretching of the magnetotail is possible during substorms. The most

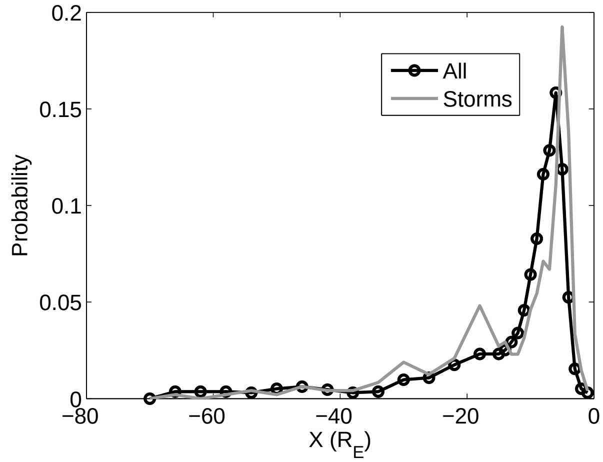

Fig. 4. Most probable mapped downtail location of the auroral brightenings. The dark curve shows the normalized result for all 2588 mappings, and the light curve shows the normalized result for space storm time mappings only.

probable mapped downtail distances are consistent with results of Frank and Sigwarth [4] that place the onset location near the ring current. They are also consistent with the results of Tsyganenko [22] "that during storms with $DST < -250$ nT the tail-like deformation of the nightside field penetrates so close to Earth that the quasidipolar approximation breaks down at distances as small as 3-4 R_E." In fact, if these results are realistic, then the tail is potentially even more stretched, since the IMAGE list gives the location of the centre of the arc that brightens [5]. If the brightening corresponds to a substorm, the real location of the onset will always be equatorward of the location given in the IMAGE list. Thus magnetic field stretching at the end of the growth phase will be even more severe than our results indicate.

Additional caveats are also in order. Figure 5a shows an auroral brightening listed as a substorm in the Frey list [5], for 30 April 2002 at 05:50:58 UT. The brightening occurs at geographic latitude and longitude of 59.53 and 251.44 degrees. The Tsyganenko model topologies for this event are shown in Figure 1. Figure 5b shows the IMAGE FUV data 6 minutes later. The original brightening is still visible, but there is an additional brightening that occurs at higher latitude and westward of the initial one. We examined CANOPUS magnetometer latitude and longitude profiles (not shown) which indicate a substorm onset just after 05:00 UT, long before the image brightening. The signal for the westward electrojet is very clear prior to the image brightening, as shown in the latitude profile at 05:49 UT in Figure 6a. It is most obvious in the X-component trace with a deep minimum near 64 degrees AACGM latitude, which remained stable at that latitude since at least 05:44 UT. A smaller minimum is observed near 70 degrees, which is a possible signature of the beginnings of a poleward border intensification (PBI). The profile at 05:53 UT shows the same two minima, but the poleward minimum has increased fivefold. The auroral brightening associated with this higher latitude current system, near the poleward edge of the oval, appears indicative of a PBI rather than an expansion phase onset.

These data clearly indicate the danger in relying on only one data source and automated techniques of substorm onset identification. Rostoker [13] previously illustrated this danger by giving several examples of PBIs that might erroneously be interpreted as substorm onsets on the basis of their auroral signatures.

5. Acknowledgments

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References

1. Cheng, C.Z., and A.T.Y. Lui, Kinetic ballooning instability for substorm onset and current disruption observed by AMPTE/CCE, *Geophys. Res. Lett.*, 25, 4091–4094, 1998.
2. Dubyagin, S. V., V. A. Sergeev, C. W. Carlson, et al., Evidence of near-Earth breakup location, *Geophys. Res. Lett.*, 30, 1282, doi:10.1029/2002GL016569, 2003.
3. Erickson, G.M., N. C. Maynard, W. J. Burke, et al., Electromagnetics of substorm onsets in the near-geosynchronous plasma sheet, *J. Geophys. Res.*, 105, 25265–25290, 2000.
4. Frank, L. A. and J. B. Sigwarth, Findings concerning the positions of substorm onsets with auroral images from the Polar spacecraft, *J. Geophys. Res.*, 105, 12747–12762, 2000.
5. H.U. Frey, S.B. Mende, V. Angelopoulos, E.F. Donovan, Substorm onset observations by IMAGE-FUV, *J. Geophys. Res.*, 109, A10304, doi:10.1029/2004JA010607, 2004.
6. Kaufmann, R.L., Substorm currents: growth phase and onset, *J. Geophys. Res.*, 92, 7471–7486, 1987.
7. Kubyshkina, M. V., V. A. Sergeev, T. I. Pulkkinen, Hybrid Input Algorithm: An event-oriented magnetospheric model, *J. Geophys. Res.*, 104(A11), 24977–24994, 10.1029/1999JA900222, 1999.
8. Lu, G., N. A. Tsyganenko, A. T. Y. Lui, et al., Modeling of time-evolving magnetic fields during substorms, *J. Geophys. Res.*, 104(A6), 12,327–12,338, 1999.
9. Pulkkinen, T. I., A study of magnetic field and current configurations in the magnetotail at the time of a substorm onset, *Planet. Space. Sci.*, 39, 833–845, 1991.
10. Pulkkinen, T. I., D. N. Baker, R. J. Pellinen, et al., Mapping of the auroral oval and individual arcs during substorms, *J. Geophys. Res.*, 100, 21987–21994, 1995.
11. Pulkkinen, T. I., D. N. Baker, M. Wiltberger et al., Pseudobreakup and substorm onset, Observations and MHD simulations compared, *J. Geophys. Res.*, 103,14847–14854, 1998.
12. Pulkkinen, T. I., D. N. Baker, L. L. Cogger, et al., Spatial extent and dynamics of a thin current sheet during the substorm growth phase on December 10, 1996, *J. Geophys. Res.*, 104, 28475–28490, 1999.
13. Rostoker, G, Identification of substorm expansive phase onsets, *J. Geophys. Res.*, 107, doi:10.1029/2001JA003504, 2002.
14. Samson, J.C., et al., Proton aurora and substorm intensifications, *Geophys. Res. Lett.*, 19, 2167–2170, 1992.
15. Tsyganenko, N. A., Global Quantitative Models of the Geomagnetic Field in a Cislunar Magnetosphere for Different Disturbance Levels, *Planet. Space. Sci.*, 35, 1347–1358, 1987.
16. Tsyganenko, N. A., A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space. Sci.*, 37, 5–20, 1989.
17. Tsyganenko, N.A., M. Peredo, Analytical Models of the magnetic field of disk-shaped current sheets, *J. Geophys. Res.*, 99, 199, 1994.
18. Tsyganenko, N. A., Modelling the Earth's magnetospheric magnetic field confined within a realistic magnetopause, *J. Geophys. Res.*, 100, 5599–5612, 1995.
19. Tsyganenko, N. A., Effects of the solar wind conditions on the global magnetospheric configuration as deduced from data-based models, in Proceedings: *Third International Conference on Substorms (ICS-3)*, ed. E. J. Rolfe and B. Kaldeich, European Space Agency Spec. Publ., ESA SP-399, 181–185, 1996.
20. Tsyganenko, N.A., A model of the near magnetosphere with a dawn-dusk asymmetry 1. Mathematical structure, *J. Geophys. Res.*, 107, 10.1029/2001JA000219, 2002a.
21. Tsyganenko, N.A., A model of the near magnetosphere with a dawn-dusk asymmetry 2. Parameterization and fitting to observations, *J. Geophys. Res.*, 107, 10.1029/2001JA000220, 2002b.
22. Tsyganenko, N.A., H.J. Singer, J.C. Kasper, Storm-time distortion of the inner magnetosphere; How severe can it get?, *J. Geophys. Res.*, 108, 10.1029/2002JA009808, 2003.
23. Voronkov, I., E. Friedrich, and J.C. Samson, Dynamics of the Substorm Growth Phase as Observed using CANOPUS and SuperDARN Instruments, *J. Geophys. Res.*, 104, 28491–28505, 1999.
24. Wanliss, J.A., J.C. Samson, and E. Friedrich, On the use of photometer data to map dynamics of the magnetotail current sheet during substorm growth phase, *J. Geophys. Res.*, 105, 27673–27684. 2000.
25. Wanliss, J. A., Substorm onset location and dipole tilt angle, *Annales Geophysicae*, 24: 577-588, 2006.
26. Yoon, P. H., J. F. Drake, A. T. Y. Lui, Theory and simulation of Kelvin-Helmholtz instability in the geomagnetic tail, *J. Geophys. Res.*, 101, 27327–27339, 1996.

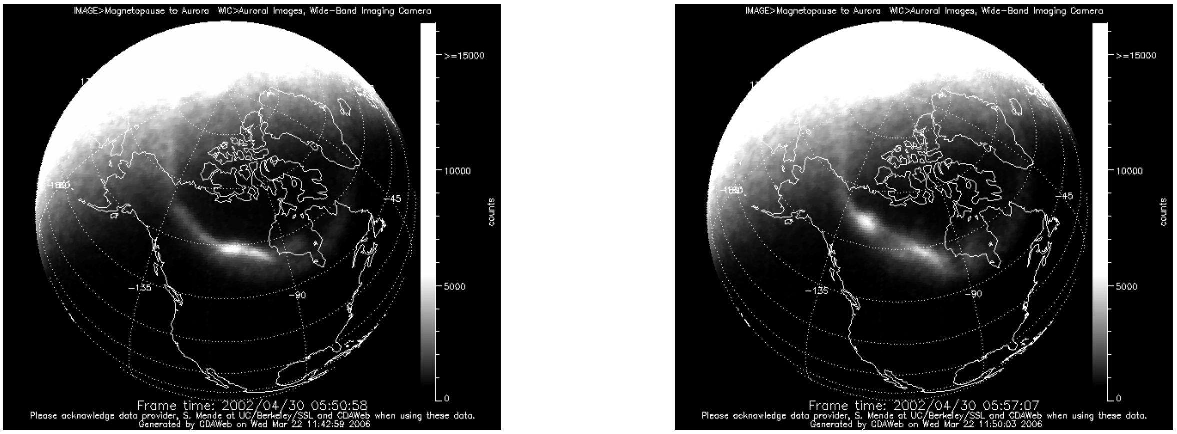

Fig. 5. IMAGE FUV observations of the auroral oval at (a.) 05:50:58 UT and (b.) 05:57:07 UT.

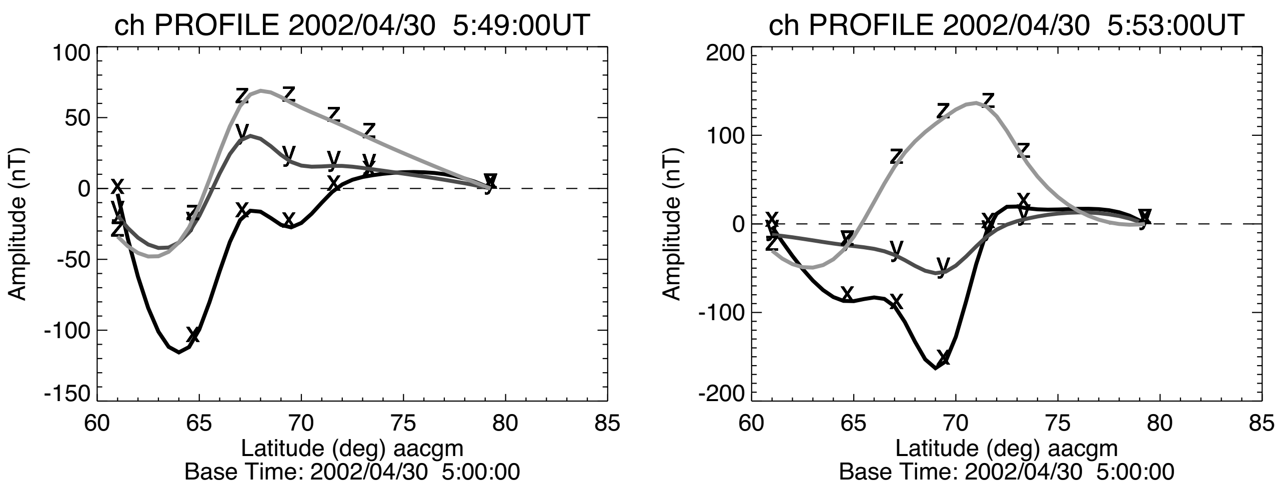

Fig. 6. CANOPUS magnetometer latitude profiles from the Churchill line at (a.) 05:49 UT and (b.) 05:53 UT.