Gravity Waves and Irregularities in Es Observed During the Solar Eclipse of 22 July

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Abstract

The ionospheric disturbances during the total solar eclipse of 22 July 2009 were observed by two ground-based high-frequency radio systems in Wuhan, China. An ionosonde recorded the ionogram every 5 min; the Wuhan Ionospheric Oblique Backscattering Sounding System detected the echo range and Doppler variations with 1-min period. We found that the periodic fluctuation in the top penetration frequency of Es (*f*Es) and the irregularities in the spread Es appeared and disappeared simultaneously after the eclipse maximum. Moreover, the wavelet analysis results show that the same ~35 min period are contained in the fluctuation on the *f*Es curve and the variation of the irregularity Doppler velocity. Atmospheric gravity waves are considered to be generated in the ozone layer during the solar eclipse and propagate upward and passed through the Es layer. The gravity waves modulated the plasma in the Es and may produce the field-aligned irregularities we have been observed.

1. Introduction

Generally, the ionospheric response to the solar eclipse is manifested as variations in plasma density and reflection altitude induced by the photochemical effect [1-3]. However, aside from the sunshine, the ionosphere will also be affected by some other disturbances. Chimonas and Hines [4] were the first to suggest that the supersonic travel of the lunar shadow disturbs the heat balance of the atmosphere to generate gravity waves and the modulation of gravity waves can be observed in ionosphere. Before long, the detection of a wavelike ionospheric disturbance with ~20 min period during the solar eclipse of 7 March 1970 was recorded [5] and the recorded period was consistent with the theoretical prediction [6]. After that, many efforts have focused on the eclipse-induced atmosphere gravity wave (AGW) and the observed period generally distributed in the range between 20 and 60 min [7-8]. Recently, the cooling of the ozone layer in the stratosphere during a solar eclipse has been experimentally shown to be the major source of gravity waves [9]. The gravity waves can be responsible for the significant perturbations in the altitude and density of an Es layer [10] and for the occurrence of the field-aligned irregularities in Es layer [11]. The polarization electric field produced by gravity wave modulation was used to explain some effects observed in the QP Es structures [12]. And computer simulation has shown that a horizontally stratified Es layer can be modulated by gravity waves to form large-scale wavelike structures [13]. The gravity waves and Es layer are rarely observed at the same time. The continuous appearance of Es layer over Wuhan in July 2009 provided a unique opportunity to investigate the variations of the Es layer as a response to the solar eclipse of 22 July 2009 and the associated eclipse-induced AGWs.

2. Experimental Configuration

The longest total solar eclipse of this century occurred in East and South Asia on 22 July 2009. The path of the lunar umbral shadow commenced in India, crossed through Nepal, Bangladesh, Bhutan, Myanmar, and then reached China. The ionosonde and WIOBSS located in Wuhan, China (30°21′N, 114°16′E) was on the center of the eclipse path with a maximum obscuration of 100% as shown in Figure 1. The first, second, third and fourth contact times of the solar eclipse at 100 km altitude over Wuhan were 08:13, 09:22, 09:28 and 10:45 LT respectively. The ionosonde and WIOBSS were located in Wuhan and stood 24 km apart. The two radio systems were continuously operated on the eclipse day and the day before and after. The ionosonde in the southern suburb recorded the ionograms between 3 and 20MHz with 100 kHz step every 5 minutes. The height bins of the recorded ionograms were from 65 to 800 km with 3.84 km step. The WIOBSS was located in Wuhan university and employed a log-periodic antenna pointing northeast with a broad antenna pattern in the east-west plane to record the backscatter echoes from the east. The WIOBSS detected the ionosphere at 6.6, 8.2 and 10.6 MHz operating frequencies sequentially every 1 minute. The group range, SNR and peak Doppler velocity of echoes have been estimated to compose the height-time-SNR plots and height-time-velocity plots of each operating frequency. The echo range and Doppler resolutions were 6.25 km and 0.0732 Hz respectively.

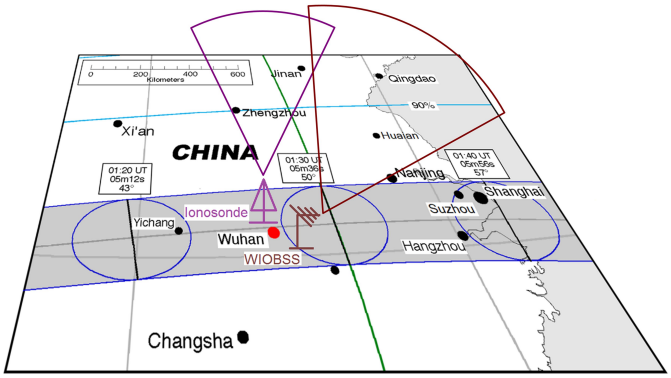

Figure 1. Map of the eastern China showing the movement of the solar eclipse on July 22, 2009 and the locations of the ionosonde and WIOBSS in Wuhan.

3. Observations and Discussion

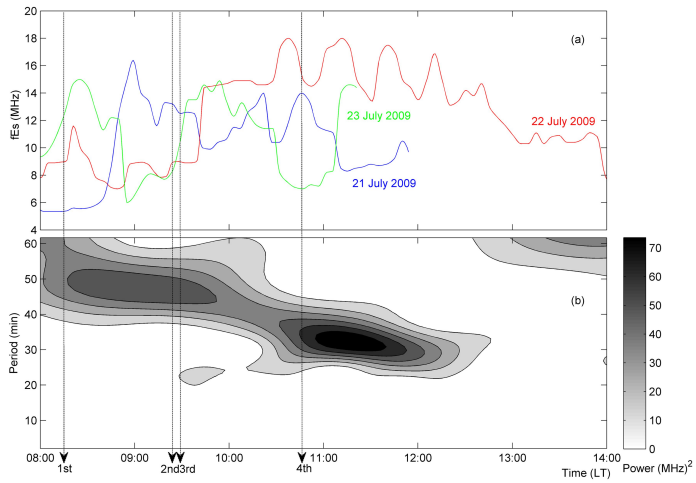

Figure 2. (a) Time variation of *f*Es during the solar eclipse on 22 July 2009 and the day before and the day after. (b) Time-period spectrum of the *f*Es curve recorded on the eclipse day. Vertical dotted lines mark the time of the first, second, third and fourth contacts of the solar eclipse at 100 km altitude over Wuhan.

The total blanketing Es layer continually occurred during the observing period of 21-23 July 2009 centered on the total solar eclipse day. The top penetration frequency of Es (*f*Es) of 21-23 July 2009 recorded by the ionosonde in Wuhan is displayed as a function of time in Figure 2a. The red *f*Es curve recorded on the eclipse day is very distinctive from the blue and green *f*Es curves recorded on the day before and after. Firstly, there is a sudden increase in *f*Es at 9:43 LT, shortly after the third eclipse contact. The enhancement of the maximum electron concentration in Es during the solar eclipse has been explained by the supposition of eclipse enhanced windshear [14]. The subsequent wavelike fluctuations on the *f*Es curve, which included five complete cycles from 10:30 to 12:45 LT. The first cycle began at 10:36 LT and *f*Es increased rapidly from 14.6 to 18 MHz. The maximum amplitude of the second cycle was almost the same as that of the first one. The subsequent cycles began to wear off and the last observable cycle appeared at 12:40 LT with 14.7 MHz peak frequency. The wavelet analysis method was applied to the *f*Es curve of the eclipse day to investigate its time-period distribution. The estimated time-period spectrum in Figure 2b has indicated a periodicity of ~35 min occurring from 10:30 to 12:45 LT. The periodic disturbance in ionospheric electron density indicated the existence of gravity waves [5]. The periodicity of the recorded gravity waves is similar to the previous observations during solar eclipse. Eclipse-induced gravity waves have been experimentally shown to stem from the ozone layer when the supersonic lunar shadow passed by [12].

Besides the periodic variations in the electron density, some extra traces were found at greater ranges than the main trace of the Es layer at 100 km. The spread echoes induced by the off-vertical radiowave reflections from the

irregularities of the Es layer had been cleared detected by WIOBSS. The recorded height-time-velocity plots of the eclipse day and the day after are shown in Figure 3. The blanketing Es occurring at the 100 km altitude and irregularities echoes between one-hop and two-hop regular Es echoes were observed by all the three operating frequencies in the two days. The range of the irregularity echoes extended from 137 to 190 km. It should be noted that the occurring period of the spread Es during the eclipse was the same as that of the periodic fluctuation on *f*Es curve. The irregularity displayed much more intense Doppler fluctuations than the regular Es. The maximum Doppler velocity has reached +50 and -50 m/s respectively. The positive and negative Doppler velocities occurred intermittently, indicating some periodicities contained in the Doppler disturbance. The wavelet analysis method was also applied to the Doppler velocity of the irregularities at the 162.5 km range. The estimated time-period spectrum of the velocity variations at three different operating frequencies is shown in Figure 4. The three periodic fluctuations have the same features. They all appeared at ~10:00 LT and then disappeared at ~12:00 LT and have a dominant oscillation concentrates in the range of 30-40 min.

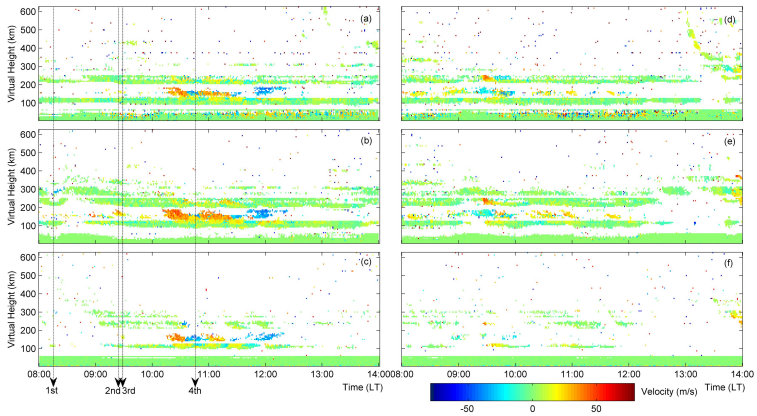

Figure 3. Height-time-velocity plots of Wuhan. Subplots (a), (b), and (c) were recorded with 6.6, 8.2, and 10.6 MHz, respectively, on 22 July 2009. Subplots (d), (e), and (f) were recorded with the same frequencies on 23 July 2009. Vertical dotted lines mark the time of the first, second, third and fourth contacts of the solar eclipse at 100 km altitude over Wuhan.

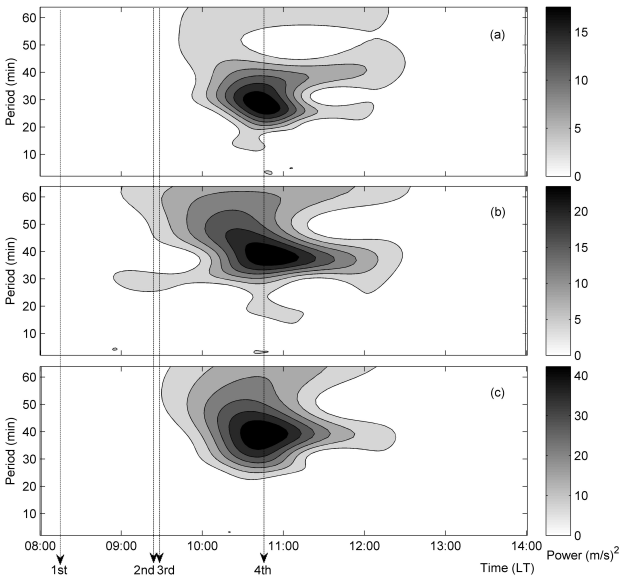

Figure 4. Time-period spectrum of the Doppler velocity values of 162.5 km range spread Es recorded by 6.6, 8.2, and 10.6 MHz operating frequencies on the eclipse day. Vertical dotted lines mark the time of the first, second, third and fourth contacts of the solar eclipse at 100 km altitude over Wuhan.

Comparing with the variations of the *f*Es and irregularities, there are two main similarities between them. One is the same occurrence time. The periodic disturbance in the Es and the occurrence of the irregularities occurred simultaneously as shown in Figures 2 and 3. They both appeared at ~10:30 LT and disappeared at ~12:30 LT. The other is the similar periodicity. The wavelet analysis results indicate that both the varying *f*Es and the irregularities contained the same periodicity of ~35 min. Therefore, a conclusion can be reached. The eclipse induced AGWs propagated

upward and passed through the Es layer to modulate its plasma and driven the irregularities in the Es. The presence of off-vertical scattering from E layer irregularities has been known for a long time and measurements have indicated that Es layers contain tilts as much as 25° according to the incline of the geomagnetic field [15, 16, 12]. The frontal structures with close separations and the frontal clouds of ionization, which are possibly associated with the gravity waves, are considered to induce the off-vertical reflections as we have observed [17].

4. Conclusion

The intense *Es* occurring over Wuhan during the total solar eclipse of 22 July 2009 provided a unique opportunity to investigate the variations in the Es layer as a response to the sudden withdrawal and recovery of solar radiation. The ionograms and echo Doppler velocity were recorded by the ionosonde and WIOBSS respectively. The most important and unique finding reported here is that the same periodicity of ~35 min appeared simultaneously in both the Es top frequency and the drifting velocity of the irregularities in the Es. The AGWs induced by the solar eclipse are considered to deform the *Es* layer and produce the moving wavelike structures.

Acknowledgments: This research is funded by the CRSRI Open Research Program (CKWV2013224/KY) and the National Natural Science Foundation of China (41074115).

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