The north-south asymmetry of Martian ionosphere and thermosphere

Huijun Le[1], Libo Liu[2], Yiding Chen[1], and Hui Zhang[1]

[1]Institute of Geology and Geophysics, Chinese Academy of Sciences
[2]Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences

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Abstract

Based on the data of Maven's NGISM neutral composition and Langmuir probe electron density and temperature, we statistically analyzed the climatic variations of the Martian thermosphere and ionosphere, and found significant north-south asymmetry. In winter and summer, it mainly comes from the north-south asymmetry of solar zenith Angle. The observational data still show significant north-south asymmetry in equinox seasons. Under low solar EUV radiation, the thermosphere density in the northern hemisphere is higher than that in the southern hemisphere. With solar radiation increase, the thermosphere density in the southern hemisphere gradually exceeds that in the northern hemisphere. In addition, the southern hemisphere increases non-linearly with the increase of solar radiation, while the northern hemisphere increases linearly. The electron density in Martian ionosphere also shows significant north-south asymmetry in seasons. The electron density in the southern hemisphere is higher than that in the northern, and the electron temperature in the southern hemisphere is lower than that in the northern. The asymmetries in the ionosphere and thermosphere between the northern and southern hemispheres are likely related to significant differences in Mars' north-south topography or to north-south asymmetries in the residual magnetic field. After preliminary analysis, we found that the north-south asymmetry of Mars' remaining magnetic field would intensify the hemispheric asymmetry of the ionospheric electron density, but have no effect on the thermospheric neutral density. The hemispheric asymmetry may be mainly related to the significant difference in Mars' north-south topography.

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Huijun Le[1,2,3,4], Libo Liu[1,2,3,4], Yiding Chen[1,2,3,4], Hui Zhang[1,2,3,4]

[1] Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China

[2] Institutions of Earth Science, Chinese Academy of Sciences

[3] Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China

[4] College of Earth and Planetary Sciences, University of the Chinese Academy of Sciences, Beijing 100049, China

Corresponding author: Huijun Le (lehj@mail.iggcas.ac.cn)

Key Points:

- Significant hemisphere asymmetry of thermosphere neutral density and ionosphere electron density
- The hemisphere asymmetry depends on solar EUV radiation flux
- The hemisphere asymmetry might be mainly related to the martian topography.

Abstract:

Based on the data of Maven's NGISM neutral composition and Langmuir probe electron density and temperature, we statistically analyzed the climatic variations of the Martian thermosphere and ionosphere, and found significant north-south asymmetry. In winter and summer, it mainly comes from the north-south asymmetry of solar zenith Angle. The observational data still show significant north-south asymmetry in equinox seasons. Under low solar EUV radiation, the thermosphere density in the northern hemisphere is higher than that in the southern hemisphere. With solar radiation increase, the thermosphere density in the southern hemisphere gradually exceeds that in the northern hemisphere. In addition, the southern hemisphere increases non-linearly with the increase of solar radiation, while the northern hemisphere increases linearly. The electron density in Martian ionosphere also shows significant north-south asymmetry in seasons. The electron density in the southern hemisphere is higher than that in the northern, and the electron temperature in the southern hemisphere is lower than that in the northern. The asymmetries in the ionosphere and thermosphere between the northern and southern hemispheres are likely related to significant differences in Mars' north-south topography or to north-south asymmetries in the residual magnetic field. After preliminary analysis, we found that the north-south asymmetry of Mars' remaining magnetic field would intensify the hemispheric asymmetry of the ionospheric electron density, but have no effect on the thermospheric neutral density. The hemispheric asymmetry may be mainly related to the significant difference in Mars' north-south topography.

1. Introduction

The structure and dynamics of the Martian atmosphere including lower atmosphere and ionosphere is important for Mars exploration and understanding the fundamental processes that sustain and drive various changes in the Martian atmosphere. The martian ionosphere is also an important source of atmosphere escape. Thus the Martian ionosphere has always been a focus of planetary scientists since the era of space exploration. From Mariner 4 in the 1960s through Mars Express, MAVEN in the 2010s, and Tianwen in the 2020s (Kliore et al. 1965; Gurnett et al., 2008, Mahaffy et al., 2015), the Martian ionosphere has received numerous observations. Based on the observations, We also have a basic understanding of the Martian ionosphere. The Martian ionosphere is thought to be dominated by photochemical processes below 180-200km, and above this height is more complex, with dynamics and transport processes becoming increasingly important (Gurnett et al., 2010; Mendillo et al., 2011, 2013; Haider et al., 2011; Mahaffy et al., 2015). The Martian thermosphere is thought to be strongly influenced by lower atmosphere via tides, planetary waves, gravitational waves, and dust storms (Haider et al., 2014). It is also coupling with the exosphere through solar radiation and solar wind particles (Bougher et al., 2008, 2014; Krymskii et al., 2004).

It is well known that the terrain of Mars has a very significant north-south difference, and overall the southern hemisphere is flat, lower above Mars datum, and a lowest basin, with an altitude of -8.2 km. And the northern hemisphere has many mountains, the highest reaches 21.2 km. The large north-south differences in Mars' topography may have resulted in hemispheric differences in the wave processes in the lower atmosphere that interact with the upper atmosphere to produce hemispheric differences in the upper atmosphere. In addition, we already know that Martian dynamo stopped about 4 billion years ago. So Mars doesn't have a similar polar magnetic field like the earth. But Mars still has some rock residual magnetic field. MGS and Maven's magnetic field observations suggest that the residual magnetic field of the Martian rock has a strong north-south hemisphere difference (). Martian ionosphere can be influenced and controlled by the rock residual magnetic field (Ness et al., 2000; Nielsen et al., 2007; Shane et al., 2016; Flynn et al., 2017)

In this study, we focus for the first time on the hemisphere asymmetry of the Martian upper atmosphere including the thermospheric neutral gas and ionospheric plasma. And try to find what is the main cause for the significant hemisphere asymmetry.

2. Observations

In this study, the thermosphere and ionosphere measurements from MAVEN (Mars Atmospheric and Volatile EvolutioN) mission would be used to investigated the spatial and temporal variations of the thermosphere and ionosphere. MAVEN is the first spacecraft for direct measurements of the Martian atmosphere. MAVEN also can reach an lowest height of 130 km above the planet to sample Mars' upper atmosphere. MAVEN mission was lunched on November 18, 2013, reached the Martian orbit on September 22, 2014, and then achieve the scientific measurement data on October 2014. So far, MAVEN has been collecting data from the orbit of Mars for more than six years (2015-2020) to help us understand the evolution of the planet climate and weather.

The Neutral Gas and Ion Mass Spectrometer (NGIMS) is designed to measure ambient densities of both the thermal neutrals and ions in the Martian upper atmosphere (Mahaffy et al., 2015b). Here we analyzed the data of CO and CO2 number density from 160 km to 200 km. In order to avoid potential adhesive contamination (), only the inboard data are used. At the same time, the electron density and electron temperature derived from MAVEN Langmuir Probe and Waves (LPW) instrument (Andersson et al., 2015) are employed to analyze the ionospheric variations. The values of neutral gas density and electron density and temperature at fixed height from 160 km to 300 km with height resolution of 1 km are obtained by linear fitting. The MAVEN EUV Modelled data are used here to represent solar activity. The solar EUV flux at wavelength of 30nm from the modeled EUV was selected the proxy for the solar EUV radiation.

3. Statistical results

The seasonal variations of neutral component CO density at 180 km at different latitude area in both northern hemisphere and southern hemisphere are shown in Figure 1. The component CO2 has similar seasonal variations. The results of CO2 are not shown here. Solar EUV radiation incident to Mars is inversely proportional to the square of the distance to Mars from the sun. Thus the Mars' elliptical orbit results in significant seasonal variations in the solar EUV radiation received by Mars, even though the radiation remains constant. Meanwhile, the influence of solar zenith Angle (SZA) on the incident solar EUV radiation in different latitudes should be considered. The calculated relative variation of EUV (EUV) is as follows

$EUV = \frac{1}{D^2} \bullet \cos(\theta) \bullet \mathrm{Dm}^2$ (1)

Where D is the distance of Mars to the Sun, Dm is the farthest distance of Mars to the Sun, and θ is the solar zenith angle. We analyzed the data in daytime (10 LT - 16LT). The results show significant seasonal variations of neutral CO density at different latitudes in northern and southern hemispheres. The neutral density has the similar seasonal variations with the solar EUV flux in both hemispheres especially in southern hemisphere. Thus these seasonal variations of neutral density should be mainly caused by the EUV seasonal variations due to the combined effects of the distance to Mars from the sun and the solar zenith angle.

As shown in Figure 1, the largest seasonal variation of solar EUV flux occurs in southern hemisphere high latitudes and the smallest one occurs in northern hemisphere low latitudes. Then we can find the same seasonal variation feature in neutral density. Furthermore, on the whole the southern hemisphere has stronger seasonal variation than the northern hemisphere, because the effect of the distance from Mars to the sun and the effect of the solar zenith Angle on solar EUV flux are in the same direction in the southern hemisphere but in the opposite direction in the northern hemisphere. In the southern hemisphere, the distance of Mars to the Sun is the shortest and the solar zenith angle is the smallest when the solar longitude (abbreviated Ls) equals to 270°, thus the solar EUV flux reaches the maximum at this time; when the Mars moves to the location with Ls=90°, the distance of Mars to the Sun is the longest and the solar zenith angle is the largest, which results in the smallest solar EUV flux.

To further study the difference of Martian upper atmosphere between in the northern hemisphere and in the southern hemisphere, we statistically analyzed the latitude distribution of martian neutral density and electron density in equinox with Ls ranging from 150 to 210 at various heights from 180 km to 220 km under low solar activity. The solar activities in 2012-2015 were relative high. The data in low solar activity years 2016 - 2020 were used here. The results of CO and CO2 in day time (LT :09-15) are shown in the Figure 2. As illustrated in Figure 2, despite nearly five years of data, Maven's observations still can not cover the entire latitudes from the South pole to the North Pole. The results of polynomial fitting show a very clear latitude structure in neutral density of CO and CO2. The maximum density is located near the equator and decreases gradually as latitude increases both in the southern hemisphere and northern hemisphere. These results also clearly show the north-south asymmetry of the neutral atmosphere. On the whole, the neutral density is higher in the northern hemisphere than in the southern hemisphere.

The latitude distribution of martian neutral gas CO and CO2 density in equinox in relative high solar activity years of 2014-2015 were analyzed. The results are shown in Figure 3. The number of observation data is much less than that in lower solar activity years 2016-2020. The results also show significant North-South asymmetry. The neutral density is lower in northern hemisphere than in the southern hemisphere. The difference between the northern and southern hemispheres is reversed during periods of low and high solar activity. The hemispheric asymmetry of neutral density increases with height. The peak density gradually moves from the equator to low latitudes in southern hemisphere. Then we further analyzed the variation of neutral density with solar radiation intensity in the northern and southern hemispheres. The solar EUV flux data at 30nm from FISM-M model (Thiemann et al., 2017) are used. The results of neutral gas CO at 200 km are plotted in Figure 4. These results also clearly show the variation of hemispheric asymmetry with solar EUV flux at both low latitudes (0° - 30°) and middle latitudes (30° - 60°). When the 30nm EUV radiation is less than ~7.8×10^{-6}W/m^2, the neutral density in the northern hemisphere is greater than that in the southern hemisphere. However, the neutral density in the southern hemisphere is greater than that in the northern hemisphere if the 30nm EUV radiation is more than ~7.8×10^{-6}W/m^2.

Figure 5 illustrates the latitudinal variations of electron density and electron temperature at heights from 160 km to 300 km in equinoxes in years 2016-2020. These results show a significant north-south asymmetry in both electron density and electron temperature. The electron density at all heights from 160 km to 300 km is larger in southern hemisphere than that in northern hemisphere. At the same time, the electron temperature is lower in southern hemisphere than that in northern hemisphere. The change of electron density is opposite to the change of electron temperature, which accords with the process of energy conservation in the atmosphere. We can also find that the correlation between electron density and latitude decreases with height. For example, the correlation coefficients between electron density and latitude in the southern hemisphere are 0.83, 0.51, 0.37, and 0.05 at 160km, 180km, 200km, and 300km, respectively.

Then we further analyzed the variation of electron density at low latitudes and middle latitudes with solar radiation intensity in the northern and southern hemispheres. The results are plotted in Figure 6. We can find that the rate of change of electron density with solar radiation both at low latitudes and at middle latitudes is greater in the southern hemisphere than in the northern hemisphere. Although the electron density is lower in the southern hemisphere than in the southern hemisphere under low solar activity condition (EUV flux at 30nm less than 6×10^{-6}W/m^2), it would be larger in the southern hemisphere for higher solar EUV flux. The mean value of 30nm EUV flux in years 2016-2020 is about 6.8×10^{-6}W/m^2. Thus we can find the significant hemisphere asymmetry with higher electron density in southern hemisphere as shown in Figure 5.

4. Discussion

Due to the effect of Mars' elliptical orbit, the seasonal variation of the Martian ionosphere/thermosphere is affected not only by the periodic movement of the sun's direct point in the northern and southern hemispheres, but also by the periodic variation of the distance from Mars to the Sun. As shown in Figure 1, there are also different seasonal variations in solar radiation reaching different latitudes. The observed results show, although there are similar seasonal variations between the neutral density and solar EUV flux reaching the Mars. But the seasonal variation of neutral density and electron density is much more complicated than that of solar radiation reaching the Mars especially in the northern hemisphere. These results suggest that the Martian ionosphere is influenced by more factors than solar radiation.

For the Earth ionosphere, it is well known that, due to the equatorial dynamo process driven by the dipole magnetic field and horizontal wind, both ionospheric electron and neutral density shows a double peaks structure on both sides of the equator. Mars has no inner dynamo to create a major global magnetic field. Thus there is no equatorial dynamo process like in the Earth. The statistical results show both neutral density and electron density in Martian upper atmosphere in equinox have one peak at the equator/low latitude and then gradually decrease towards poles. According to the photochemical equilibrium theory, the Martian ionospheric electron density and thermospheric neutral density should be asymmetry between the northern and southern hemisphere because the two hemispheres receive the same solar EUV radiation flux. But the Maven's observations show both the plasma and neutral gas have the similar hemisphere asymmetry. Under lower solar radiation conditions, the electron density and neutral density in the northern hemisphere are larger than those in the southern hemisphere. With the increase of solar radiation, the electron density and neutral density in the southern hemisphere gradually surpass those in the northern hemisphere. But the intensity of conversion solar radiation in the southern hemisphere over the northern hemisphere is different for electron density and neutral density. It is ~$8\times10^{-6}W/m^2$ for neutral density and ~$6\times10^{-6}W/m^2$ for electron density. The mean solar EUV flux in 2016-2020 is about $6.7\times10^{-6}W/m^2$. Thus we can find in the same period of 2016-2020 the neutral density is larger in northern hemisphere, but the electron density is larger in southern hemisphere.

As mentioned earlier, there are significant hemispheric differences in the morphology of Mars, as well as large hemispheric differences in the residual magnetic fields of Martian rocks. The large hemispheric differences in Martian topography and the consequent influence of dust storms can lead to significant wave processes that may affect the lower atmosphere. The lower atmosphere is coupled with the upper atmosphere mainly through upward propagation of various wave processes. .However, it is difficult to study hemispheric differences in such a coupling process with current data. The magnetic field effect on the martian ionosphere and thermosphere have been studied by some scientists (e.g. Shane et al., 2016; Flynn et al., 2017). Furthermore, the difference in the magnetic field between the northern and southern hemispheres of Mars is strongly dependent on longitude. Between longitude 120°-240°, the southern hemisphere has a strong residual magnetic field, while the northern hemisphere has a weak magnetic field. In other longitude regions, the magnetic field difference between the northern and southern hemispheres is small. Therefore, we can check the relationship between the magnetic field difference and the north-south asymmetry of the ionospheric thermosphere by comparing the results of the two regions with different magnetic field differences.

We reanalyzed the latitudinal variations of electron density at various heights from 160 km to 300 km in high magnetic field difference area (longitude 120°-240°) and low magnetic field difference area(longitude 0°-120° and 240°-360°) between the northern and southern hemispheres. The results are illustrated in Figure 7. We can find that the hemispherical asymmetry of electron density below 200 km is basically the same in the low and high magnetic field differences, but the hemispherical asymmetry of electron density at higher altitudes is more significant in the longitude sector with large magnetic field differences (120°-240°). The results of hemispherical differences in neutral density in different magnetic field differential sectors are plotted in Figure 8. These results indicate that the north-south difference in the magnetic field of Mars may increase the north-south difference in the electron density of the higher heights of above 200km, but has no significant effect on the north-south difference in the ionospheric electron density below 200km and neutral density. we can draw a preliminary conclusion that the north-south asymmetry of electron density and neutral density of the ionosphere and thermosphere in spring and autumn does not result from the north-south difference in the residual magnetic field of Martian rocks. Another possibility is that there is a great difference between the north and the south of Mars terrain, resulting in the North-South difference of various wave process (e.g. gravity waves, tides, and planetary waves) and dust storm activity in the lower atmosphere.

Richardson et al. (2002) found that Mars' global north–south elevation difference can effectively change southern summer circulation and also affect interhemispheric transport of water. The topography imprints a strong effect on lower atmosphere climate and then affect upper atmosphere by coupling of lower atmosphere with upper atmosphere via waves upward propagation. On one hand, Martian atmosphere is much less dense than Earth's; on the other hand, it doesn't have an inversion layer due to ultraviolet absorption by ozone. These conditions make it is very conducive to the propagation of lower atmospheric fluctuations upward into the ionosphere and thermosphere. Therefore, we considered that the significant north-south asymmetry in neutral density and electron density might be highly related to the north-south altitude differences.

5. Summary

The Maven entered Mars orbit in September 2014 and has been operating continuously for more than six years, generating a wealth of Martian exploration data, including data from the Planet's ionospheric thermosphere.These data provide a good coverage of Martian seasons and latitudes, allowing investigations of Martian ionospheric and thermospheric climate changes.Based on NGIMS neutral atmospheric density and LPW electron density temperature data, we mainly study the seasonal variations of the Martian ionosphere/thermosphere at different latitudes, with special attention to the differences between the northern and southern hemispheres.It is found that the seasonal variation of neutral atmosphere density and ionospheric electron density of Mars thermosphere is significantly different at different latitudes, which is mainly due to the combined effect of solar radiation variation caused by Mars elliptical orbit and solar zenith angle in different seasons.

We then focus on the north-south asymmetry of the ionosphere and thermosphere near the two equinoxes and find that there are significant north-south hemispheric asymmetry in both ionospheric electron density and thermospheric neutral atmosphere density.During the period of low solar activity, the ionospheric electron density and thermospheric neutral density in the northern hemisphere are larger than those in the southern hemisphere. With the gradual increase of solar radiation, the electron density and neutral density in the southern hemisphere gradually surpass those in the northern hemisphere. It is not clear why this asymmetry reversal occurs, and more observed data are needed to confirm such changes.

Through the exploration of several Mars mission like Mars Global Surveyor, Mars Odyssey, Mars Express, and MAVEN, we know that there are significant north-south differences in Mars terrain and residual magnetic field of Mars rocks, and the north-south differences of residual magnetic field of Mars rocks are significantly longitude dependent. The north-south magnetic field difference is most significant at longitude 120-240 degrees, while the north-south magnetic field difference is small at other longitude regions. By comparing the ionospheric asymmetry between the two regions, it is found that the north-south magnetic field difference can enhance the north-south asymmetry of ionospheric electron density above 200km, but has no significant effect on the thermospheric neutral atmosphere density. Therefore, we believe that the north-south difference of the lower atmosphere fluctuation process caused by the north-south difference of Martian topography may be the main reason for the north-south asymmetry of the Martian ionosphere/thermosphere

Data Availability Statement

The electron density and temperature data from LPW Instrument are publicly available at NASA Planetary Plasma Interactions of Planetary Data System (https://pds-ppi.igpp.ucla.edu/search/view/?id=pds://PPI/maven.lpw.derived/data). The neutral component data are provided by the Planetary Data System (PDS) (https://atmos.nmsu.edu/PDS/data/PDS4/MAVEN/ngims_bundle/l2/).

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Figure Captions

Figure 1. the LS variations of CO density at 180 km at low latitudes (10°±10°), middle latitudes (40°±10°), and high latitudes (70°±10°) in Northern hemisphere and Southern hemisphere. The corresponding relative variations of EUV (EUV) are also plotted in each panel.

Figure 2. The latitudinal distributions of neutral CO and CO2 density in daytime (LT 09 - LT 15) at various heights from 160 km to 220 km under low

solar activity condition (2016-2020). The median values and standard error are also plotted. The black solid curves represent the results of a polynomial fit.

Figure 3. Same as Figure 2. but for relative high solar activity years 2014-2015.

Figure 4. The variation of neutral gas CO density with solar radiation intensity in the northern (middle panels) and southern hemispheres (left panels). The solid lines and dashed lines are the polynomial fitting. The comparisons are plotted in right panels.Top panels show the results at middle latitudes. Bottom panels show the results at low latitudes.

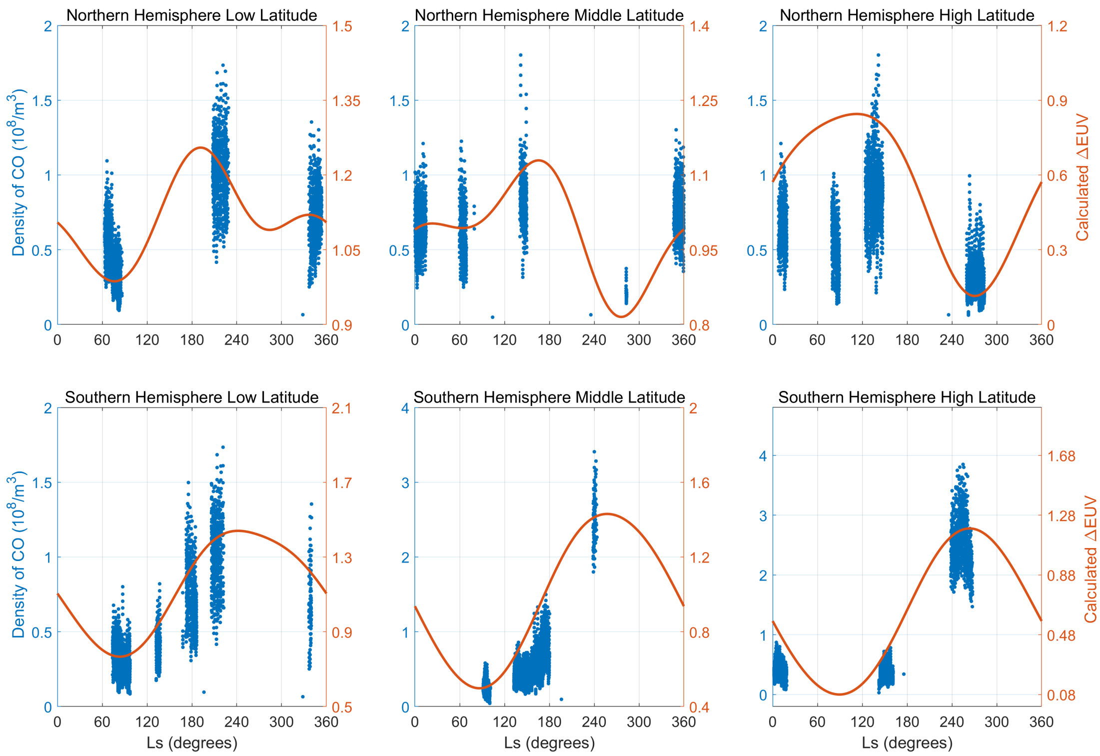
Figure 5. Same as Figure 2, but for electron density and electron temperature.

Figure 6. The variation of electron density at 200 km with solar radiation intensity in the northern (middle panels) and southern hemispheres (left panels). The solid lines and dashed lines are the polynomial fitting. The comparisons are plotted in right panels.Top panels show the results at middle latitudes. Bottom panels show the results at low latitudes.

Figure 7. The latitudinal variations of electron density at various heights from 160 km to 300 km in high magnetic field difference area (top panels) and low magnetic field difference area between the northern and southern hemispheres. The high magnetic field difference area refers to longitude sector of 120°-240°. The low magnetic field difference area refers to the other longitude sector.The median values and standard error are also plotted. The black solid curves represent the results of a polynomial fit.

Figure 8. Same as Figure 7, but for neutral density of CO.

Figures



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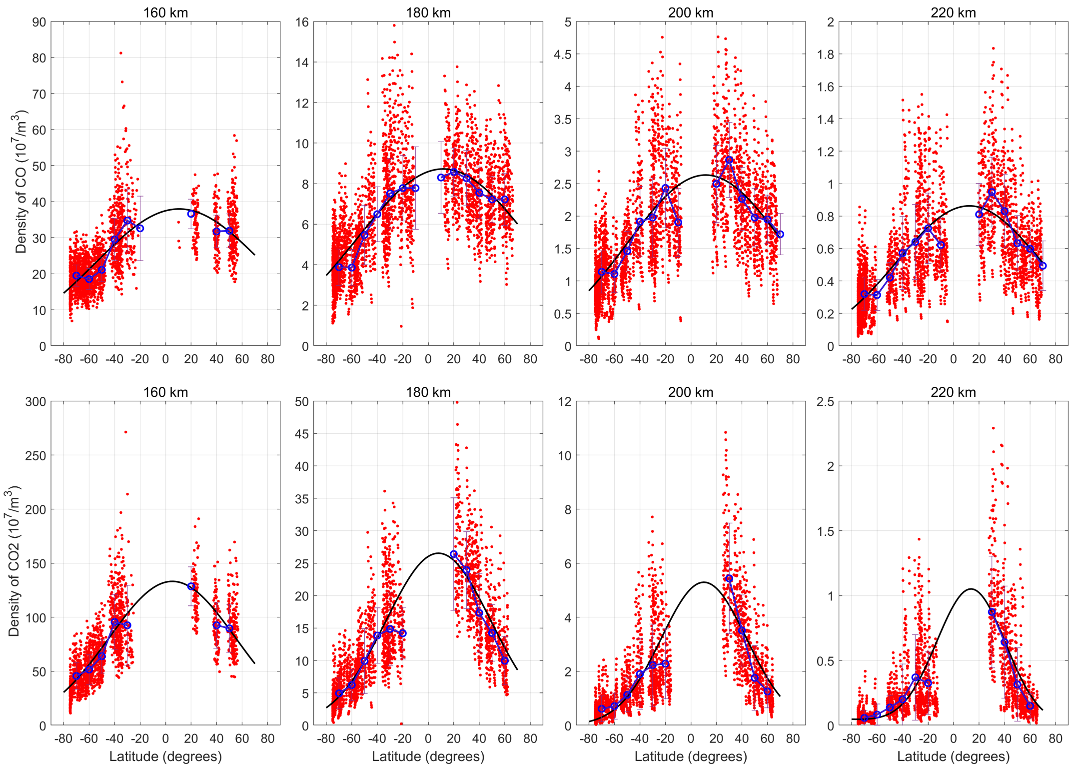

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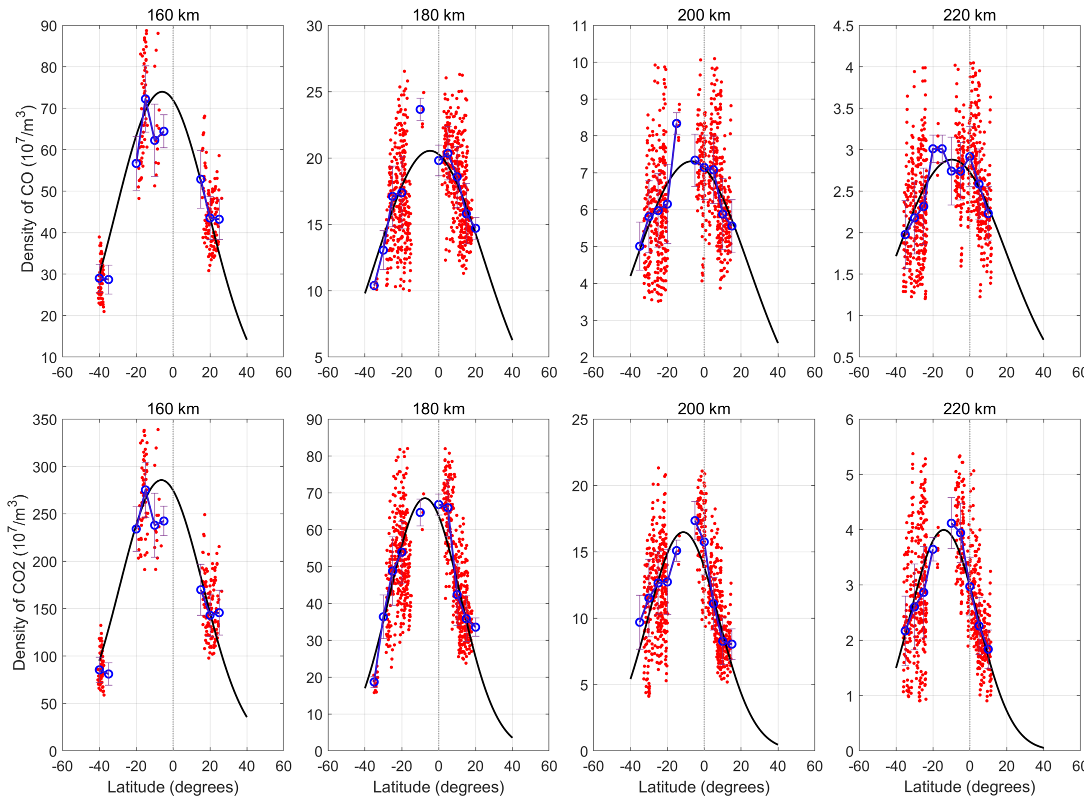

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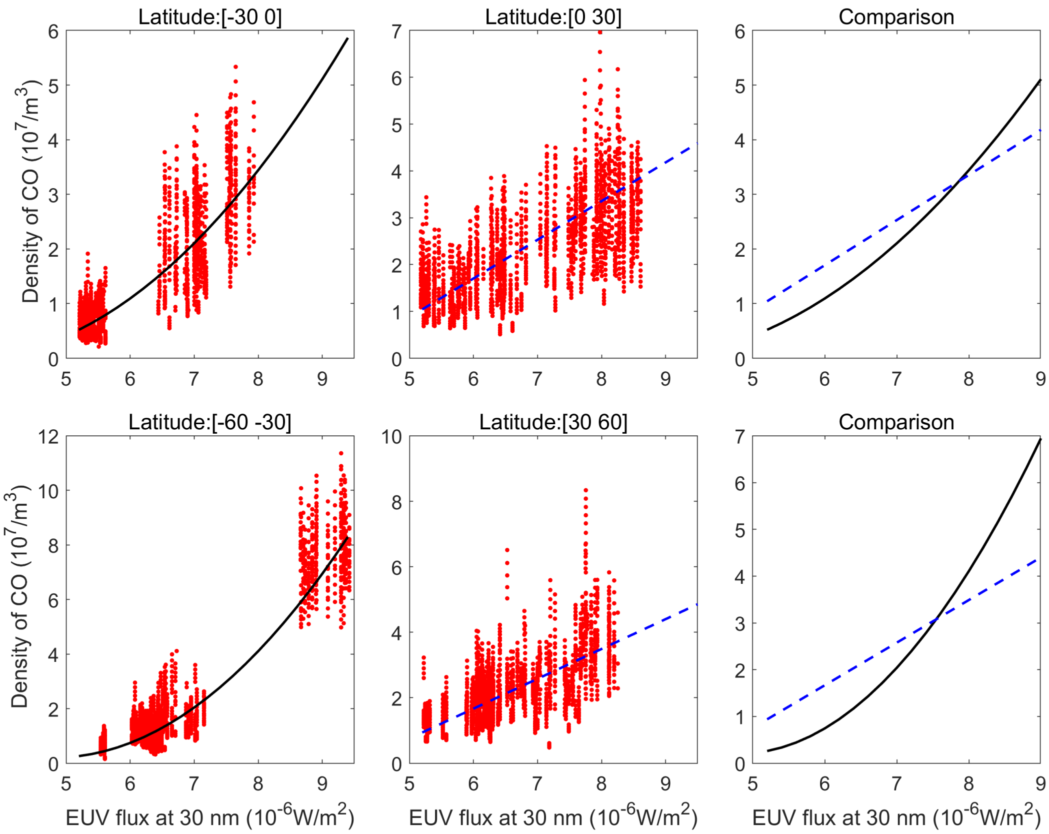

Figure 4. The variation of neutral gas CO density with solar radiation intensity in the northern (middle panels) and southern hemispheres (left panels). The solid lines and dashed lines are the polynomial fitting. The comparisons are plotted in right panels.Top panels show the results at middle latitudes. Bottom panels show the results at low latitudes.

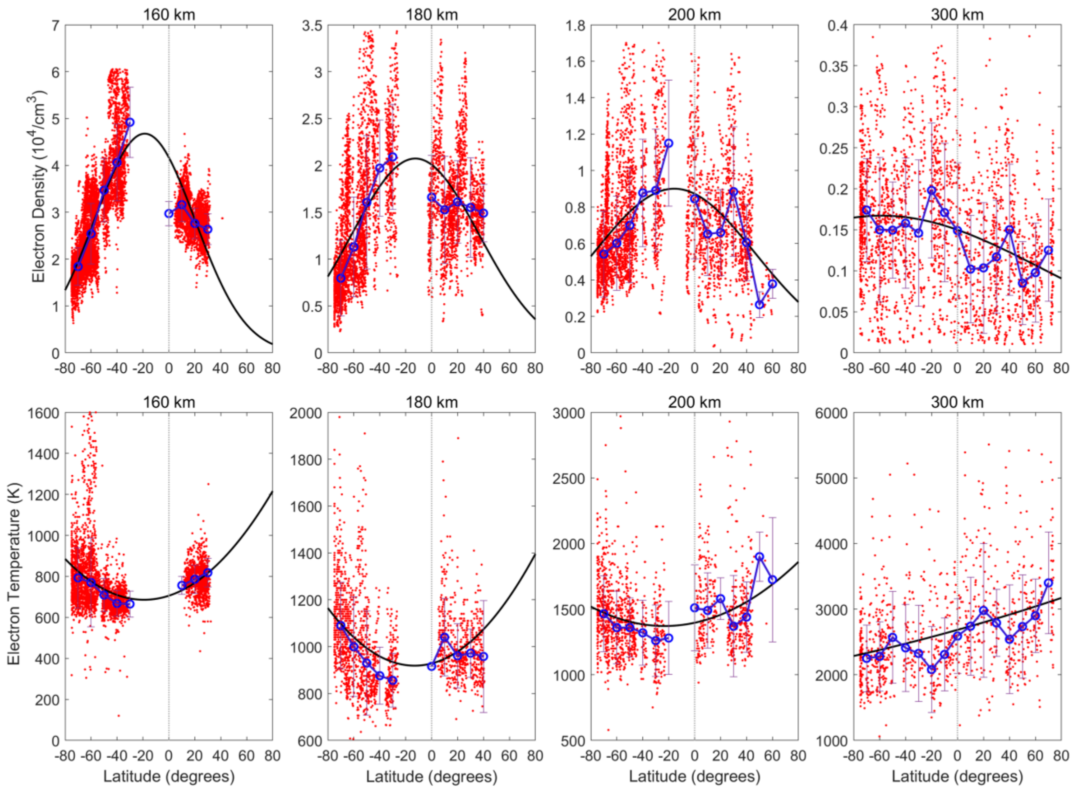

Figure 5. Same as Figure 2, but for electron density and electron temperature.

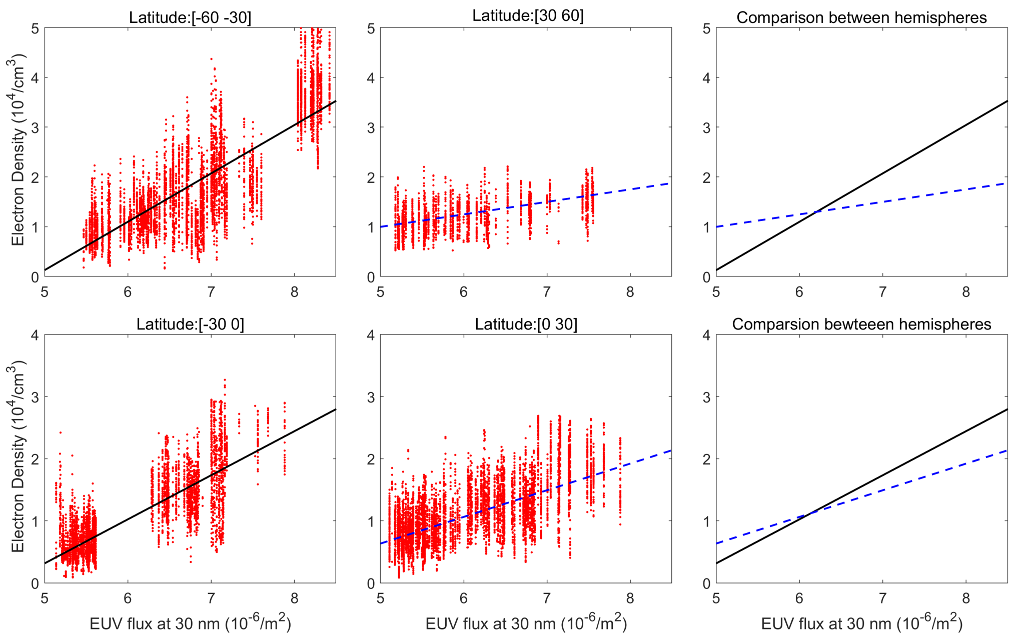

Figure 6. The variation of electron density at 200 km with solar radiation intensity in the northern (middle panels) and southern hemispheres (left panels). The solid lines and dashed lines are the polynomial fitting. The comparisons are plotted in right panels.Top panels show the results at middle latitudes. Bottom panels show the results at low latitudes.

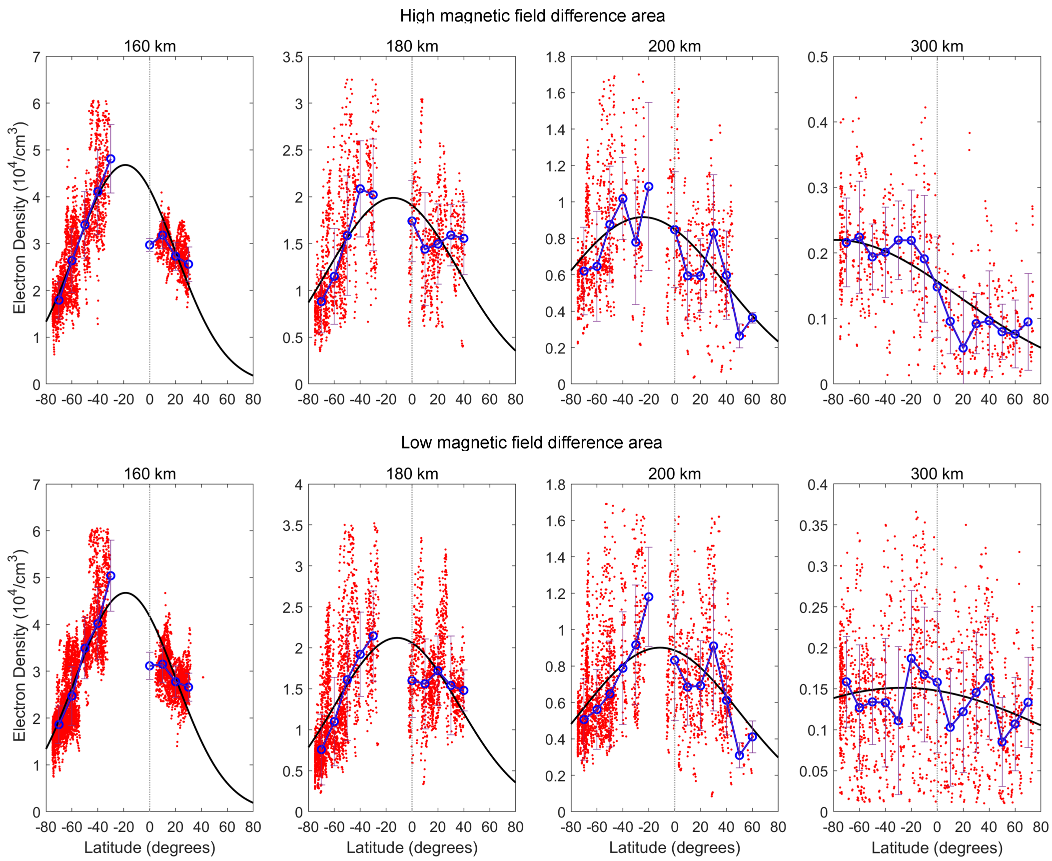

Figure 7. The latitudinal variations of electron density at various heights from 160 km to 300 km in high magnetic field difference area (top panels) and low magnetic field difference area between the northern and southern hemispheres. The high magnetic field difference area refers to longitude sector of 120°-240°. The low magnetic field difference area refers to the other longitude sector.The median values and standard error are also plotted. The black solid curves represent the results of a polynomial fit.

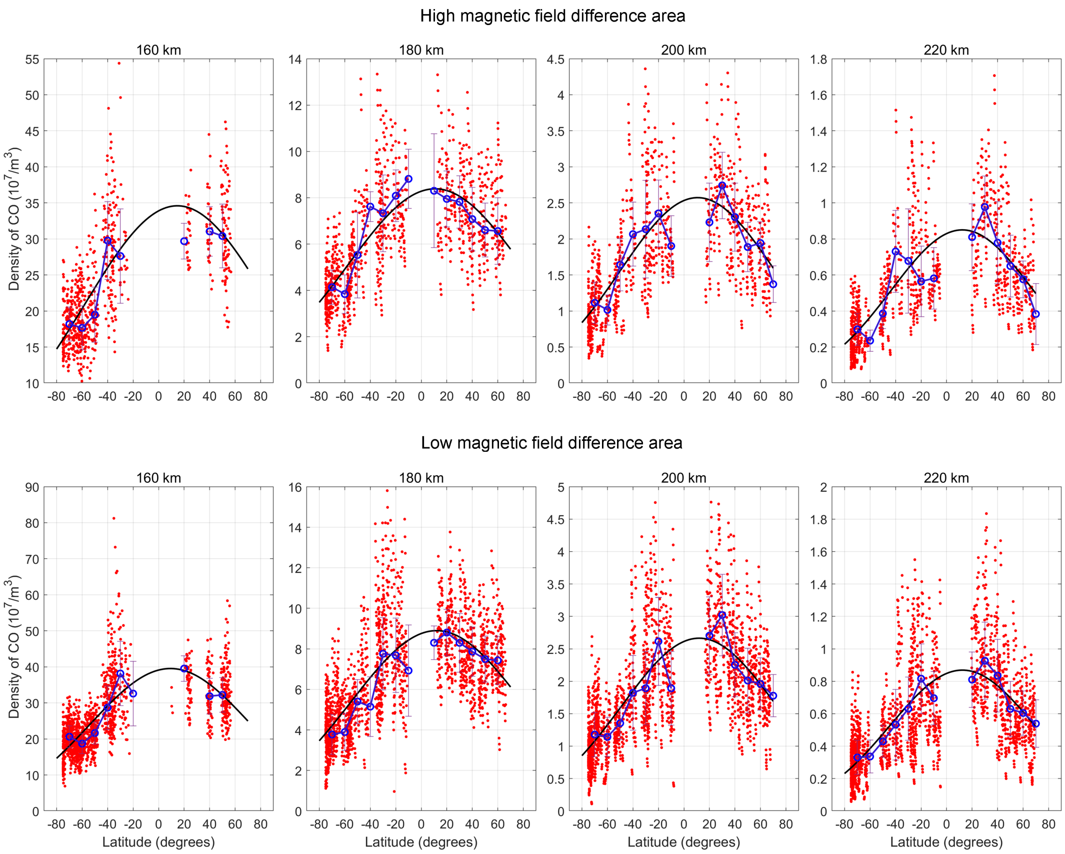

Figure 8. Same as Figure 7, but for neutral density of CO.