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Effect of meteor ionization on sporadic-E observed at Jicamarca

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[1] Relatively little progress has been made in the study of equatorial Sporadic-E when compared to the study of mid-latitude Sporadic-E. Indeed, it is unclear if Sporadic-E has been observed at all near the geomagnetic equator using any technique other than the ionosonde. In particular, there have been no reports of Sporadic-E observed using the Jicamarca Radio Observatory (JRO) 50 MHz radar. The overwhelming—in SNR terms—presence of the nearly ubiquitous Equatorial Electrojet (EEJ) is the likely reason Sporadic-E has not been reported at JRO as well as at other similar radars near the geomagnetic equator. We present here what we believe to be the first Sporadic-E (defined here as altitude-narrow E-region layers that last tens of minutes) observations from JRO. The structure and characteristics of these equatorial Sporadic-E layers is compared with their mid-latitude counterparts. We also demonstrate the immediate effect of meteor-produced ionization on the formation and evolution of the equatorial Sporadic-E layers.
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1. Introduction

[2] Considerable, and well-documented, progress has been made in the study of mid-latitude Sporadic-E (SpE) over the years (see *Mathews* [1998] for review) with the "wind shear" mechanism being the most widely accepted explanation for the formation of these altitude-thin, long lasting layers. Before proceeding further, we would like to note that the term "Sporadic-E" originates from ionosonde measurements in the 1950s and has since been used to describe a variety of E-region echoes [Tidal-Ion layers, Intermediate Echoes, Ion-Rain etc.], with the common ground being that all these phenomena can be explained with slight modifications to the wind shear theory [*Mathews*, 1998]. The nature of the phenomena described as "Sporadic-E" throughout the years has been a function of the instrument used, latitudes, sensitivity of the viewing system etc. For example, the very sensitive Arecibo ISR [Incoherent Scatter Radar] observes "Sporadic-E" layers which are highly periodic in nature and are present almost all the time, thus making the term "sporadic" a misnomer, at least in this case [*Mathews et al.*, 1993].

[3] Equatorial Sporadic-E (ESpE), in direct contrast to the mid-latitude Sporadic E (MLSpE), has not been well studied mainly due to the lack of observational data. The presence of the nearly ubiquitous and very strong - in SNR terms - Equatorial Electrojet (EEJ), which covers a large part of the E-region - almost 100 to 110 km - at the geomagnetic equator, makes it difficult to observe ESpE at these regions. This is the main reason why SpE observations have never been reported by radars in the equatorial region, even from the sensitive Jicamarca Research Observatory (JRO) 50 MHz radar (11°57′, 76°52′W, ∼1° dip angle). It should be noted here that Equatorial Sporadic-E, as observed from ionosondes, has been classified as Slant (q-type) Sporadic-E and Blanketing Sporadic-E. As these terms obviously originate from the observed characteristics of Sporadic-E as seen from ionosondes, we make a conscious decision not to apply either of these terms to our Sporadic-E layers observed using a VHF (Very High Frequency) radar, instead adopting the more generic term — Equatorial Sporadic-E.

[4] In order to explain the large time scales over which Sporadic-E is observed (tens of minutes to hours), it has long been accepted that metallic ions are dominant ions in the formation of Sporadic-E. And that meteor ionization is the source of these long-lived metallic ions has been a subject of speculation and considerable study for a very long time, in fact long before even the wind shear theory was first developed [*Pierce*, 1938]. Over the years, there have been many reports of high to low correlation between the meteor shower activity and Sporadic-E [*Chandra et al.*, 2001; *Grebowsky et al.*, 1998; *Naismith*, 1956] to absolutely no correlation between meteor shower activity and the occurrence of Sporadic-E (*Baggaley and Steel* [1984] using 30 years of observational data) and in fact even an inverse relationship between the meteor activity and the occurrence of Sporadic-E [*Kotadia and Jani*, 1967]! However, the increasing use of HPLA (High Power Large Aperture) radars since the late 1990's for the study of meteor echoes has now firmly established that the mass influx due to sporadic (non-shower) meteors is far greater than that from the meteors showers [*Mathews et al.*, 2001], which makes it obvious there is no need for an obvious correlation to exist between meteor shower activity and Sporadic-E occurrence. Recently, *Haldoupis et al.* [2007] explained the seasonal variability of Sporadic-E in terms of the seasonal dependence of the meteor influx. In all these years, no direct relationship between meteor induced ionization and the formation and evolution of Sporadic-E has been found.

[5] We report here the first ever observations of Sporadic-E from the JRO 50 MHz radar. We also present what we believe are the first ever results showing a direct relationship between meteor ionization and the Sporadic-E. In section 2, we present the experiment configuration. Our observations are presented in section 3 and discussed in detail in section 4. A summary of our investigations with the future scope of study is presented in section 5.

2. Experimental Set-Up

[6] The results presented herein all derive from observations at JRO carried out on 7 June and 10 August 2006. The

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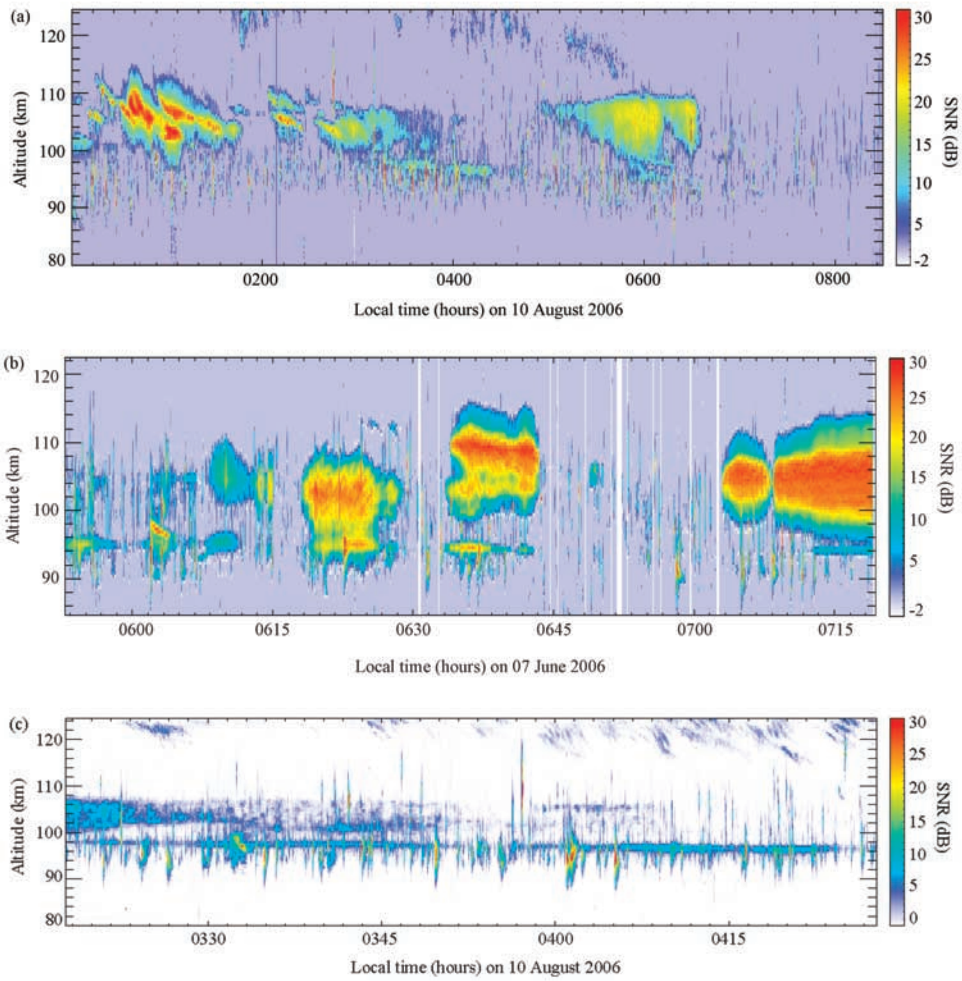

Figure 1. RTI (Range-Time Intensity) plots showing the presence of Sporadic-E (SpE) over Jicamarca. (a) SpE can be easily observed beginning at 98 km altitude at 0300 hours and then again at 0545 hours on 10 August 2006. The layer is seen to descend in altitude over time. (b) SpE as observed from JRO on 07 June 2006. (c) High-Resolution RTI plot of the SpE observed in Figure 1a over a shorter time period.

north and south quarters of the Jicamarca array were combined for transmission. A 39 μs 13 Baud Barker coded pulse was transmitted on both the days with an IPP (Inter Pulse Period) of 870 μs on 7 June and 900 μs on 10 August. In reception, three subarrays (each 1/64th of the main antenna) were sampled independently at a sampling rate of 3 μs to conduct interferometric analysis of received echoes, thus providing a 450 m range resolution. For 10 August observations, the radar beam was pointed vertically, hence away from the $\mathbf{k} \perp \mathbf{B}$ ($\mathbf{k}$ = radar wave vector, $\mathbf{B}$ = geomagnetic field) region of the radar (JRO is located at $\sim$1° dip angle) to minimize interference from EEJ. However, the $\mathbf{k} \perp \mathbf{B}$ region can be observed through the sidelobes, and hence the EEJ can be clearly observed as shown in figures later. A detailed description of the experimental set-up and parameters for 7 June is provided in *Malhotra et al.* [2007b].

3. Observations and Analysis

[7] Figures 1a and 1b show RTI (Range Time Intensity) plots of our data collected on 10 August and 7 June respectively. In Figure 1a, the Sporadic-E can be seen beginning at 0300 hours at $\sim$98 km and lasting for $\sim$1.5 hours before reappearing at $\sim$0545 hours. The EEJ can also be seen at heights varying from 98–114 km altitude. In Figure 1b, the layer can be observed sporadically beginning at 0553, 0618, 0633 and 0713 hours. The layer can also be observed in early morning hours when there is a very strong EEJ present i.e. beginning at 0713 hours. It should be noticed that while the occurrence of the convergence layer has an obvious correlation with the EEJ in Figure 1b, there is no such correlation to be seen in Figure 1a. Figure 1c is a high-resolution RTI plot of the Sporadic-E layer observed in Figure 1a over a shorter period. The effect of the large number of meteor echoes occurring in this time period on the Sporadic-E can easily be observed on this layer that is seen to clearly descend in altitude by about 1 km over this period.

[8] Figure 2 shows the position of the layer shown in Figure 1c obtained via interferometric analysis of the layer at a time period when there was no "interference" by the meteor echoes. The black dashed line represents the $\mathbf{k} \perp \mathbf{B}$ region of the Jicamarca radar at 100 km. The dashed ellipse indicates the region within which unambiguous echo position can be calculated. The contours represent the transmitting and receiving patterns of the JRO radar. Interferometric

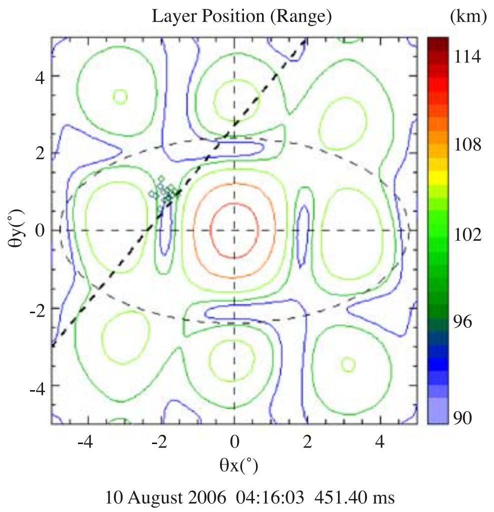

Figure 2. Interferometry plot showing the positions of the scatterers responsible for the Sporadic-E radar signature observed in Figure 1a. The black dashed line represents the **k** ⊥ **B** region of the JRO radar at 100 km. It can be clearly observed that the scatterers lie in the **k** ⊥ **B** region of the radar.

analysis is carried out via the technique described by *Farley et al.* [1981]. Calibration is done using the highly aspect sensitive EEJ [*Kudeki and Farley*, 1989] and long-duration meteor echoes [*Malhotra et al.*, 2007a, 2007b]. It can be clearly observed in Figure 2 that the scatterers responsible for the Sporadic-E radar signature lie in the **k** ⊥ **B** region of the radar.

[9] Figures 3 and 4 show the direct effect of meteor ionization on Sporadic-E, the first-ever results showing this relationship. In Figure 3, the effect of the meteor echo occurring at ∼10 seconds can be easily observed on the Sporadic-E. The ionization produced by the above-mentioned meteor event can be seen strengthening or reinforcing the Sporadic-E return. Figure 4a shows another RTI plot depicting the effect of meteor induced ionization on the Sporadic-E, though in this case the relationship is not as obvious as that shown in Figure 3. We utilize interferometry to study this relationship. Figures 4b and 4c are interferometry plots, similar to Figure 2. Figure 4b shows the position of the scatterers associated with the initial

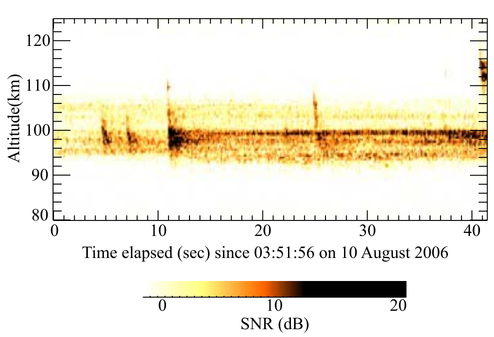

Figure 3. RTI plot showing a direct relationship between meteor induced ionization and Sporadic-E. The ionization produced by the meteor event occurring at ∼10 seconds can be clearly seen strengthening the Sporadic-E return.

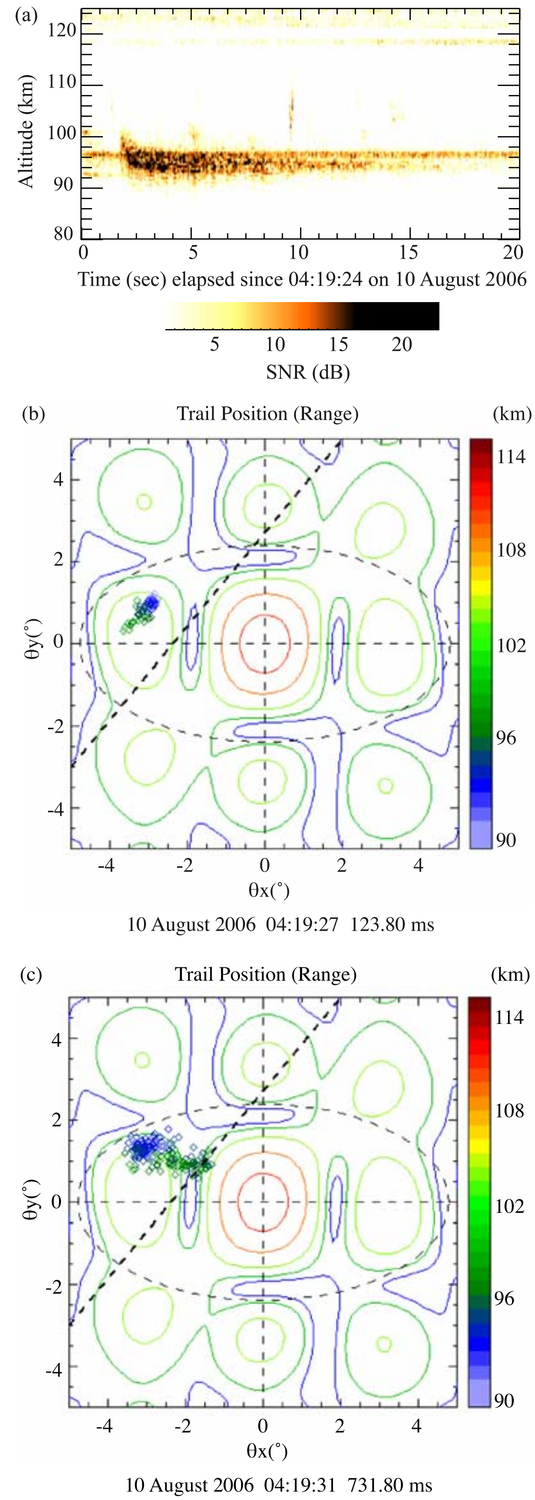

Figure 4. (a) RTI plot showing direct relationship between meteor ionization and Sporadic-E. (b) Interferometry plot showing the position of the scatterers associated with initial 2 seconds of the meteor trail's duration. The meteor echo starts well away from the **k** ⊥ **B** region of the radar, and hence away from the Sporadic-E return. (c) Position of the scatterers associated with a 12 second time period of the trail's duration starting from 04:19:31 hours. As time progresses, it can be clearly observed that the scattering associated with the meteor trail originates from the position of Sporadic-E return (Figure 2).

2 seconds of the meteor trail's duration. It can be seen that the meteor echo starts well away from the **k** ⊥ **B** region of the radar and hence as shown by Figure 2, lies well away from the Sporadic-E return. Figure 4c shows the position of the scatterers associated with the latter part of the trail (12 second time period starting from 04:19:31 hours). One can observe that as time progresses, the scattering associated with the meteor trail originates exactly from where the layer was observed (Figure 2). Thus, it can be concluded that in this case too meteor ionization affects the Sporadic-E, though the effect is not as easily noticeable as in Figure 3. Numerous other such examples are available.

4. Discussion

[10] Figures 1a–1c show the first observations of Sporadic-E by the JRO 50 MHz radar, and quite possibly by any radar located near the geomagnetic equator. As noted earlier, wind shear theory is the widely accepted explanation for the formation of Sporadic-E. Simply stated, the wind shear theory refers to the vertical component of the ion motion in response to the Lorentz Force ($\mathbf{F}_{ion} = q_{ion}$ ($\mathbf{v}_{ion} \times \mathbf{B}$); where q_{ion} is the ion charge, $\mathbf{v_{ion}}$ is the ion vector speed, and large-scale electric fields are taken to be absent) where the long-lived metal ions are taken to be collisionally embedded in the neutral wind that is responding periodically due to tides and/or acoustic gravity waves (AGWs). In particular, convergent vertical ion motion occurs when there is a westward wind above and an eastward wind below. A correspondingly large wind shear also yields ion convergence. Most often the necessary convergence is taken to be the result of tides or acoustic-gravity waves that have a downward phase speed yielding the oft observed slow vertical descent of the resultant ion layers.

[11] The layer shown in Figure 1a, also shown at a larger time scale in Figure 1c, shows a descent with time at the rate of 0.53 m/s. This descent, as stated earlier, is a well-known feature of mid-latitude Sporadic E attributed to the influence of diurnal and semi-diurnal tides on the layer [*Mathews*, 1976; *Whitehead*, 1989]. There is no reason for these tides, which are known to influence Sporadic-E layers observed by the Arecibo ISR [18.3°N, 66.75°W] [*Mathews and Bekeny*, 1979; *Mathews et al.*, 1997] not to influence the Sporadic-E layers observed using the Jicamarca radar (Figure 1a) when both the Arecibo and Jicamarca ISRs lie at similar latitudes in northern and southern hemispheres respectively. The layers observed in Figure 1b do now show any noticeable descent with time.

[12] The altitude at which the equatorial Sporadic-E is seen to first appear in Figure 1a i.e. 98 km agrees well with the altitudes at which the mid-latitude Sporadic-E is observed and also happens to be a preferred altitude for the formation of mid-latitude Sporadic-E [*Whitehead*, 1989]. Obviously, the presence of EEJ would make it difficult to observe Sporadic-E at higher altitudes at Jicamarca.

[13] While discussing the wind-shear theory, *Kelley* [1989] points out that at the dip equator i.e. when the magnetic field is perfectly horizontal, the highly magnetized electrons would not be able to move perpendicular to **B** to join the converging ions, thus leading to building up of a huge space charge electric field and bringing the plasma accumulation process to a halt. However, as they point out even a slight dip angle would allow the electrons to move along the field lines from a region of ion divergence to one of ion convergence, thus allowing the building up of layers. This point becomes important as JRO radar is not located exactly at the geomagnetic equator, but at a ~1° geomagnetic dip angle. It should be noted that there have been reports of Blanketing Sporadic-E observations using ionosondes attributed to horizontal wind shears from similar geomagnetic dip angles [*Reddy and Devasia*, 1973].

[14] Figures 3 and 4 are the first ever results showing a direct relationship between meteors and Sporadic-E. Though it has been established for a long time that long-lived metallic ions are necessary for the formation of Sporadic-E, until now no direct relationship has been found between meteor induced ionization and Sporadic-E. One of the main reasons why we are able to observe this relationship (Figures 3 and 4) is the different scattering mechanisms responsible for observing the Sporadic-E at different regions — Mid-latitude ISRs observe Sporadic E by means of incoherent scattering whereas Sporadic-E is observed over Jicamarca by means of **k** ⊥ **B** (FAI-like) scattering (Figure 2). This allows us to clearly study the effect of meteors while they "paint" the convergence layer. Also, the interferometric capabilities of the Jicamarca radar allow us to observe the transport and effect of meteor induced ionization on the Sporadic-E — Figure 4 being a case in point.

[15] Lastly, we would also like to note the occurrence of descending higher altitude layers in Figures 1a and 1c which bear a remarkable structural similarity to intermediate layers observed at mid-latitudes [*Mathews*, 1998]. On conducting interferometric analysis on these layers, we find these layers to also be highly field aligned. Unfortunately, the lack of appropriate height ranges in our present data sets hinders further study of these layers and they will be a subject of future study.

5. Conclusions

[16] We have reported the first-ever observations of Sporadic-E from the JRO 50 MHz radar, and quite likely the first such observations from any (non-ionosonde) radar located close to the geomagnetic equator. These layers show a descent in time similar to that observed in mid-latitude Sporadic-E, thus pointing to the influence of tides on these layers. These layers are also observed to occur at similar altitudes as their mid-latitude counterparts. However, the Equatorial Sporadic-E is observed via **k** ⊥ **B** (FAI or Fresnel) scattering whereas incoherent scattering is responsible for observing mid-latitude Sporadic-E. These layers observed at Jicamarca appear to be "truly" sporadic in nature but this might purely be a function of the observing instrument. We have also reported the first-ever results showing a direct relationship between meteor ionization and Sporadic-E, something that has been a subject of much speculation and mystery in the community for many years. More observations of the layer need to be carried out in order to study the diurnal and seasonal variability of Equatorial Sporadic-E and also to study the effect of Equatorial Electrojet on the layer, if any.

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