Solar eclipse-induced E-region plasma irregularities observed by the Gadanki radar

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[1] We investigate the generation of low latitude E-region plasma density irregularities that were triggered during a solar eclipse on 11 August 1999. The observations were made using the Gadanki radar. The present study shows that a solar eclipse can provide night-like ionospheric conditions which allow the excitation of plasma instabilities and the generation of irregularities in the E-region at multiple height regions, as happens routinely during post-sunset hours. We surmise that the echo layers were associated with long-lived metallic ion layers that were made manifest when the more abundant ordinary molecular ions disappeared through recombinination in the absence of photoionization. We propose that the layers turned unstable via the gradient-drift instability mechanism. This is the first time that a solar eclipse has been conclusively shown to generate E-region plasma irregularities. Citation: Patra, A. K., R. K. Choudhary, and J.-P. St.-Maurice (2009), Solar eclipse-induced E-region plasma irregularities observed by the Gadanki radar, Geophys. Res. Lett., 36, L13105, doi:10.1029/2009GL038669.

1. Introduction

[2] A solar eclipse provides a unique opportunity to study the ionospheric response to the sudden withdrawal of solar radiation. Two consequences have so far been recognized over the years: (1) the generation of gravity waves due to the transit of locally cooled region of the atmosphere moving at supersonic speed [Chimonas and Hines, 1970] and (2) a reduction in the plasma density as the source of ionization switches off [e.g., Van Zandt et al., 1960]. In the latter case, given the lack of a source of ionization and the fast recombinination time, the E- and F1- region density should undergo a substantial decrease during a solar eclipse. Indeed a bite-out of up to 40% in the E- and F1- region densities was observed during a solar eclipse [Van Zandt et al., 1960]. In turn, a natural question arising from the local depletion in ionization is whether or not the sudden reduction in electron density on the eclipse path could generate plasma irregularities in association with the creation of sharp density gradients. This question has, to our knowledge, never been addressed until now and provides the main thrust of the present publication.

[3] In this article, we present and discuss Gadanki MST radar observations (13.5° N, 79.2° E, 6.4° N magnetic latitude) of low latitude E-region plasma irregularities generated during a solar eclipse, on 11 August 1999. In addition to the single thin layer observed on other days below 100 km, we noticed the appearance of two more layers higher up. The multiple layering was particularly well developed right around the time of maximum obscurity. Given that only one echoing region is ever observed during sunlit conditions [e.g., Choudhary et al., 1996; Patra et al., 2004], this observation makes the case for the generation of the low latitude irregularities to be associated with the conditions that prevailed during the eclipse. They also make a strong case for a key element in the generation of low latitude E-region night-time irregularity to be the lack of photoionization. The observations reported here should therefore be useful for an improved understanding of night-time E-region irregularities at low latitudes. From a complementary point of view, our work should also prove useful in elucidating yet another aspect of the effect of eclipses on the earth’s ionosphere.

2. Observations

[4] The solar eclipse of 11 August 1999 was a partial one. At Gadanki, 85% obscuration was reached at the maximum phase. The event occurred in the interval 17:12–18:56 Indian Standard Time (IST = UT + 5.5 h) with maximum obscuration at 18:12 IST. Local E-region (~100 km) sunset occurred at 19:19 IST. Radar observations were made on 10, 11, and 12 August 1999 to study the effect of the solar eclipse on E-region plasma processes. The geomagnetic conditions during 10–12 August were quiet (Kp < 3). This meant that any observation of a deviation from the normal behavior could not be attributed to disturbed-time low latitude electric fields.

[5] The three-day radar experiments were designed to meet a dual objective: (1) to study how the solar eclipse affects low latitude E-region plasma density irregularities and (2) to study eclipse-generated gravity waves in the troposphere. Accordingly, the experiments were conducted cyclically. The E-region observations were made with an antenna beam pointing in a direction transverse to the magnetic field (13° off-zenith due north). Power spectral data covering ranges between 60 and 148.2 km, and a 600-m range resolution were recorded every 26 s. Gaps in the ionospheric data occurred whenever the tropospheric experiment was conducted. However, these data gaps did not affect the present investigation in any significant way.

[6] To clearly illustrate the eclipse-induced effects, a small segment of the data obtained during the 17:25–18:30 IST interval is presented in Figure 1, which depicts, in three superposed plots, the height-time distribution of the signal-to-noise ratio (SNR) of the radar echoes observed on
[61x213]been observed before at Gadanki [Patra et al., 2004]. However, on 11 August, this echo region occurred a few km lower than on 10 and 12 August. In addition, on 11 August, two additional regions of echoes were also observed higher up in the E-region. The middle echoing region appeared 18 min prior to maximum obscuration. The top region (107–112 km) was only detected for a short while (~5 min), and was triggered in close coincidence with the main phase of the eclipse. It also displayed a curious ascending pattern (ascent rate = 15 m s$^{-1}$), right from the moment of its trigger. Unfortunately, the top region disappeared some time during the 5 min data break that followed its observation, so that the altitude evolution could not be determined during the full lifetime of the irregularities. It should be stressed that at this local time, radar echoes from altitudes greater than 105 km have never been observed before at Gadanki [Patra et al., 2004]. Finally, we also note that the middle echoing region underwent a significant evolution in terms of its height extension and level of turbulence (i.e., spectral width). As seen in Figure 1 (and also in Figure 2), during the main phase of the eclipse, the echo characteristics of the middle layer differed very clearly from the behavior observed before and after the main phase.

[8] Figure 2 displays samples of Doppler spectra observed before (17:55:00 IST), during (18:11:50 IST), and after (18:23:08 IST) the main phase of the eclipse, respectively. Note that positive/negative mean Doppler shifts translate into field-aligned irregularities that move towards/away-from the radar along the line-of-sight (13° off zenith due north). For the northward bearing of the Gadanki radar, the Doppler shift observed above 100 km is normally attributed to a zonal electric field (ambient plus polarization electric field), while Doppler shifts below 100 km are believed to be increasingly influenced by meridional neutral winds [Krishnamurthy et al., 1991]. As seen in Figure 2, the mean Doppler shifts of the echoes above 100 km, although small, are upward/northward while they are downward/southward for echoes observed below 95 km. The upward/northward velocities above 100 km altitude are consistent with what is normally expected from the daytime eastward electric field. It is also not surprising to notice the rather small Doppler speeds at that height, considering the fact that the ambient zonal electric field at that time of day should be close to zero [Fejer et al., 1991].

[9] Another interesting feature of Figure 2 is the enhanced turbulence level at the middle echoing region during the main phase of the eclipse and its relation to the appearance of the top echo layer. The narrow spectral shapes of the latter and its short duration both suggest that the plasma was barely unstable at the time and that there was just enough free energy available to trigger a plasma instability, i.e., conditions were not destabilizing enough for a long time sustenance or for the trigger of strong turbulence. By contrast, the central echo region near 102 km had its largest spectral width at the main phase of the eclipse, and had its largest altitude spread, indicating that the weakly turbulent upper layer was triggered at a time when the middle layer was at its most turbulent.

3. Discussion

[10] The comparison between the eclipse day and the days that preceded and followed it strongly suggests that the solar eclipse was responsible for dramatic changes in the formation and evolution of m-scale E-region irregularities. The most interesting observations were (1) the occurrence of two additional echo layers at the time of the eclipse and (2) the special echo properties observed at maximum obscurity time, namely, the apparition of a short-lived upper layer and its very clear ascending pattern, with the simultaneous occurrence of the height expansion and spectral broadening of the middle echoing region. In this section, we discuss how these features could have been triggered by the eclipse.

3.1. Gradient-Drift Instability as the Generation Mechanism

[11] Strong currents and electric fields do not normally exist outside the equatorial electrojet belt (±3° magnetic
follows that the appearance of multiple echoing regions in the solar eclipse data should, like its nighttime counterpart, be due to multiple Es-layers associated with metallic ions concentrated in tidal and/or gravity wave wind nodes. Indeed, Arecibo incoherent scatter radar observations provide plenty of evidence for the existence of multiple electron density layers in the E-region during the night and sometimes even during the day [e.g., Christakis et al., 2009].

3.1.2. Indirect Evidence for Reduced Background Plasma Densities

[14] It is one thing to argue that metallic Es layers were present and another to state that their appearance was due to a reduction in the background molecular ion density. Indirect evidence for an overall reduction in the low latitude E-region plasma densities came from ionosonde data at the magnetic equator. Using observations made during the 11 August 1999 eclipse from Trivandrum (8.5° N, 77° E, 0.5° N dip latitude), Sridharan et al. [2002] uncovered an unusual increase in the height of the F-layer. They interpreted this rise in terms of a local enhancement in the F-region electric field resulting from a plasma density reduction in the low latitude E-region that is electrodynamically connected to the equatorial F-region through geomagnetic field lines.

[15] In Figure 3, we reproduce the Trivandrum observations of hF from 11 August 1999 (the eclipse day) and two control days (9 August 1999 and 12 August 1999). Data gaps occurred on August 11 due to the difficulties in retrieving an unambiguous determination of hF, owing to overlapping echoes from strong blanketing E, conditions that created multiple reflections (for details, see Sridharan et al. [2002, Figure 1]). Despite this limitation, one can clearly notice a considerable increase in the F-layer virtual height on 11 August compared to the other days. Over Trivandrum, the eclipse occurred in the interval 17:18–18:15 IST. Interestingly, the height rise of the F-layer occurred prior to 17:18 IST (local onset of the eclipse) and coincided very well instead with the arrival of the eclipse-related shadow in the northern hemisphere E-region (17:02 IST), to which the F-region over Trivandrum is connected. Of course, the Trivandrum F-region was also connected to the southern hemisphere. However, the conjugate E-region densities should have been low, since the southern hemisphere was in winter. Furthermore, the rise in the height of the F-layer started well before the usual onset time (19:00 IST) of the pre-reversal enhancement of the zonal electric field [Hari and Krishnamurthy, 1995]. We conclude that it is quite reasonable to consider that the rise of the F-layer was an indicator of reduced low latitude E-region plasma densities over the Gadanki region. This conclusion is consistent with the Fesen et al. [2000] simulations on the development of the pre-reversal enhancement of the F-region zonal electric field.

3.1.3. Possible Origin of Wind Fields Responsible for Metallic Ion Layers

[16] A natural question that arises from our conclusion that the multiple layers were associated with Es layers of metallic origin is whether these layers already existed or whether they were generated by gravity waves induced by the solar eclipse itself. In this regard, it turns out that there is abundant observational evidence that points to the generation of gravity waves in the low latitude ionosphere during
the 11 August 1999 solar eclipse [e.g., Altadill et al., 2001; Sridharan et al., 2002; Sauli et al., 2006]. Sridharan et al. [2002] used radar observations from Trivandrum to uncover a “bursty type” of electrojet echoes with a 30–35 min periodicity. They attributed these bursts to a gravity wave modulation of the gradient-drift instability. It follows from our observations that if our echoing layers were generated by ion layers formed by gravity waves, the gravity wave wind fields had to have a vertical wavelength of ~5 km (altitude separation of the echoing layers). It is simply not known at this time whether or not the solar eclipse could generate gravity waves with this 5 km vertical wavelength.

[17] No matter what their origin might be, high altitude echoing layers are regularly observed over Gadanki soon after sunset [Choudhary et al., 1996; Patra et al., 2004]. If, in similarity with observations reported by Christakis et al. [2009] for Arecibo, multiple ions layers constantly exist over Gadanki, the radar observations would suggest that these layers (presumably existing in response to tidal or gravity wave nodes) became unstable when the background electron density underwent its considerable decrease during the eclipse.

3.1.4. Electric Field and Wind Requirements

[18] While the existence of metallic ion layers is certainly plausible, the second requirement for the generation of gradient-drift structures is the presence of strong enough ambient electric fields or neutral winds. For vertical density gradients to become unstable, a zonal relative drift between ions and electrons is required in the plasma. Such a drift could either be due to a vertical electric field or to a zonal neutral wind. The vertical field needs not be large if the gradient scale is sufficiently steep. It is also possible that special electric field conditions prevailed, particularly when the short-lived top echoing region appeared. This short appearance would indicate that polarization electric fields were generated over some discrete plasma structures, in a way similar to what was argued by Haldoupis et al. [1996] in terms of a Hall polarization process.

3.2. Possible Meaning of the Changing Spectral Characteristics

[19] We have argued thus far that conditions for a large scale gradient-drift instability were met due, in large part, to the appearance of sporadic Es layers made of metallic ions that became evident once the background molecular ions disappeared. In this context, the multiple layers should have been associated with neutral wind nodes related to tides or gravity waves. This does not explain why the middle echoing layer became more turbulent right around 18:12 IST. One plausible explanation is that this was the time when the vertical gradients were the steepest in relation to metallic ions, since sunlight reached in minimum intensity at that very time.

[20] There remains the ascending pattern of the top echoing region, which did not match the very weak Doppler shift of the plasma. The fact that the thickness was not changing and the Doppler shift was negligible argues against the simple north-south passage of a latitudinal boundary through the field of view and suggests instead that a tilted region of irregularities must have been passing through the field of view. To produce no visible Doppler shift, the tilt must have been basically aligned in the east-west direction. Its occurrence precisely at maximum obscurity time would also suggest that the feature was tracking the maximum phase of the eclipse, which also would be reason to associate it with a basic westward motion. However, we cannot speculate further on what this feature might have been.

4. Summary and Conclusion

[21] In conclusion, it can be restated that the 11 August 1999 solar eclipse led to the production of multiple layers of low latitude E region irregularities. However, our study indicates that the local observations of the background plasma density and gravity waves or even special tidal modes are required before definite conclusions can be reached about the detailed mechanisms. Knowing what we now know, it is hoped that the solar eclipse of 15 January 2010, which will occur during noon hours over India, and especially over Gadanki, will provide a unique opportunity to investigate in more detail the various manifestations of this natural ionospheric phenomenon.

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References


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