

Comparisons Between HEOS Magnetic Field Data and Tsyganenko 87 Model Near Cusp Crossings

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Abstract: Magnetic field models are currently used for mission planning. For the ESA's Cluster mission the Tsyganenko 1987 (T87) model was used to optimise the planned cusp crossings by the 4 Cluster spacecraft. Nevertheless the validity of this model in this particular region of interest is not well known. Using previous works based on HEOS magnetometer data collected when cusp crossing were identified, we compare the location of the cusp deduced from HEOS observations with the one deduced from the T87 magnetic field model computed for the K_p value of the corresponding hour interval. Two types of tests are made. First the magnetic field measured along HEOS trajectory is compared with the corresponding vectors determined from T87. Second, we carry out topological tests and compare HEOS magnetic field data and cusp determination to magnetic field maps obtained from T87. Finally we estimate the mismatches ΔX , ΔZ between the location of the magnetic cusp, deduced from data and from the model. It is concluded that the location of the exterior cusp or high latitude magnetopause is closer from the Earth, by about $2 R_E$, than the T87 model would predict.

Introduction

The predictions of exterior cusp crossings by the 4 Cluster spacecraft have been made principally with the Tsyganenko magnetic field model [1]. It is well known that this model gives relatively good results near the Earth and, to a lesser extent, inside the tail region [2]. The cusp region is also a key region of interest for the Phoenix/Cluster II mission. The validity of the Tsyganenko model in predicting the cusp position has been investigated at low altitudes by Escoubet and Bosquet [4], and at medium altitudes by Stasiewicz [5] but to date we are not aware of any such study for the exterior cusp which is one of the prime target of either the Phoenix or Cluster II missions. Since the HEOS data has been used, in the high latitude dayside, to build the T87 model, we expect the model to fit pretty well with HEOS data. One problem is that the T87 model does not provide a estimate of the magnetopause and cusp location, but these boundaries can be computed from the field lines, for instance by computing the last closed lines on the day side. To check the validity of this determination, we examine a series of events already studied by Haerendel et al. [3] corresponding to the identification of cusp crossings by HEOS spacecraft, and compare (i) the magnetic field deduced from HEOS measurements with the corresponding T87 magnetic field along HEOS trajectory, (ii) the location of the cusp crossing deduced from observations and from the topology of the magnetic field lines taken at the time of the crossing of the cusp by the spacecraft. Finally, we estimate the mismatches ΔZ and ΔX between the center of the cusp deduced from T87 and the location of the cusp deduced from HEOS measurements.

HEOS Data and the Identification of Cusp Crossings

The HEOS data plots

Figure 1 gives an example of HEOS data plots. The direction and the intensity of the magnetic field are plotted along HEOS trajectory, in SM coordinates, in the Z-X and Z-Y plane. The data plots are also available in GSM coordinates, but SM coordinates are more appropriate, because the variation in the cusp location is smaller in this system. The direction towards the sun is positive X. The black circles correspond to the position of the spacecraft along the orbit, at different time steps given by the UT hours marks indicated on the top of the figure. The direction and the intensity of the observed magnetic field along HEOS trajectory is indicated by the direction and the length of the arrows in the Z-X (left) and Z-Y (right) planes. The phase angle (ϕ) in X-Y plane of the $\mathbf{B}$ vector is plotted in the middle of the figure, as well as the modulus of the magnetic field (on a logarithmic scale). The date is indicated at the top right.

Identification of cusp crossings by HEOS

Haerendel et al. [3] have identified exterior cusp or magnetopause crossings in HEOS data from a change in the direction of the magnetic field component normal to a model magnetopause. From the data plotted in figure 1, a cusp crossing or a magnetopause crossing can be deduced from topological considerations. First, for this August 9th 1973 event, we can observe in the Z-X plane an abrupt change in the direction of the magnetic field, between 5 and 6 UT. This abrupt change of direction is associated with a change in the modulus of the magnetic field: before this time, during the period where HEOS was inside the magnetosphere, the modulus was decreasing roughly like r^{-3} . After the cusp/magnetopause crossing the modulus of the magnetic field is almost constant (inside the magnetosheath). Later, one observes fast irregular variations that probably correspond to (multiple) crossings of the bow shock were observed.

Simulated Data from the Tsyganenko Model

The Tsyganenko model plot

Presently HEOS data are only available as papers plots. Thus, the first thing which had to be done was to digitize these data, so that we could compare spacecraft position and magnetic field to the corresponding values in the T87 model. The T87 model is parametrized by the Kp index; we have used the Kp values for the intervals around the cusp or magnetopause crossing under consideration. To compare the experimental data with the simulated data, we plot the model values in the same form as HEOS data, and obtain a series of simulated data, such as those plotted in figure 2. Of course, the evolution of the magnetic field along the trajectory is more smoothed when the model is considered, but we can observe the same kind of abrupt change in the direction of the Z-X component of $\mathbf{B}$, at the same time. To allow comparisons, in figure 3 we have plotted side by side, and on the same scale, the magnetic fields obtained from the HEOS data and from the T87 model. One can see at first glance that the model

fits roughly with experimental data, except outside the magnetosphere, but this is not surprising since the model has no meaning beyond the magnetopause.

Determination of the cusp location

The main problem is to know where is the HEOS spacecraft with respect to the cusp or to the magnetopause. From HEOS data, it is possible to identify cusp or magnetopause crossings, but it is difficult to know exactly what part of the boundary (exterior cusp/magnetopause) was encountered. In order to get an idea about the complete geometry of the cusp, we use the T87 model associated with a dedicated algorithm which computes the field lines close to the cusp. The method used is the following: first, in the Z-X plane, we compute the last closed field line along the X direction in SM coordinates, which gives the topology of the closed field lines and determine the subsolar point. Note, however, the T87 model contains no open flux that threads the dayside magnetopause (only lobe flux which may, or may not, thread the boundary outside the range of X covered by the model). Thus, the presence of dayside open flux would erode the subsolar point Earthward and move the open/closed boundary to lower latitudes than is derived here by neglecting the open flux. Second, from starting positions, spaced by $0.05R_E$ along the Z direction in GSM coordinates, at $X = -15R_E$, we compute the last field lines that returns to the Earth (i.e. lobe flux). This method allows us to create field lines maps such as the one shown in figure 4, hereby providing a map of the near cusp field lines and a determination of its location at a given time in the spacecraft frame.

Comparison Between Data and Model

Comparison between cusp location based on T87 and on HEOS data

Tsyganenko magnetic field line maps such as the one displayed in figure 4 allow a comparison between the magnetic cusp location deduced only from HEOS observations and the one deduced only from the T87 model. We can indeed superimpose the cusp crossing deduced from the event of figure 1 onto the Tsyganenko field lines map of figure 4. The result is shown in figure 5. Notice that the entire map is computed for a single time, and therefore the comparison is strictly valid only for the point along the trajectory which corresponds to that time. Nevertheless, on a time scale of 1 to 2 hours, the map does not change very much at least in SM coordinates, which justifies the choice of this coordinate system. In figure 5, the time is 05:30 UT, the time of the cusp intersection defined by the HEOS experimenters. At first glance one gets the impression that the agreement between data and model is rather good. But if we look more carefully at the time where the cusp crossing was identified, we do not find an agreement between the cusp position obtained from the T87 model and from the data. If we want to force the fit between the data and the model, we can obtain a good agreement by shifting the whole T87 magnetic field lines map towards the Earth by about $2R_E$, as shown in figure 6a. In this case, the T87 magnetic field line map fits the direction of the measured magnetic field, as long as HEOS is inside the magnetosphere. Note that we cannot obtain the same result by rotating the field line map; a rotation by about 15° allows us to get a good agreement up to $8R_E$, as shown on figure 6b, but the magnetopause remains at a large distance

from its position deduced from the data. Thus, the T87 model does not give a good estimate of the position of the exterior cusp at least for the event considered here. Let us now use the same method to examine other cusp crossings.

Examination of other events

Events studied in this paper were already studied by Haerendel et al. [3], and already identified as single or multiple cusp crossings. Figure 7 shows a more complex event (June 18, 1973); data suggest a double cusp or magnetopause (MP) crossing. The model shows an abrupt change in the direction of the magnetic field at the same time, but the direction deduced from T87 is not in agreement with the data; we can observe up to 45° rotation between the model and the data (figure 7a). Furthermore, the shear-like variation of the magnetic field seen during the cusp or magnetopause crossing cannot be found in the model. If we use the field line map model, and if we force the agreement with the data, as we did in the preceding case, we obtain results displayed in figure 7b. Then, we can identify the first event as a cusp crossing, but the second events, about 30 minutes later, should be a magnetopause crossing, instead.

To obtain the good fit shown in figure 7b one needs a radial displacement by 1 or 2 R_E of the location of the exterior cusp, depending upon the event under consideration. So, even when the data and the model do not fit very well, the experimental ambiguity between a cusp crossing or a magnetopause crossing can be cleared up by using the T87 field line map. If we look at the July 9 1973 event (figure 8), once again the difference between the direction of the field in the data and in the model can reach 45° , and the rotation of the fields does not occur at the same time (figure 8a). Nevertheless, if we use the field line map, and force the agreement by a translation of the map towards the earth by about $2R_E$, we can obtain a rather good fit inside the magnetosphere (figure 8b), and identify without ambiguity a magnetopause crossing. Thus, it seems that the real magnetopause is much nearer to the Earth than expected from the T87 model.

Of course it seems somewhat arbitrary to "force" the agreement with model by an arbitrary translation. For a few events, however, we could get a good agreement with the data without such a translation; this is the case for the August 14 1973 event, shown on figure 9, where there seems to be a good agreement between data and model. Yet, if we replace HEOS data in the T87 field line map (figure 9b), we are surprised to see that the event does not correspond to the exterior cusp defined by T87. Once again, we are obliged to translate toward the Earth the field lines map to force the agreement with the T87 cusp location (figure 9c), taking as a criterion the agreement between the directions of $\mathbf{B}$. In this case, we can identify a cusp crossing at the edge of the magnetopause.

The events discussed above give evidence for a mismatch between the location of the exterior cusp/high latitude magnetopause deduced from HEOS measurement and what is obtained from magnetic field maps deduced from the T87 model for the same time and K_p value. Table I summarizes what has been found by applying the same kind of analysis to the 11 events studied; it shows the mismatch ΔZ (along Z axis), ΔX (along X axis) and ΔR (in radial distance) between the two location of the exterior cusp/high latitude magnetopause crossings by HEOS trajectory. We notice that ΔX is always negative, ΔZ is usually negative (except the last case), and ΔR is negative or zero.

Influence of Kp on T87 field lines map

One could think that the disagreement between the HEOS data and the T87 model in the cusp region is due to an inappropriate choice of the Kp value. The value chosen for Kp is indeed defined every 3 hours, a time duration which is longer than that of the cusp crossing. On figure 10, we have plotted an example of T87 field lines computed for (i) the minimum value of Kp: $Kp=0,0^+$, (ii) the mean value: $Kp=2,2^+$ and (iii) the maximum possible value: $Kp \geq 5^+$. All cases are computed for the same date and time. We notice that by increasing the Kp value, we change the latitude of the cusp by 10 to 15° and the radial position by about $2R_E$. More precisely the location of the exterior cusp deduced from T87 moves along Z, but does not change along the X direction. Nevertheless, if we try to fit the T87 model with the data by using an arbitrary Kp value, the result are rather disappointing, and this hypothesis is not sufficient to explain the difference between the HEOS data and the T87 plots. Thus, we must conclude that the Kp index is an inappropriate index for defining the cusp magnetic flux topology. Elsewhere in this volume, Pulkkinen et al. discuss why the solar wind dynamic pressure (via magnetospheric compression) and the IMF (via reconnection/erosion) are a much better combination (note also both correlate to some extent with Kp).

Preliminary Conclusions

Eleven exterior cusp or magnetopause crossings already identified by Haerendel et al. [3] have been studied. From this limited sample, the following preliminary conclusions can be drawn. The direction of the magnetic field deduced from the Tsyganenko 1987 model (T87, parametrised by Kp alone) does not fit well with the measured values. Maps of the magnetic field lines have been produced from T87 for the time interval where HEOS was crossing the exterior cusp/high latitude magnetopause. These maps allow an independent "theoretical" localization of the cusp. Even when the evolution along HEOS trajectory of the measured and computed values of **B** agree, the location of the cusp/magnetopause crossing obtained from the data differs from what is obtained from the T87 map. In general the cusp/magnetopause found from HEOS measurements is about $2R_E$ closer from the Earth than the maps based on the T87 model would suggest.

The use of the field lines maps allows to make topology checks, in particular to check if the events correspond to an exterior cusp crossing or to a high latitude magnetopause crossing. These checks lead to conclusions which are in a rough agreement with earlier HEOS events identification [3]. The magnetic field along HEOS trajectory shows fast variations, both in amplitude and direction, which are obviously not described by an average model like T87.

Acknowledgments

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Tables

Date	ΔZ	ΔX	ΔR
2.6.73	-1.5	-2.	-3.
18.6.73	-0.5	-1.	-1.2
23.6.73	-1.	-2.	-1.7
28.6.73	-1.7	-2.5	-3.
9.7.73	-1.	-0.5	-1.4
14.7.73	-1.5	-1.5	-2.3
19.7.73	-2.	-2.	-3.5
29.7.73	+0.5	-2.5	-2.
9.8.73	0.	-1.5	-1.
14.8.73	0.	-3.5	-2.
27.2.74	+3.5	-4.	0.

Table I: Distance between the location of the exterior cusp/high latitude magnetopause crossing by HEOS and the correspondent location deduced from the T87 model.

Figures

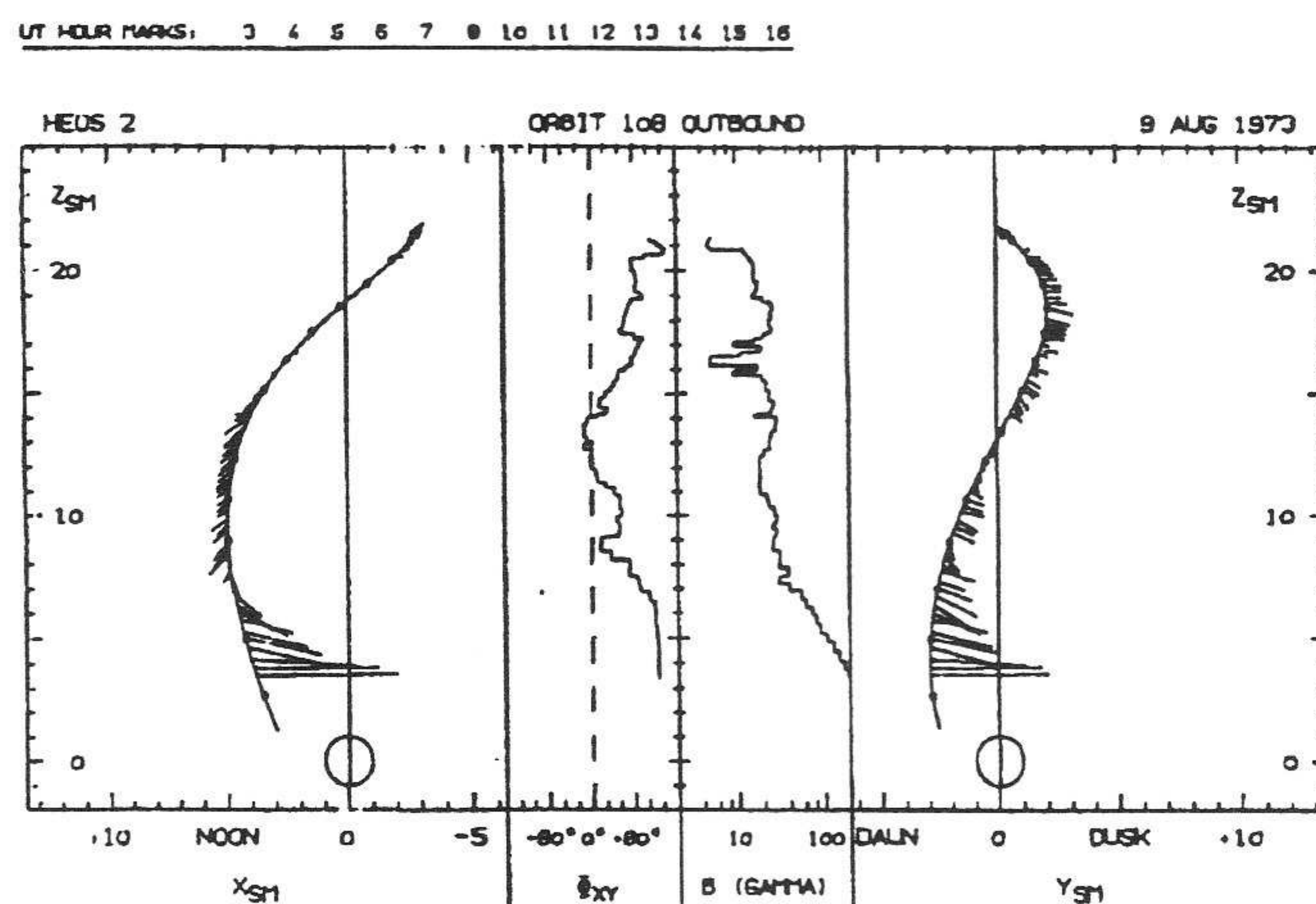


Figure 1: Example of HEOS magnetic field data plot for August 9, 1973, showing (i) the magnetic field in the XZ and YZ (SM) plane (panels 1 and 4), (ii) the azimuthal angle (panel 2) and (iii) the magnitude (panel 3) of the field vector.

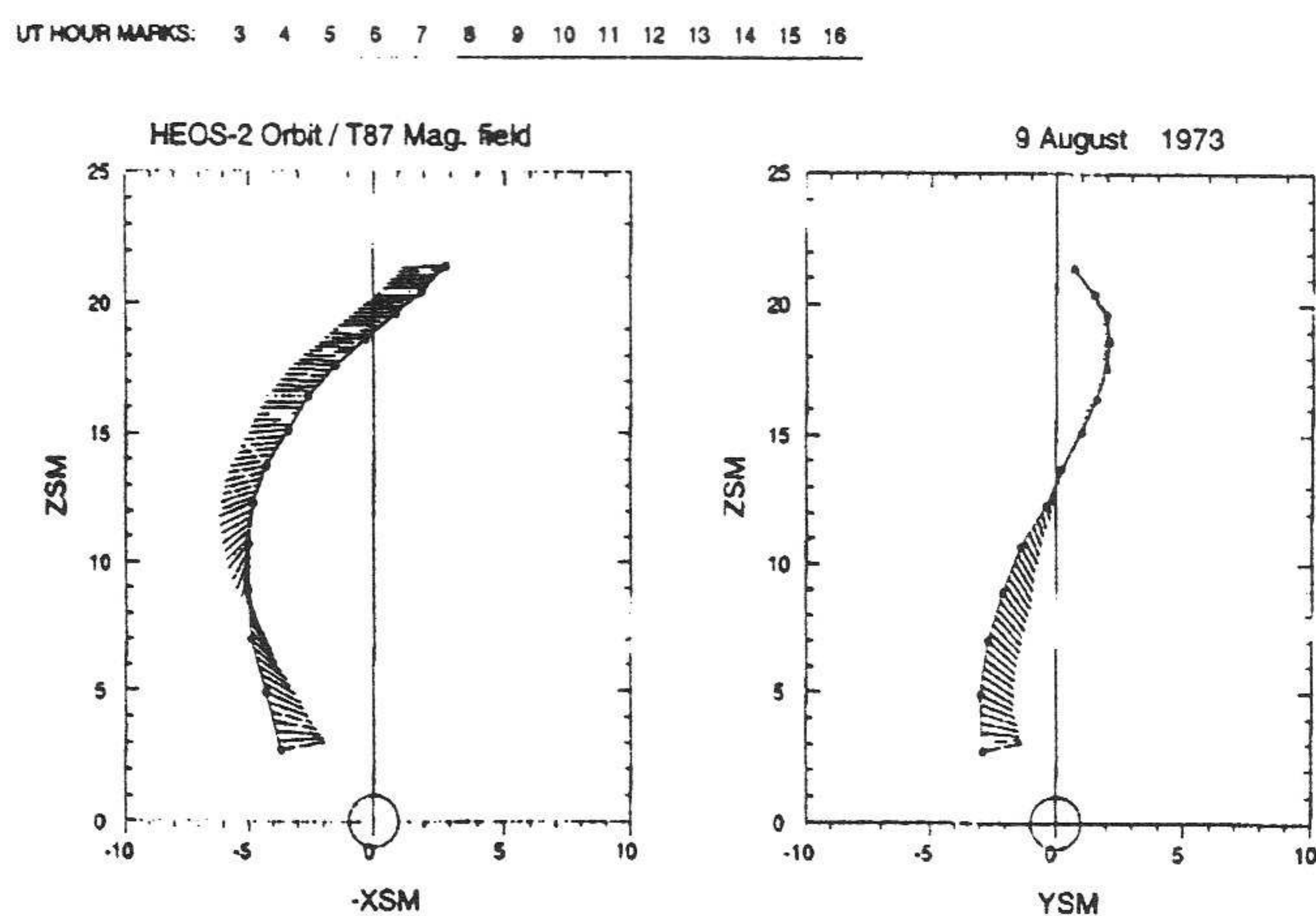


Figure 2: Tsyganenko 87 simulated field vectors for the same event and the same time, taken for the Kp value corresponding to the crossing of the cusp/magnetopause identified from HEOS measurements.

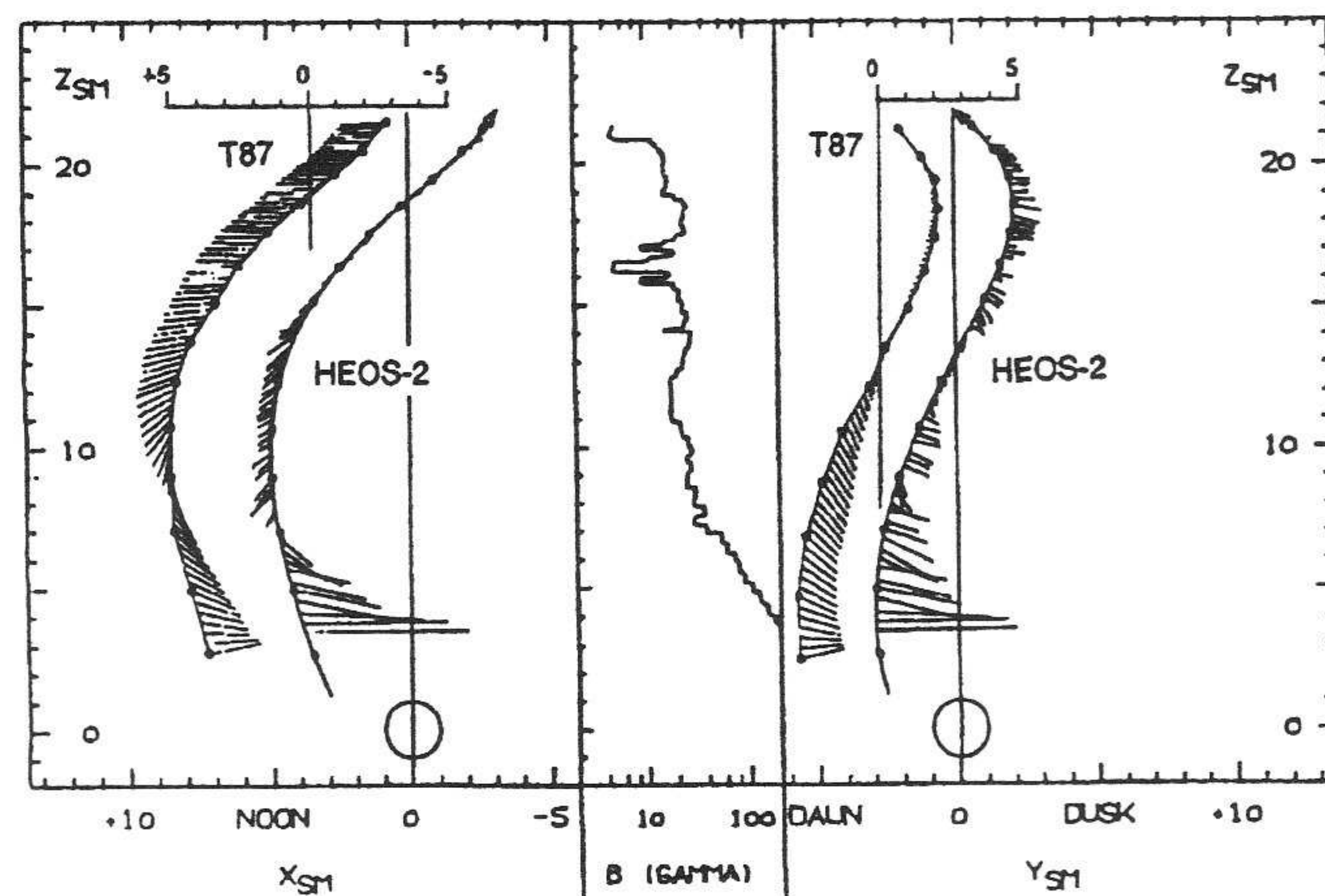


Figure 3: Comparison between the HEOS magnetic field and the one deduced from the T87 model for August 9, 1973 (figures 1 and 2).

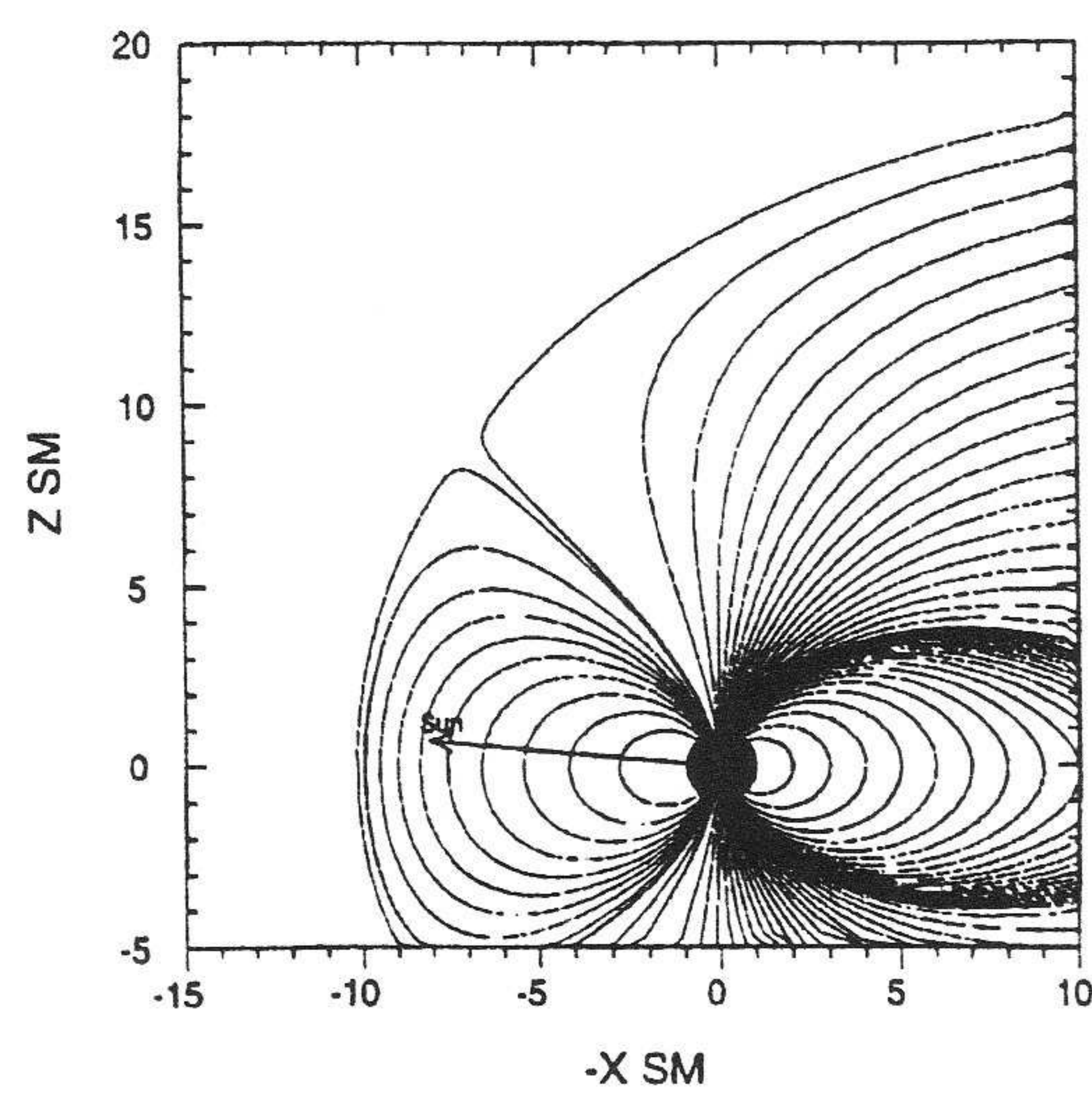


Figure 4: T87 magnetic field line map. Notice that the shape of the cusp and the magnetopause boundaries deduced from the model (see text) are given.

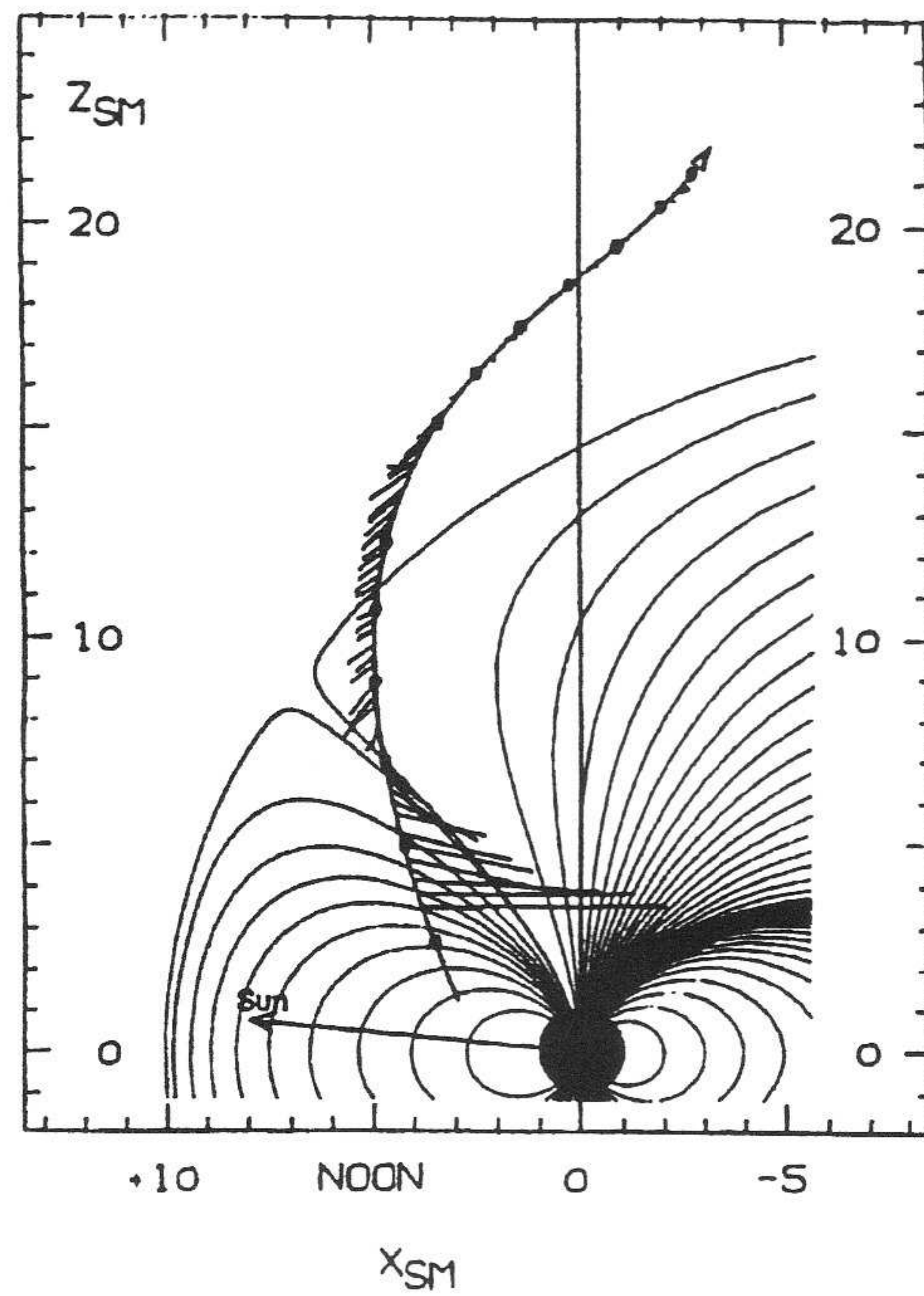
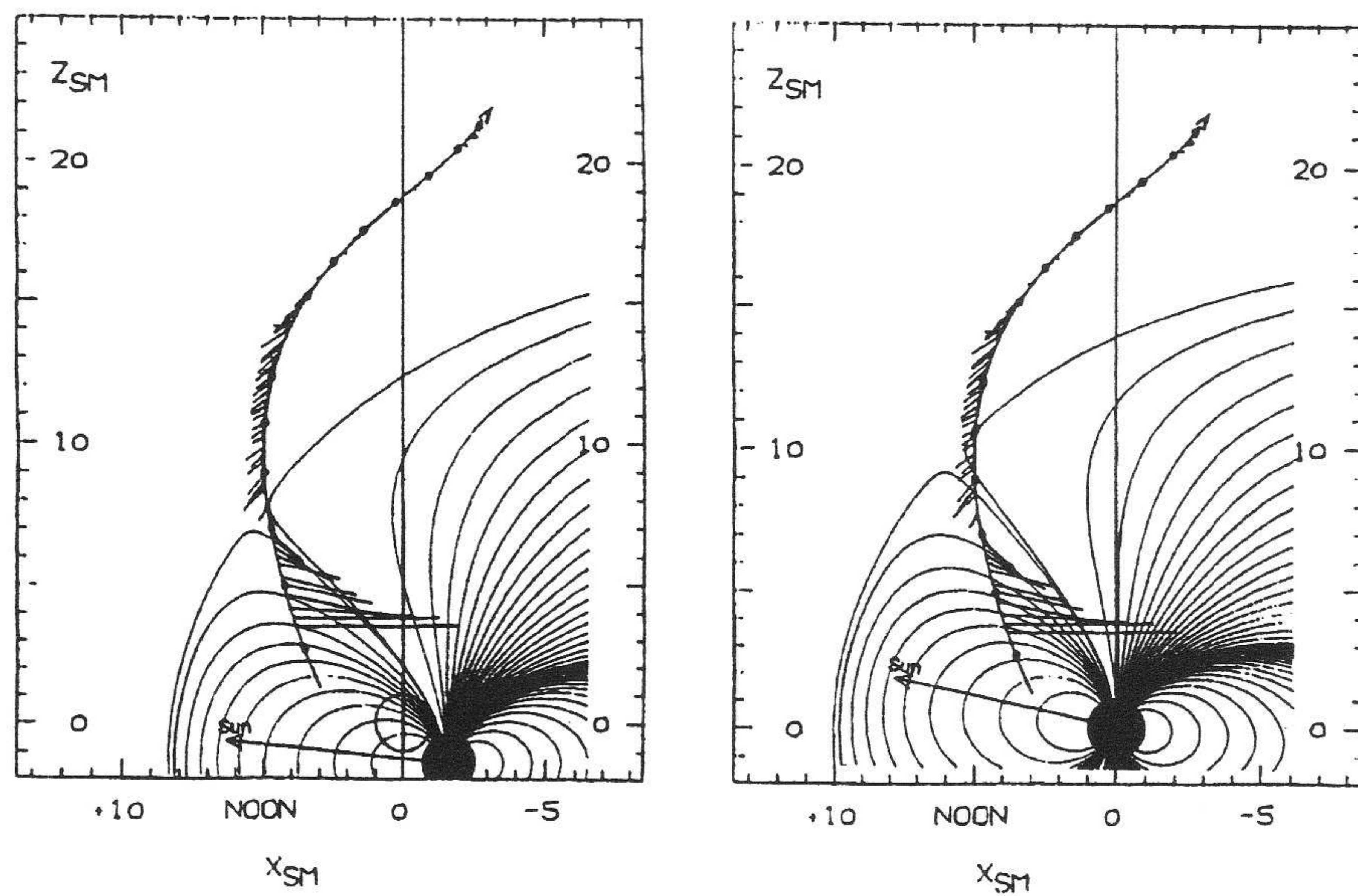


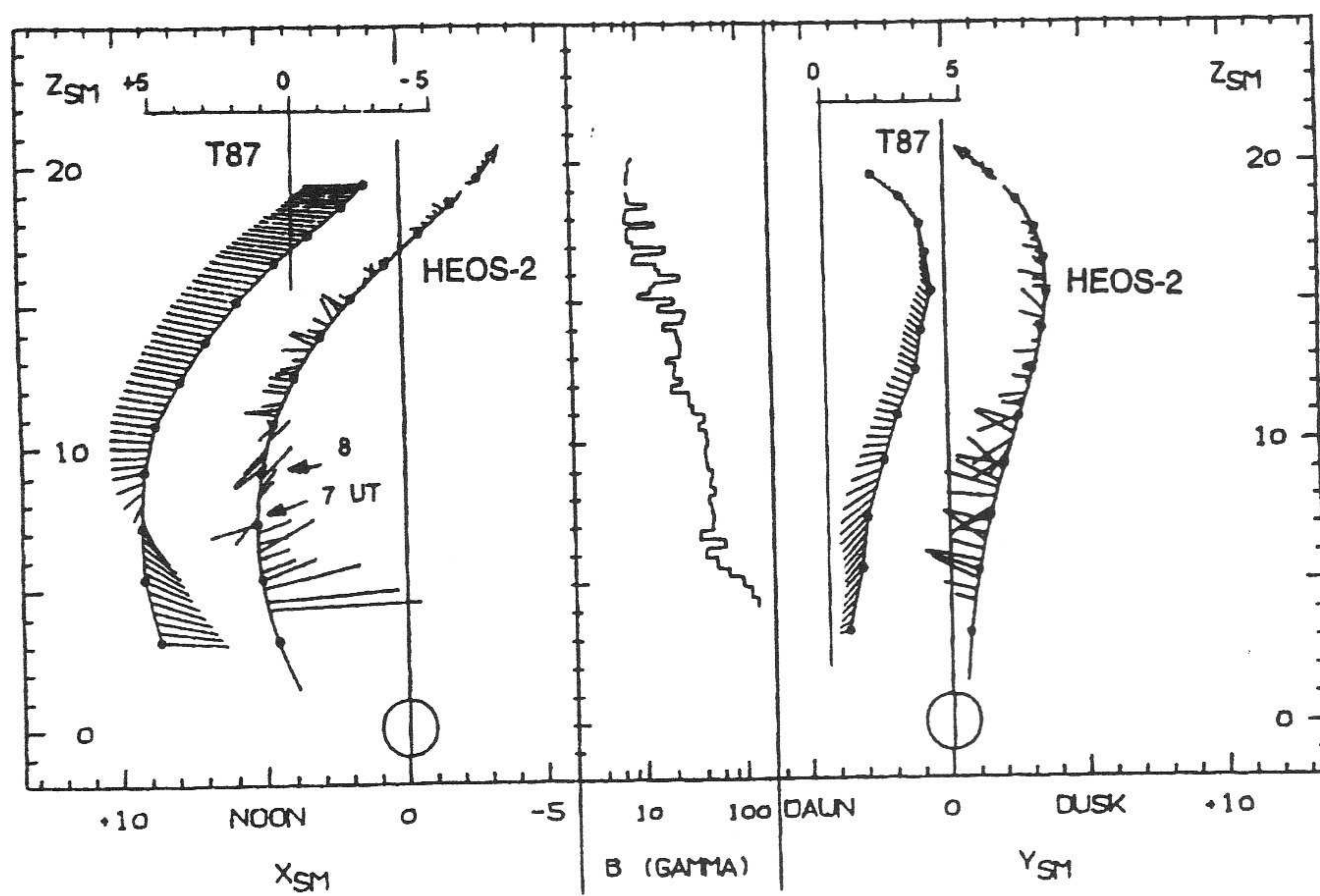
Figure 5: HEOS trajectory and observed magnetic field, plotted along this trajectory and superimposed on T87 field lines map.



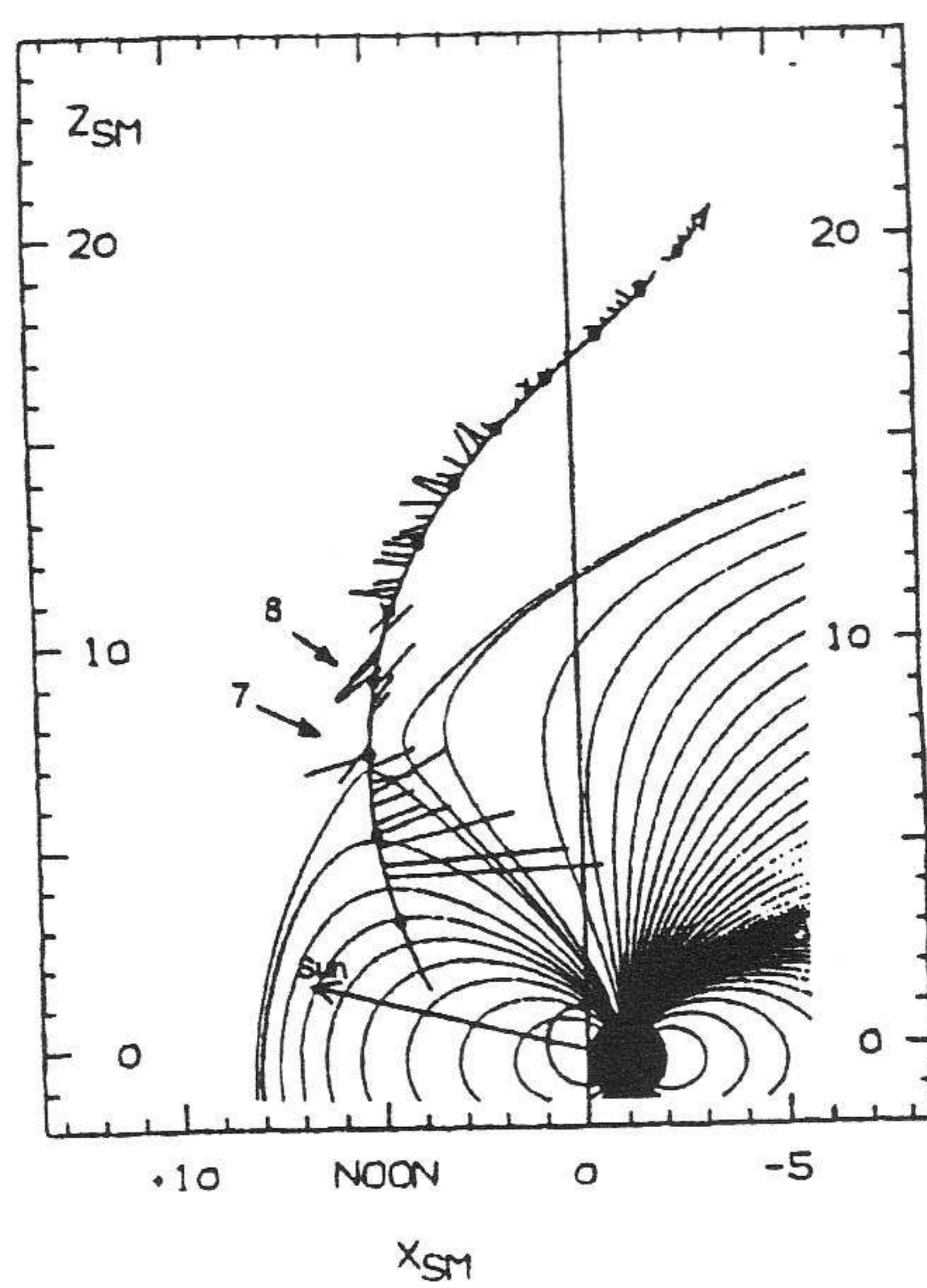
(a) Radial shift of T87 field line map

(b) Rotation of T87 field line map

Figure 6: Attempts to use the T87 model in figure 5 to force agreement with HEOS data.

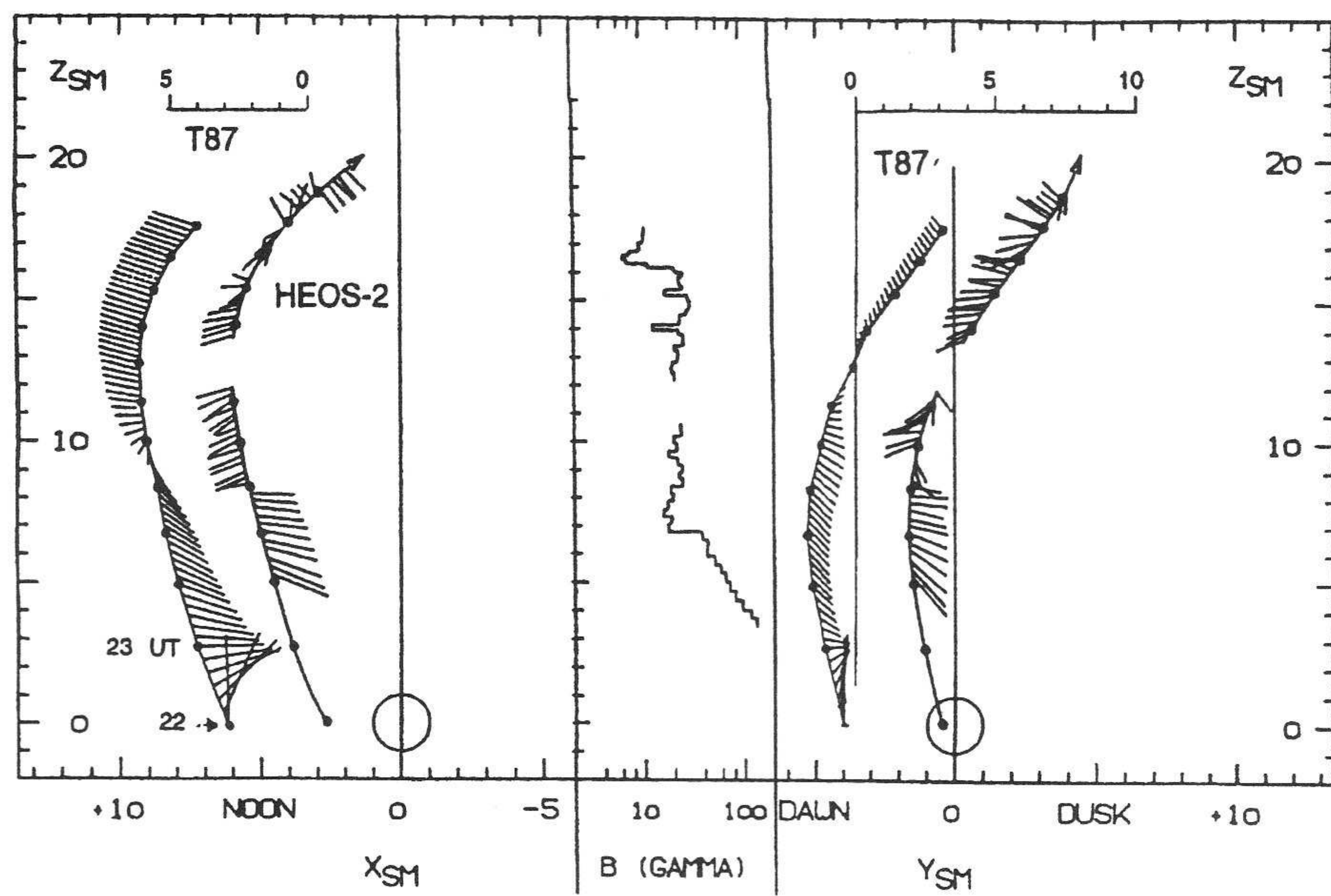


(a) Comparison between B field data along HEOS trajectory and T87 model

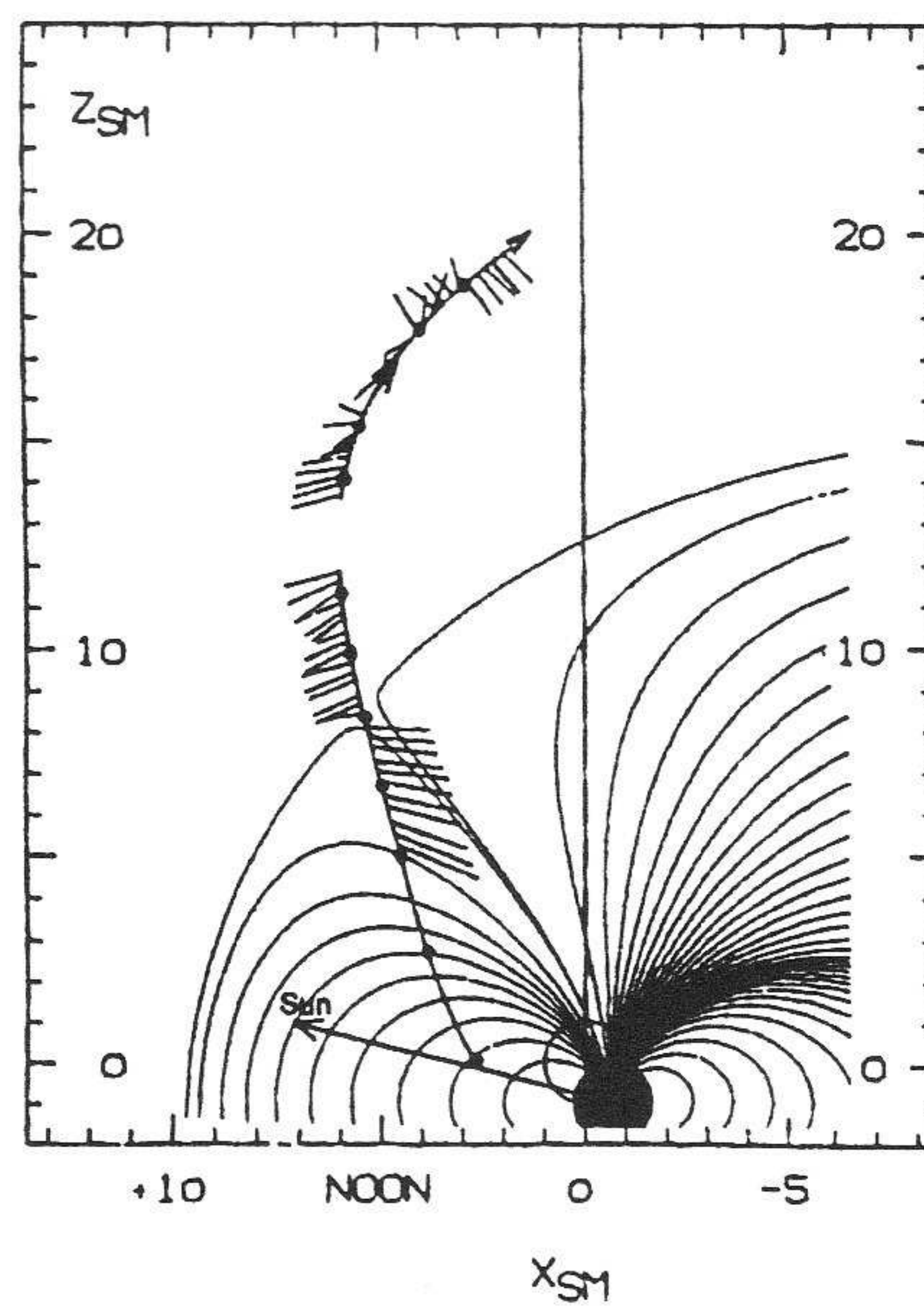


(b) B along HEOS trajectory and T87 magnetic field line map

Figure 7: June 18, 1973 event.

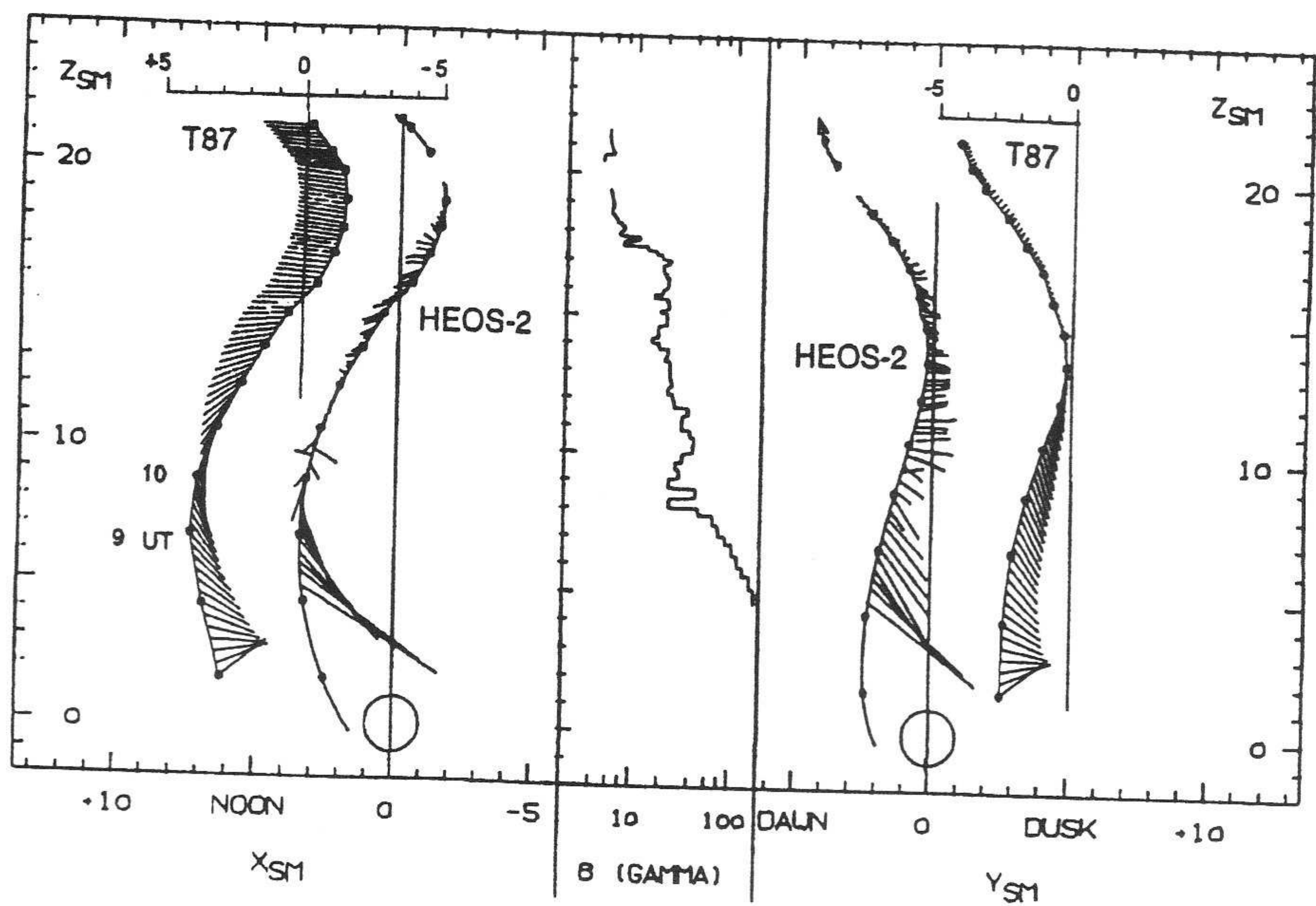


(a) Comparison between B field data along HEOS trajectory and T87 model

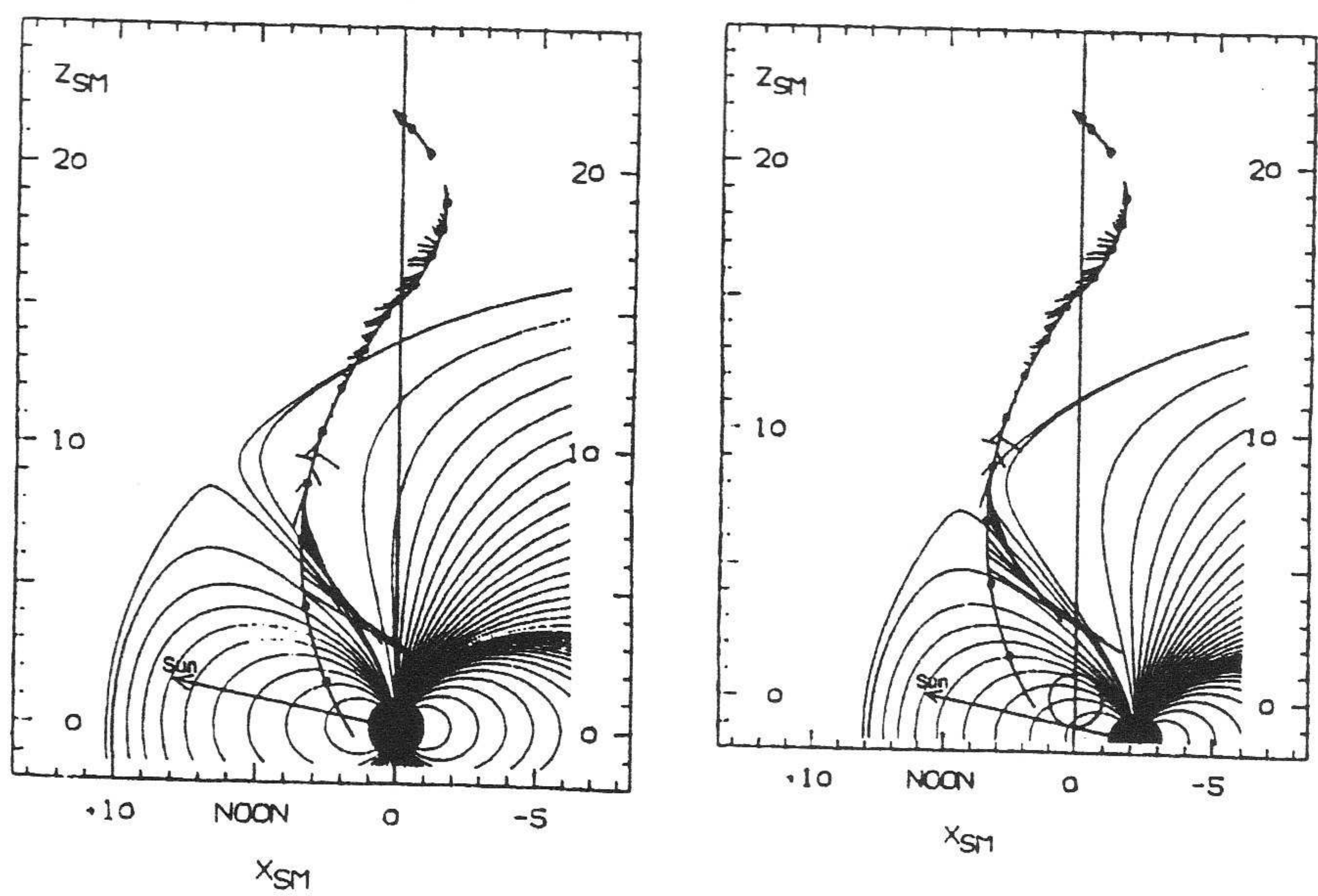


(b) B along HEOS trajectory and T87 magnetic field lines map

Figure 8: Same as figure 7 for the July 9, 1973 event.



(a) A good agreement between magnetic field direction from HEOS and from T87 model



(b) HEOS magnetic field along trajectory is not consistent with T87 field line map

(c) Consistency can be obtained by an arbitrary shift of the field map towards the Earth

Figure 9: Same as figure 7 for the August 14, 1973 event.

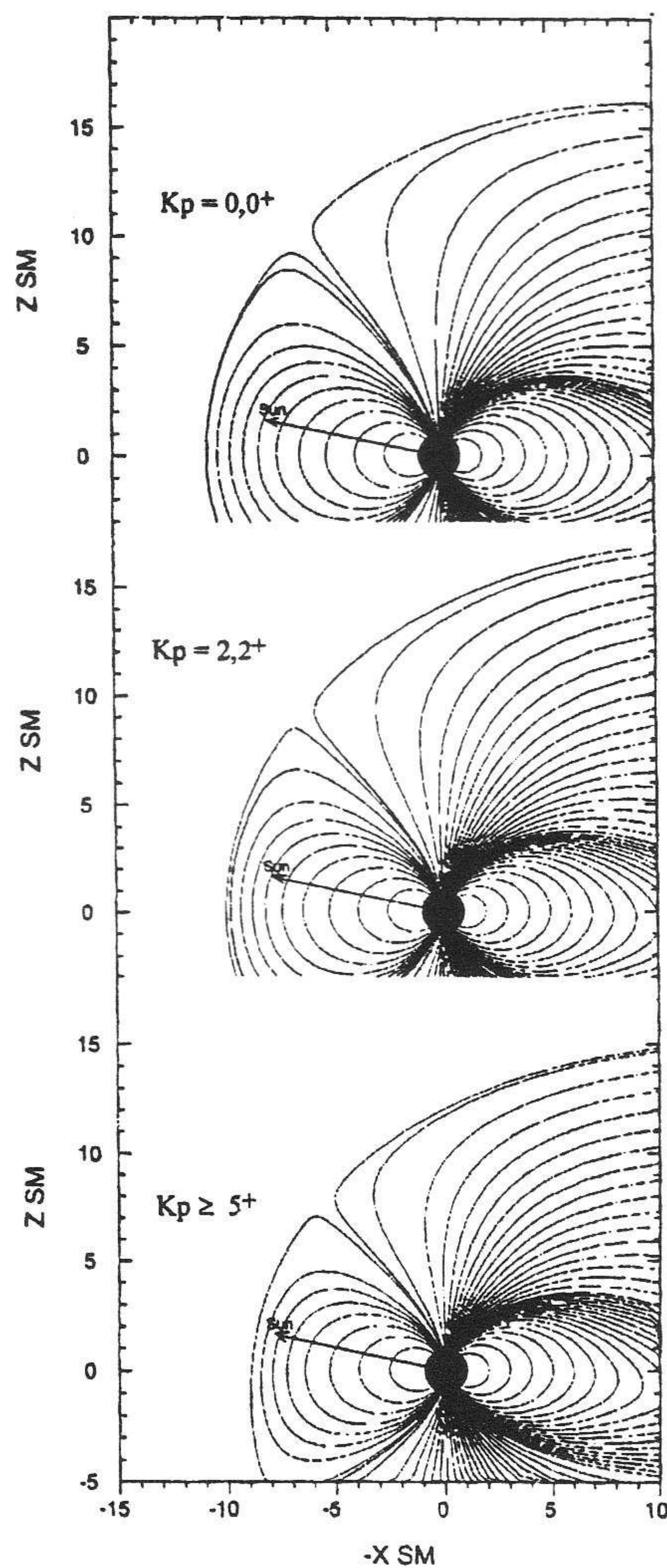


Figure 10: Variations of the location of the cusp deduced from T87 for various values of the K_p parameter (August 14, 1973).

Satellite - Ground Based Coordination Sourcebook

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Foreword

On 4th June 1996, the four identical satellites of the Cluster mission were lost when the Ariane 5 rocket veered off course and exploded at 3500 meters, 39 seconds into its maiden flight. This disaster was a devastating setback to the many scientists who had devoted so much effort and time to what was a revolutionary and highly significant mission. It was also a major setback for many other scientists around the globe who had hoped to make measurements from the ground in co-ordination with those by Cluster. To this end, an ESA working group chaired by H.J. Opgenoorth had put in place mechanisms to plan the co-ordinated measurements and to distribute summaries of the combined data quickly, so as to facilitate science exploitation and further operations planning. The working group met several times and held open workshops in Orleans and Rome. It drew together comprehensive information about the ground-based instruments, their capabilities and how to best use them in co-ordination with spacecraft. This book is a distillation of that information.

Cluster was a unique mission because it was to have made the first three-dimensional measurements in space. It was also one part of a co-ordinated attempt to measure the interactions of widely-spaced parts of the magnetosphere-ionosphere-thermosphere system and their coupled responses to variations in the interplanetary medium. These activities are organised in the USA under the title of the "International Solar-Terrestrial Program" (ISTP) and between the various national and multi-national space agencies by the "Inter-Agency Consultative Group" (IACG). Here we refer to these international collaborations as "ISTP/IACG".

Several major new facilities were constructed specifically to be ready for Cluster. A good example is the EISCAT Svalbard Radar (ESR) and the staff of the EISCAT Scientific Association are to be congratulated for their remarkable achievement in constructing this new incoherent scatter radar facility so quickly. Sadly, although the radar was ready for it, Cluster was destined not to reach its orbit. Nevertheless the ESR is an excellent research facility in its own right, especially when combined with the EISCAT radars in mainland Scandinavia. Other incoherent scatter radars making vital observations relevant to ISTP/IACG activities are at Søndrestrømfjord and Millstone Hill. In addition, two chains of coherent HF backscatter radars have been developed, one in each hemisphere. These are collectively called SuperDARN and will, for the first time, directly image the patterns of high-latitude convection with high time resolution. They will provide excellent complementary information to the networks of magnetometers detecting ionospheric currents. Images of the ionosphere, of unprecedented quality and time resolution, are now being obtained from new CCD optical cameras, imaging riometers and digital ionosondes. All of these facilities can, and will, be used in conjunction with the many ISTP/IACG satellites, as well as in co-ordination with each other. We have learned much about making such co-ordinated measurements from experience with past space missions such as Viking, CRRES, DMSP, Dynamics Explorer, IMP-8, SCATHA, ISEE, AMPTE, Freja and various geostationary satellites. At the time of writing, there is much activity to co-ordinate ground-based observations with newer satellites such as Interball, Geotail, Polar, Wind, SOHO and FAST and missions yet to be launched, for example Equator-S, ACE, IMAGE and, we very much hope, Cluster II.

At the time of writing, the future of a replacement mission for Cluster is not

decided. The fifth, spare, satellite has been made ready and could be flown as a single-craft mission, called Phoenix, with launch as early as the latter part of 1997. Although this meets some of the objectives of the ISTP/IACG multi-point comparisons (on spatial scales of tens and hundreds of Earth radii, R_E), it does not provide the three-dimensional measurements of Cluster by giving comparisons on spatial scales of less than one R_E . At its meeting in November 1996, ESA's Science Programme Committee agreed the principle of flying a replacement four-craft mission, probably making use of the flight spare with three new craft. This new space odyssey could be flown by the year 2001 if the national agencies are able to provide the necessary funds to re-build the instruments.

The ground-based community has, arguably, a unique perspective on the debate about how Cluster should be replaced. Because remote sensing can continuously monitor large parts of the coupled magnetosphere-ionosphere system at high time resolution (typically from 1 minute down to 1 second), scientists using ground-based instruments, collectively, have a strong sense of the importance of temporal variability. This cannot be gained from studying in-situ data from lone spacecraft which, although of higher precision, are subject to temporal/spatial ambiguities. Examples of phenomena to which this different view applies include substorms, auroral arcs, travelling convection vortices and poleward-moving auroral forms in the cusp/cleft region. As a result, scientists using ground-based data were highly enthusiastic about the four-craft Cluster concept and its ability to resolve some of the spatial-temporal ambiguities in the in-situ satellite data. Thus we strongly support the Cluster scientists in their attempts to replace the four-craft mission. Indeed, we know that we are not alone in believing that it would give such revolutionary and important measurements, that sooner or later such a mission will be flown: we very much hope it is possible in the near future, while the ground-based facilities discussed in this volume are still in place. In the meantime, the ground-based facilities are already turning their attention to co-ordination with the many other ISTP/IACG missions that are in orbit at the present time or are soon to be launched. The Cluster-Ground Based working group and contributors have found the activity so valuable that it had been agreed, long before the loss of Cluster, that it should be continued and expanded after the Cluster mission. This book should therefore provide a valuable source of information for scientists involved in both ground-based and satellite observations for a number of years to come.

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re: Cluster-ground based coordination source book

Dear Author,

Dr Robert

We are, at last, close to publishing what was the Cluster-Ground Based source book. After the dreadful events of 4 June, we have re-named it "Satellite-Ground Based Coordination Sourcebook". We are sorry about the delay, but we were not sure of the best way to respond after Cluster was lost.

Enclosed is a copy of the contents page, the foreword and a copy of your paper. You will find that we have made some minor corrections and editorial changes, so that papers are consistent with each other, as far as is possible. Specifically, Hermann and I have made some small changes, based on the referees' reports (any more major changes were discussed with the relevant author), and the style and grammar has been standardised with the help of the ESA publications department. We have also, where appropriate, reduced the emphasis on Cluster, such that we refer to satellites in general (except where the multi-point nature of Cluster was important for the proposed coordinated studies). The foreword introduces ISTP and IACG - this is important as in many places we replaced "Cluster satellites" with "ISTP/IACG satellites". Please look over your paper carefully and let us know immediately if you want anything changed. We certainly would like to keep this to minor changes to avoid any further delay. We hope to send the whole electronic journal to ESA, so that production can begin, in mid-January.

Thank you all very much for your contributions. Having read every paper carefully over the last few weeks, I can tell you that together they form an outstanding set. Meanwhile, have a very happy Christmas and all the best for 1997. Hopefully we will hear in February that Cluster II will go ahead.

Best Regards,

Mike
Prof. Michael Lockwood
Space Science Department