Discovering the Low-Latitude Ionospheric Trough Associated With the Inner Radiation Belt

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Research Article

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Abstract

The dynamics of ionospheric troughs during great geomagnetic storm on April 11–13, 2001 is considered. An analysis is based on measurements of electron density at altitudes of the CHAMP satellite 410–465 km. The subauroral, mid-latitude and low-latitude troughs were observed at nighttime, sometimes simultaneously. The subauroral trough is usually defined as the main ionospheric trough. The mid-latitude trough is associated with the magnetospheric ring current. It appears at the beginning of the storm recovery phase at latitudes of 40–45° GMLat ($L=1.7–2.0$) and exists for a long time at the late recovery phase at latitudes of the residual ring current 50–55° GMLat ($L\sim 2.4–3.0$). The low-latitude trough was revealed for the first time. It is developed at the latitudes of the inner radiation belt 34–45° GMLat ($L=1.45–2.00$). This trough is associated with the precipitation of energetic particles from the inner radiation belt.

Introduction

The dynamics of ionization trough is an important manifestation of a magnetospheric storm in the ionosphere¹. An ionization trough is usually understood as the main ionospheric trough, MIT. However, during the storm recovery phase, usually at night, another trough is formed, the so-called ring ionospheric trough, RIT. It is associated with the process of hot ions precipitation from the magnetospheric ring current during its decay^{2,3,4}. The RIT has been first separated from the MIT as a distinct structure according to the Kosmos-1809 data⁴ and was in detail studied from the Intercosmos-19, Kosmos-900 and CHAMP satellites data^{2,5,6,7,8}. Paradoxically, the RIT formation mechanism has been developed long ago, in the 70's to explain the red subauroral arc, SAR-arc^{9,10} and later refined to explain the SAR-arc related ionospheric trough³. At the maximum of a severe storm, the MIT appears at extremely low latitude. According to the data of the Millstone Hill radar for 18 MLT during the magnetic storm on February 8, 1986, the trough was recorded at latitude of 45° GMLat¹¹. Since the RIT is observed equatorward of the MIT, it can appear at lower latitude, up to 40° GMLat. However, sometimes, the ionospheric trough can be a joint, inseparable structure of the MIT and RIT. As the storm recovery phase develops, the MIT returns to quiet latitudes $> 60^\circ$ GMLat, and the RIT can be observed for a long time at typical latitudes of the residual magnetospheric ring current 54–56°. Besides, the analysis of strong storms based on the CHAMP satellite data showed the existence of another, third trough at very low latitudes of 35–45°. These are the latitudes of the inner radiation belt (IRB) $L=1.5–2.0$. All three troughs are sometimes observed simultaneously. In this paper the dynamics of all troughs, the MIT, RIT and low-latitude trough (LLT) during the magnetospheric storm on April 11–13, 2001 is analyzed.

Observation Data

The analysis is based on the data of the CHAMP satellite for high solar activity, obtained in 2000–2002. At high solar activity, the magnetospheric storms follow one another. Therefore, the data set for analysis is large; over 40 strong geomagnetic storms. The paper presents a detailed analysis of the troughs

dynamics for the severe storm on April 11–13, 2001. The satellite carried out *insitu* measurements of electron density N_e . Variations in N_e are presented below in terms of plasma frequency f_p ($N_e(\text{cm}^{-3}) = 1.24 \cdot 10^4 f_p^2(\text{MHz})$). The CHAMP altitude has changed from 2000 to 2002 from 465 km to 410 km, which is close to the height of the F_2 layer maximum. It revolved on nearly polar orbit with the inclination of 87.3° . The CHAMP data time resolution of 15 s is less than 1° of latitude, which allows determining the position of trough with enough accuracy. The CHAMP satellite data are available on the website:

<http://op.gfz-potsdam.de/champ>.

Dynamics of troughs during the storm on April 11-13, 2001

The storm on April 11–13, 2001 was extremely strong: the Kp-index reached 8+, and Dst was -271 nT. Figure 1 shows variations in the position of ionospheric troughs for ~ 1.5 LT in the Northern hemisphere and ~ 2.1 LT in the Southern hemisphere. For the discussion convenience, the time is counted from 00 UT on April 11. Variations in the Kp-index are related to the variations in the MIT position (black circles) according to the model¹². This model takes into account the changes in the MIT position with Kp and local time. The recently revealed dependence on the hemisphere¹³, has been considered, too. In Fig. 1 the MIT in the Southern hemisphere is on average at $\sim 3^\circ$ equatorward than in the Northern hemisphere, just because of the difference in local time and the hemispheres asymmetry. The variations in the Kp-index are shifted to the right, since a delay in the trough response in both hemispheres is about 2.0 h. This delay depends on the growth rate of geomagnetic activity at the main phase of the storm¹². Considering this delay, the variations in the MIT position quite clearly follow of variations in the Kp-index. The deviations from the model are mainly related to the longitudinal effect. For example, in the Northern hemisphere at the initial phase of the storm (08–13 UT), the trough turned out at lower latitudes, and during the periods of 26–32 UT and 50–54 UT it was at higher latitudes than according to the model, just due to the longitudinal effect. An updated model of the longitudinal effect for both hemispheres and all hours of local time is presented in study¹⁴. During the storm maximum, the MIT in both hemispheres is located at extremely low latitudes $44\text{--}46^\circ$, as should be expected.

The ring ionospheric trough (blue squares) appears in the Northern hemisphere during the main phase of the storm a few degrees equatorward of the MIT. In this case, the RIT was formed as a separate trough from the MIT, which is clearly seen in the latitudinal cross-section of f_p for satellite pass 30 in Fig. 2. Then the RIT on several passes was recorded as a weak decrease in the electron density (not shown) and was most clearly expressed on pass 18 on April 12. Then the RIT is manifested as a knee on a steep decline in the electron density on several more passes (20, 22, and 28 in Fig. 2), but only on pass 20 pronounced knee is marked in Fig. 1 as a trough. Note in this regard, that on a very steep slope of the electron density, it is difficult to detect a shallow trough. As the deep f_p minimum, the RIT was again recorded on pass 4 on April 13. The RIT was last time recorded in the Northern hemisphere on pass 20 on April 13 after another increase in geomagnetic activity. It can be seen from Fig. 1 that the RIT, as well as the MIT, in general, tracks variations in the Kp-index.

On pass 30 on April 11, the shallow minimum of electron density is observed in the Northern hemisphere at very low latitude of $\sim 35^\circ$. This minimum was clearly manifested on pass 2 on April 12, so that only it is marked in Fig. 1 as a trough at latitude of $\sim 34^\circ$ ($L \sim 1.45$). However, the low-latitude trough was especially pronounced on pass 18, which is shown in Fig. 2 as an example. This example is unique, since all three troughs were extremely expressed: the MIT, RIT, and LLT. The cases of simultaneous observation of three troughs are marked in Fig. 1 by vertical lines. On pass 18, the LLT was observed at latitude of 36° . The formation of three troughs, although not on each satellite pass, suggests the presence of three branches of the trough. In Fig. 1 they are marked by thin lines. In the Northern hemisphere, the LLT was also clearly visible on next pass 20, and on pass 18 on April 13 after another increase in geomagnetic activity. On remaining passes, the LLT was recorded as a shallow minimum of electron density, which can be easily missed during the analysis, if not to consider the situation holistically and in the dynamics. Note, that the LLT also tracks changes in the geomagnetic activity.

In the Southern hemisphere, the situation is similar. All relatively large ($2-3^\circ$) the MIT position deviations from the model are associated with the longitudinal effect (Karpachev et al., 2018). And since the character of the longitudinal effect differs in the Northern and Southern hemispheres, this leads to rather strong asymmetry in the MIT position.

The RIT in the Southern hemisphere appears at the maximum of the storm main phase. On pass 5 it is deeper than the MIT, as seen in Fig. 2. On next passes, the RIT is weakly expressed, including pass 19, where the RIT and MIT are in fact, representing a joined structure. On pass 21, the RIT appeared as a narrow and deep trough. On passes 23 and 25, there is an inflection in the latitudinal variations of fp just at the assumed latitude of the RIT. However, these cases are not marked in Fig. 1 as the troughs. On pass 7 on April 13, deep RIT seems to mask the MIT, whose position can be approximated by the base of steep polar wall. Finally, on pass 11 on April 13, the position of the higher-latitude trough is more likely to correspond to the MIT, as reflected in Fig. 1.

A well defined low-latitude trough in the Southern hemisphere appeared on pass 7 at latitude of -33.5° also in the beginning of the storm recovery phase. The LLT is more pronounced in the Southern hemisphere than in the Northern hemisphere, especially on passes 23 and 25 on April 12 and pass 21 on April 13, after increased geomagnetic activity. In the Southern hemisphere, three troughs simultaneously were most clearly recorded on pass 21 on April 12. The LLT position is subject to the magnetic activity changes, as it is in the Northern hemisphere.

It can be seen from Fig. 1 that the RIT and LLT are in general better conjugated than the MIT. The non-conjugacy of the MIT is associated with a hemispheric asymmetry, and strong dependence on local time and longitude, as noted above.

Figure 3 illustrates the aforesaid. It shows the entire latitudinal fp profile in terms of geographical latitude for the 18/19 passes in the Northern and Southern hemispheres, respectively. In the Northern hemisphere, there are three most extensive troughs (LLT, RIT, and MIT) at geomagnetic latitudes of 37.2° , 45° , and 55° . In the Southern hemisphere, the LLT is located at latitude of 40° , i.e. the non-conjugation is 2.8° . The

structure with two minima is observed poleward of LLT. The left minimum at latitude of -53.8° corresponds to the MIT, the discrepancy with the Northern hemisphere in this case being small, 1.2° . The right minimum at latitude of -50° seems to correspond to the RIT, which is 5° poleward than in the Northern hemisphere, possibly due to the formation of a wide f_p peak at latitudes equatorward of the LLT.

Discussion

During a geomagnetic storm, the strong asymmetric ring current is formed in the night sector of the magnetosphere¹⁶. It mainly consists of ions with energies of 10–100 KeV. The RIT is developed as a result of hot ions precipitation from the magnetospheric ring current during its decay at the recovery phase of the storm³. The precipitation occurs when hot ions interact with the cold particles of the plasmasphere. During the recovery phase, the plasmasphere fills up and expands gradually. Therefore, the decay process is most intense in the outer part of the plasmasphere, i.e., in relatively narrow latitude belt. The precipitating ions heat the thermosphere, its temperature rises, the recombination increases, and an ionization trough is formed.

During the great storm ($Dst < -300$ nT), the equatorward edge of the ring current reaches $L \sim 1.7$, i.e. the geomagnetic latitude of $\sim 40^\circ$ ¹⁷. This is extremely low latitude for the RIT at the maximum of the main phase or the beginning of the recovery phase of the storm. As the recovery phase develops, the plasmasphere expands, and the equatorward edge of the ring current, due to its decay, also moves to the larger L-shells. At the late stage of the recovery phase, the ions precipitation from the region of the residual ring current is observed for a long time at $L \sim 2.7-4.0$ ($52-60^\circ$)¹⁸. The RIT is most often observed at latitudes of $54-56^\circ$. Thus, the region of the RIT existence is located in the latitude belt from 40° to 60° ($L \sim 1.7-4.0$).

The magnetospheric ring current is located in the region of quasi-trapped particle population; the lower the height of the mirror point in the atmosphere, the more intense the ions precipitation is. The height of the mirror point depends on the geomagnetic field magnitude. The magnitude, in its turn, strongly depends on longitude. Thus, we can assume that the RIT behavior should also depend on longitude. In Fig. 1 in the Southern hemisphere, bold lines indicate longitudes of $270-360-45^\circ$ with low geomagnetic field magnitudes. It can be seen, that the RIT is actually formed mainly at longitudes where the geomagnetic field is weak. It appeared just at the latitude of $\sim 40^\circ$ and was observed for a long time at the latitude of $\sim 54^\circ$ at the late stage of the storm recovery phase. In the Northern hemisphere, the longitudes with reduced geomagnetic field magnitudes are almost the same as in the Southern hemisphere. However, in absolute values, they are much larger than the ones in the Southern hemisphere. Therefore, being oscillate along the magnetic field line and drift around the Earth, all the particles should be precipitated in the Southern hemisphere at longitudes with low geomagnetic field magnitudes¹⁹. However, as seen in Fig. 1, the RIT in the Northern hemisphere was most frequently recorded in the period of 47–55 UT, just at the longitudes marked by a bold line. In this regard, it should be noted that in the same work Berg found that the intensity of proton fluxes in the Northern hemisphere is not directly related to local

longitude of observation. In addition, longitudinal effect decreased sharply when the geomagnetic activity increased.

The latitudes from 34° to 45° ($L \sim 1.45-2.00$), where the LLP is observed, refer to the region of the inner radiation belt (IRB). It is usually populated by trapped protons with energies of 20–500 MeV and occupies the region just up to $L \sim 2$, with a maximum at $L = 1.5$. During a magnetic storm, the fluxes of energetic protons and electrons increase sharply (by 1-3 orders of magnitude), apparently due to radial diffusion from higher L-shells^{20,21,22,23}. These increases are also observed during the storm recovery phase. The latitudinal cross-section of the energetic particles fluxes during a storm has the complex structure, it consists of several peaks. During various storms, the KORONAS, SERVICE-1, ACTIVE satellites and MIR station recorded peaks in proton and electron fluxes at $L \sim 1.1, 1.4, 1.5, 1.7, 1.8, 1.9, 2.1, 2.2$ ^{15,22,24,25}. These peaks are quasi-stationary time-wise, but change their position in latitude. The fluxes of the trapped particles are associated with very intense precipitation of energetic particles during great geomagnetic storms^{26,27,28}.

The quasi-trapped energetic particles precipitate into the ionosphere as a result of pitch-angular diffusion. The diffusion is caused by recharge on neutral hydrogen, scattering on magnetic field irregularities, and ion-cyclotron waves^{23,29}. In addition to the direct ionization effect, the enhanced particle precipitation causes an increase in the ionospheric conductivity at the heights of E layer, growth of the conductivity gradients and, subsequently, a generation of strong local electric fields, that are capable of producing strong upward/downward drifts of highly ionized plasma^{21,30,31}. In case of sudden changes in the Bz IMF, rapid penetration of the interplanetary electric field is also observed at low latitudes³².

Depending on the direction of the electric field, the drift is either upwards or downwards. This can lead to either increase or decrease in the ionospheric plasma density. Ion density enhancements in the topside low-latitude ionosphere during the Bastille storm on 15–16 July 2000 and Halloween storms on 29–31 October 2003 were recorded using data from ROCSAT-1/IPEI experiment²¹. Prominent ion density enhancements demonstrate similar temporal dynamics both in the sunlit and in the night-side hemispheres. The ion density increases dramatically (up to two orders of magnitude) during the geomagnetic storms. The density enhancements are mostly localized in the region of the South Atlantic Anomaly (SAA), which is characterized by very intense fluxes of energetic particles. These fluxes were investigated using SAMPEX/LEICA data on >0.6 MeV electrons and >0.8 MeV protons at around 600 km altitude. During the magnetic storms, the energetic particle fluxes in the SAA region and in its vicinity increase more than by three orders of magnitude.

An analysis of the ion temperature and drift velocity in the SAA region shows that the ion enhancements are accompanied by the enhanced temperature³³. Plasma heating leads to an increase in recombination at the heights of the F layer, and to density depletion. Thus, the processes occurring at the IRB latitudes can lead to the formation of ionization peaks and the development of troughs. Since in study²¹ sharp increases in the ion density were found and attributed to the electron precipitation, the Fig.1 was carefully

analyzed to determine whether the structures on the latitudinal f_p profiles are peaks or troughs. And yet, the clearly defined structures on passes 18 and 20 in the Northern hemisphere and 7, 23, 25 on April 12 and 21 on April 13 in the Southern hemisphere speak in favor of ionization troughs.

The mirror points for quasi-trapped particles of the inner radiation belt, as well as for the ring current, depend on geomagnetic field magnitude. They fall most low in the SAA region. Accordingly, when particles drift around the Earth, the L-shell is rapidly emptied at the longitudes and latitudes of this anomaly. Therefore, the majority of the phenomena associated with precipitation of energetic particles from IRB: an increase in plasma density, in ion temperature, atmospheric glows, etc. are most often observed in the SAA region. However, particle precipitation from radiation belts and the related phenomena are recorded at other longitudes, too^{24,25,33,34}. Fig. 1 illustrates that the most pronounced LLT were observed at longitudes with high magnetic field magnitudes, for example, at passes 19–25 in the Southern hemisphere. Thus, the dependence of the appearance of RIT and LLT on longitude is rather statistical. This issue will be conveyed in the next paper.

Conclusions

1. The main result of this study is, certainly, the discovery of LLP at IRB latitudes. The consequence is a surprising opportunity to sometimes observe all three troughs simultaneously, as on pass 18 on April 12 in the Northern hemisphere. In other words, we have three branches of trough: subauroral, mid-latitude, and low-latitude.
2. The MIT is usually understood as a trough that is located equatorward of the auroral oval, i.e. it is a subauroral trough by definition^{13,35}. This trough tracks, with a certain delay, the variations in the Kp-index according to the MIT model. The delay in the MIT response is determined by the growth rate of geomagnetic activity: the higher the rate, the greater the delay is¹². The MIT has been studied repeatedly, but there are still unclear questions. For example, it still remains unknown why the MIT in the Southern hemisphere is, on average, somewhat more equatorward than in the Northern hemisphere, as can be seen in Fig. 1.
3. The second trough, being located equatorward of MIT, is a mid-latitude trough. The RIT characteristics are also quite well-researched in a series of studies cited in Introduction. It was shown that the RIT is formed at the initial stage of recovery phase of a severe storm at latitudes of 40–45° and, at the late stage of recovery phase, it tends to the latitudes of the residual ring current 54–56°. The RIT is most often observed in the morning, during the recovery phase of even a small disturbance. The RIT and MIT separation is quite challenging though, when they are most likely to form a joined structure, as on pass 19 on April 12 and 7 on April 13 in the Southern hemisphere.
4. The third, low-latitude trough is located at the IRB latitudes of 34–45°. It appears to be formed only during a severe magnetic storm. At least, it has not been revealed in quiet conditions. There is no doubt that LLT is associated with precipitation of energetic particles from the IRB. This precipitation increases

drastically during a storm, including its recovery phase. There is reason to believe that they lead to an increase in the ionospheric conductivity in layer E and, accordingly, to variations in the vertical drift velocity. This, in turn, leads to a redistribution of the ionospheric plasma, which can manifest itself as the peak or trough of ionization. Additionally, the electric fields of magnetospheric origin and heating of the atmosphere can be affected, leading to an increase in recombination and plasma depletion. These qualitative assumptions, however, should be supported by quantitative simulation.

Declarations

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Competing interest: No

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Figures

Figure 1

Variations in the position of troughs in the Northern hemisphere for 1.5 LT and in the Southern hemisphere for 2.1 LT. The MITs are indicated by black circles, RITs by blue squares, and LLTs by red triangles. UT time is counted from 00 UT on April 11. The numbers of characteristic passes are marked. The longitudes with low geomagnetic field magnitudes in the Southern hemisphere are marked by bold blue lines.

Figure 2

Latitudinal f_p variations on satellite passes marked in Fig. 1. The minima of troughs are marked by the corresponding symbols.

Figure 3

Latitudinal f_p cross-section on orbits 18 in the Northern hemisphere and 19 in the Southern hemisphere. The inset shows the latitudinal profiles of proton fluxes recorded during and after the double storm on November 7–8 and 9–10, 2004 with Dst -370 nT and -290 nT, respectively. Measurements were carried out on board the CORONAS satellite at altitude of 500 km¹⁵.