The connection between meteor showers and VLF atmospheric noise signals

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Abstract: There have been two different interests in the past as related to meteors and very low frequency (VLF) radiation in the atmosphere. The first deals with VLF pulses being produced by meteors entering the atmosphere, while the other deals with changes in the properties of the ionosphere due to meteors. To revisit these ideas, continuous measurements of VLF electromagnetic waves were performed simultaneously with optical imaging of meteors. The measurements were obtained during the Perseids, Orionids, and Leonids meteor showers during August, October, and November, 2007 and 2009. While unique VLF pulses could not be objectively associated with incoming meteors, the results indicate a distinct change in the background VLF atmospheric noise levels recorded on the nights of the meteor showers. We observed enhancements in the atmospheric noise parameter V_d , which is a useful quantitative measure of the impulsiveness of the noise, and is defined as the ratio (in decibels) of the root-mean-square amplitude to the average amplitude of the noise envelop, ranging from 2-2.5 dB (20-25% increase) relative to the normal levels. This enhancement in V_d is associated with decreased reception of VLF sferics at our station. These changes can be explained by either the attachment of ambient free electrons to the dust particles of meteoric origin, and/or the deposition of heavy ions with low mobility in the lower ionosphere. These ionospheric modifications cause more absorption, or inferior reflection conditions, for the background VLF noise sources, primarily produced by lightning.

1. Introduction

For more than 200 years there have been claims that meteors entering the earth's atmosphere produce an audible sound simultaneously with the optical signature produced by the incoming meteors [Blagdon, 1784; Udden, 1917; Roming and Lamar, 1963; Andrews *et al.*, 1969; Keay, 1980; Keay, 1993]. The attempt to explain these sounds being produced by shock waves or other acoustic signals produced by the meteor itself was considerably difficult since given the distance of the meteor from the observer, there should always be a time delay between the optical and audible signals. However, if the meteor produced an electromagnetic wave in the audible frequencies, then this wave would reach the observer at the same instance as the visible light [Hawkins, 1958; Beech *et al.*, 1995]. This low frequency wave could induce oscillation, vibration, and sounds from many objects near the observer. Hence, any electrically conducting body (plants, hair, wires, fences, spectacles, etc.) could vibrate at audible frequencies, giving the observer the perception that the sound was produced by the meteor [Uden, 1917]. This phenomenon is known as electrophonics, and some evidence has been found to confirm

this hypothesis. During the 1999 Leonids meteor storm a strong increase of very low frequency (VLF) pulses was detected during the meteor storm, with these weak pulses showing an unusual spectral signature [Price and Blum, 2000]. Furthermore, Chakrabarti *et al.* [2002] observed VLF emissions around 19 kHz lasting for almost 3 seconds associated with a meteor.

In addition to the attention given to electrophonics, for the last 60 years scientists have studied the impact of meteors on the ionization of the upper atmosphere. Herlofson [1948] was the first to present a comprehensive physical treatment of the theory of meteor ionization showing that the distribution of ionization along the meteor track is proportional to the rate of evaporation of meteor atoms, and that the height of maximum ionization increases with the shower velocity. During meteor showers, large amounts of neutral metal atoms and metallic ions such as Fe^+ and Mg^+ are deposited between 90 and 120 km due to the ablation of the meteors, leading to the creation of very narrow metal-rich layers (0.6-2 km). Such layers are sometimes referred to as sporadic-E [Dubin, 1955; Schunk and Nagy, 2009]. In a study of the effect of meteor ionization on the nighttime E-region, Nicolet [1955] arrived at an ionization density of the order of 10^4 electrons/cm³ as being maintained by meteors, possibly near 100 km, during the nighttime hours. Furthermore, Kotadia [1958] reported that meteors contribute significantly to the sporadic E-layer ionization in low latitudes. The ablation-formed atoms and ions have fairly long relaxation times and may therefore accumulate during the shower period. Furthermore, they are often observed to appear in a matter of minutes, but can persist for as long as a few hours, and then disappear rapidly [Gardner *et al.*, 1995] or slowly fade into the background [Heinrich *et al.*, 2008]. Kane and Gardner [1993] showed a peak in Fe atoms density at an altitude of 88.1 km, with maximum concentration of 1.5×10^4 cm⁻³; these atoms are thought to be removed by oxidation and reaction with CO_2 to form solid FeCO_3 particles. Grebowsky *et al.* [1998] compared the ambient concentrations of metals during shower and non-shower days. The results clearly demonstrate a significant increase (up to 2 orders of magnitude) in peak concentrations of metals during meteor showers, at different altitudes. Furthermore, numerical studies by McNeil *et al.* [2001] showed that meteor showers generate sporadic E-layers that are 2 orders of magnitude stronger than the ambient E layer concentration. They also noted that it is not the hourly rate of meteors that determines the magnitude of the effects on the ionosphere, but rather the size-distribution of the ablated meteors.

It is now well known that dust particles play an important role in the properties of laboratory and space plasmas [Merlino and Goree, 2004]. As shown by Kulkarni and Muralikrishna [2005], neutral dust particles, when they exist in sufficient numbers, can modify the ion-neutral collision frequencies, especially in the lower E-region, where dust particles of meteoric origin are known to exist in large numbers, modifying the Cowling conductivity profile [Gelinas *et al.*, 2005; Muralikrishna and Kulkarni, 2006]. Also, the presence of dust is known to lower the threshold for shear instability onset in gases, when the ratio of dust to air mass density approaches an appreciable fraction of unity, leading to a strong interaction between the dust particles and the gas molecules [Palaniswamy and Purushotham, 1981]. It is reasonable to assume that dust particles embedded in an ambient plasma can collect electric charges from the plasma, thus reducing the electrical conductivity of the region.

In this paper we revisit these two hypotheses (electrophonics and meteoric dust attachment) by monitoring the VLF background radiation during the Perseids meteor showers in August, 2007 and 2009, the Orionids meteor shower in October, 2007, and the Leonids meteor shower in November, 2007, simultaneously with optical imaging of the incoming meteors.

2. Observation System and Data

The VLF instruments used in this study are located at the Desert Research Institute of Ben-Gurion University, at Sde-Boker in the Israeli Negev Desert (30.5 N, 34.4 E), at a remote site surrounded by low noise levels, away from industrial or human activity. The station has a highly sensitive VLF receiving system and is very similar to the antenna at Palmer Station, Antarctica, operated by the VLF group at Stanford University [Burgess and Inan, 1993]. The system utilizes two orthogonal triangular loops, each with a base line of 18 meters, and 9 meters height, giving an area of approximately 81m^2 for each loop. The loop antenna impedance is $65\ \mu\text{H}$ and 0.061 Ohms. One loop is aligned in the north-south direction of propagation, and the other loop is aligned in the east-west direction of propagation. The sensitivity of the system in the broadband range (0.1-50 kHz) is $6\ \mu\text{V}/\text{meter}$. The dynamic range of the antenna/preamp set is approximately 100 dB, allowing us to detect lightning discharges from several thousand km.

The data were collected and recorded by data acquisition (DAQ) software (provided to us by Stanford University). The entire datastream is saved as a single long waveform, at 16-bits, 100 kHz, for each antenna, which is suitable to see 50 kHz following the Nyquist theorem. These data accumulate quickly, at a rate of about 1.5 GB per hour. Therefore, the broadband data are collected only one minute out of every 15 minutes [Cohen, 2006]. Furthermore, each incoming time series is transformed to the frequency domain and then calibrated by the instrument frequency-response curve up to 50 kHz.

For the meteor optical signatures we used two panchromatic CCD cameras, mounted on a pan-and-tilt unit (PTU, with 0.013° resolution). One was a Watec100N with a 12mm f/0.8 lens, which is in PAL format (25 frames/sec) with a field of view (FOV) of horizontal (H) 30.5° and vertical (V) 23° , which was connected to a GPS clock. The other was a Watec902H with a 25 mm f/1.4 lens, NTSC format (30 frames/sec) and a FOV of (H) 14° (V) 10.5° . These cameras are routinely used for sprite observations during the ILAN (Imaging of Lightning and Nocturnal flashes) winter campaigns in Israel [Ganot et al., 2007]. The video stream from both cameras was analyzed in real time by an event detection software (UFO Capture, www.sonotaco.com/e_index.html), thus avoiding any loss of data due to destructive compression. In all observations the 2 cameras were bore-sighted ($\pm 2^\circ$) such that they were aimed in the same direction.

3. Electrophonics

Due to the fact that our antenna can detect lightning discharges from a great distance, our main objective was to distinguish between lightning and suspected individual VLF pulses from meteors. Price and Blum [2000] have shown for the Leonids meteor shower during November 1999 two distinct differences between the lightning and the meteor signals. First, while the lightning pulse lasts no longer than 1 millisecond, the meteor pulse continues for up to 10 milliseconds. Second, the amplitude of the lightning is much larger than the meteor pulse. In order to differentiate between the two phenomena we

took all the captured optical images of the incoming meteors, which had GPS time stamps, from the Perseids and Leonids meteor showers and compared them to our VLF data at the same GPS times. An example of a meteor snapshot time series extracted from a captured optical video is shown in Figure 1. Since the meteors optical signatures vary from several tens of milliseconds to several seconds, the VLF data was analyzed for different time frames before and after the first captured image of each event. For the Perseids shower during 2007, a total number of 110 events were captured, while for the Leonids shower during 2007, 59 events were captured, and as for the Perseids shower during 2009, 31 events were captured.

Figure 1. Meteor snapshot time series extracted from a captured optical video. The meteor (circled in red) path as a function of the GPS time is shown from a (left upper side) to e (bottom side). The total time of this optical captured event was 718 milliseconds.

All the VLF data which is presented in this study was high pass filtered at 300 Hz in order to reduce the large noise produced by the electric power lines that operate at 50 Hz in Israel, together with some of the higher harmonics. An example of our analysis for a suspected meteor event is shown in Figure 2 along with an example for a lightning

discharge which is shown in Figure 3. These time series and their correlated dynamic spectrum are from the same data files, and therefore, the relative amplitude can be directly compared. The dynamic spectrum represents 100 milliseconds of data, where the spectrum is calculated every 10 milliseconds. The frequency is shown on the vertical axis between 0-50 kHz, while the color code represents relative amplitude of the signals, red being the largest values. The horizontal lines shown at higher frequencies represent the man-made signals from VLF transmitters around the globe, used for navigational purposes. The vertical lines represent the instantaneous electromagnetic pulses either from lightning discharges or from suspected individual meteors entering the earth's atmosphere. Furthermore, the vertical red line shown in Figure 2 represents the GPS time of the first frame as the meteor was imaged by our cameras.

Figure 2. Dynamic spectrum and its correlated time series of suspected meteor electromagnetic pulses on the night of 12 August, 2007. The vertical red line represents the GPS time of the first frame as it was captured in our cameras.

Whether all these VLF pulses (Fig. 2) are produced by different meteors, or whether each meteor produces a series of pulses, is still unknown. Furthermore, there are some difficulties in this kind of analysis since we cannot really be sure that what we suspect as

electromagnetic pulses from meteors are no more than a series of weak (or distant) lightning discharges. Additionally, due to the fact that the counts of meteors at the peak of the shower were $\sim 100/\text{hour}$ for the 2007 Perseids shower, $\sim 60/\text{hour}$ for the 2007 Leonids shower, and $\sim 140/\text{hour}$ for the 2009 Perseids shower (compared with $\sim 100/\text{sec}$ for lightning), we had great difficulty separating out objectively the individual VLF pulses from meteors relative to the background sferics from lightning around the time of our optical meteor images. We used both time series and spectral analysis along with calculated second moment values in our analysis. Nevertheless, 75% of the optical events imaged were associated with 10 msec pulses similar to that shown in Figure 2.

Figure 3. Dynamic spectrum and its correlated time series of a lightning discharge on the night of 12 August, 2007.

4. Atmospheric ionization and conductivity reduction

4.1 Atmospheric noise parameters

The primary source of VLF "noise" is global lightning activity. There are a number of statistical measures that can be used to define the properties of low-frequency radio noise [Reuveni et al., 2010]. The most common of these quantities is the voltage deviation V_d [Fieve et al., 2007] (the descriptive term has lost significance, but V_d , being a measure of the impulsiveness of the noise, is still a very useful quantity) which is widely used to characterize radio noise particularly in the CCIR reports [CCIR, 1964; CCIR, 1978; CCIR, 1988]. Although they are less often quoted, statistical distributions of the atmospheric noise envelope have considerable practical applications.

The voltage deviation (V_d , equation (4)) is defined as the ratio (in decibels) of the root-mean-square amplitude (H_{rms} , equation (2)) to the average amplitude (H_{avg} , equation (3)) of the noise envelop (e.g., CCIR, 1964).

$$H_{total} = \sqrt{H_{ew}^2 + H_{ns}^2} \quad (1)$$

$$H_{rms} = \sqrt{\frac{1}{T} \int_0^T H^2(t) dt} \quad (2)$$

$$H_{avg} = \frac{1}{T} \int_0^T |H(t)| dt \quad (3)$$

$$V_d = 20 \log_{10}(H_{rms}/H_{avg}) \quad (4)$$

It is a useful quantitative measure of the impulsiveness, or "spikiness", of the noise, due to the well-known fact that the rms average value of a distribution skewed to high values is greater than the average of the distribution [Fraser-Smith, 1995]. Values of V_d typically range from 2 to 3 dB for moderately impulsive noise, increasing to greater than 10 dB for highly impulsive noise [Huntoon and Giordon, 1981]. Values of V_d are calculated for specific frequency bands. Using this metric one can deduce that a few large sferics will increase the rms voltage more than they will increase the average voltage, thus raising the V_d value. A useful point of reference is the value of V_d for an instantaneous noise voltage whose magnitude follows a Gaussian distribution and whose phase is uniformly distributed. For Gaussian noise, with a mean value equal to zero ($\mu=0$) and standard deviation equal to one ($\sigma=1$), the envelope will follow a Rayleigh distribution, where the mean of the resulting Rayleigh distribution will be $\sqrt{\pi/2}$ while the rms value will be $\sqrt{2}$; thus, $V_d = 1.05$ [Leon-Garcia, 1994; Boyce et al., 2003]. In order to calculate the V_d parameter for any given frequency in the broadband range of 0.1-50 kHz, we were obliged to work only with the broadband data set. For each of the recorded broadband files (each day contains 96 files, one every 15 minutes), we produced a dynamic spectrum, using the Matlab specgram function (see, <http://www.mathworks.com/help/toolbox/signal/spectrogram.html>), where the spectrum was calculated every 13.3 milliseconds. The fact that the spectrum was calculated every 13.3 milliseconds along with the sampling rate of our receiving system (10^5 samples per second), gave us a frequency domain resolution equal to 75 Hz, which in turn acts as the actual bandwidth for each of the extracted frequency dependent V_d parameters. After the entire frequency range was obtained, we were able to extract any discrete frequencies as a function of the one minute recording time. We then calculated the total magnitude of the

two channels, i.e. $H_{total} = \sqrt{H_{ew}^2 + H_{ns}^2}$, in order to get only the noise envelope. After performing the last procedure, we were able to calculate the V_d parameter in accordance with equations (2) - (4).

Figure 4 shows an example of the VLF atmospheric background noise during the Perseids 2007 shower as compared with a data file two weeks prior to the shower. In the upper panel data recorded on 21/07/2007, 09:05:00 UT, yields a V_d value equal to 5.6087 dB for a frequency equal to 8.025 kHz. In the lower panel, a file recorded on 12/08/2007, 09:05:00 UT, yields a V_d value equal to 9.8596 dB for a frequency equal to 8.025 kHz. It is clear that the data file which yields a smaller V_d value (non-shower night) contains more sferics and a higher mean background level (peak of the Perseid shower).

Figure 4. VLF atmospheric noise raw data. On the upper panel raw data for 60 seconds during a regular day, 21/07/2007, 09:05:00 UT. The V_d value which correlates to this data file, at frequency equal to 8.025 kHz is 5.6087 dB. It is clear that the mean background noise level contains more sferics than the lower panel. The lower panel indicate raw data for 60 seconds during the Perseids 2007 peak shower night, 12/08/2007, 09:05:00 UT. The V_d value calculated for this data file at frequency equal to 8.025 kHz is 9.8596 dB. Since we have more VLF absorption during this time, only the strongest sferics are detected, thus rising the rms values, while the mean background noise is decreasing.

4.2 Atmospheric noise statistics

The V_d parameter was calculated every 75 Hz for all frequencies in the entire broadband range of 0.1-50 kHz. From our V_d calculations for the entire broadband range we were able to extract the most appropriate frequencies for comparing the V_d values on the days before, during, and after the peak of meteor showers. Figure 5(a)-(c) represents our results for a period of 46 days for each of the meteor showers. The V_d values are presented by the color code, where red shows the largest value, as a function of day of the year (y axis) and hours of the day (x axis). For each 1 minute synoptic data file we calculated the V_d values for a frequency of 8.025 kHz during the 2007 Perseids shower (Figure 5(a)), and a frequency of 11.85 kHz during the 2007 Orionids and Leonids, and the 2009 Perseids (Figure 5(b)-(c)). The stack plot near the Y-axis shows the daily variability along with the optical counts of the meteor showers, based on visual data entered through the International Meteor Organization (IMO) electronic report form (plotted in red dots), while the stack plot below the X-axis shows the hourly variability. The night of maximum meteors is denoted by a horizontal dashed black line. It is clear that the V_d values are higher on the days around the meteor showers. V_d values during meteor shower peak nights increase up to 2-2.5 dB (20-25%) relative to the background levels. The differences between daytime and nighttime are mainly due to different propagation conditions in the Earth-ionosphere waveguide. In daytime, ultraviolet radiation from the Sun is a primary source of ionization, causing the effective VLF reflection height of the ionosphere to be lower than during nighttime conditions. This leads to a daytime increase in the collision frequency between free electrons and the neutral air molecules causing the electrons to lose energy, which decreases their mean free path and leads to higher absorption of radio waves. We actually have better reflection, or less absorption, during nighttime, even though there is less ionization [Hargreaves, 1992].

It should also be noted that all meteor showers occurred during the summer and fall months when lightning activity in Israel is infrequent or non existent, therefore all VLF sferics originated thousands of kilometers from our station. In addition, solar and geomagnetic activity (estimated planetary A index and X-ray flux) were also low during these meteor showers.

High V_d values can be caused by either increasing the rms values (spikes) without changing the mean, or decreasing the mean with no change in the rms. So high V_d during meteor nights could mean the increased detection of intense VLF pulses, or the decreased detection of distant lightning that makes up the mean signal. Due to the small number of meteors/minute compared with lightning discharges, and the weak VLF pulses produced (section 3), it is more likely that we are detecting less distant sferics on these meteor shower nights due to inferior propagation characteristics of electromagnetic radiation within the D-region. There are two possible explanations. One is the attachment of ambient free electrons to the natural dust particles of meteoric origin, and the other is the deposition of large amount of heavy ions, such as Fe^+ and Mg^+ , with low mobility in the lower ionosphere.

Figure 5. V_d values, measured at Sde-Boker (SB) station for bandwidth (BW) equal to 75 Hz, during 4 different meteor showers along a period of 46 days for a discrete frequency band. (a) V_d values during the 2007 Perseids shower for frequency equal to 8.025 kHz. The stack plot near the Y-axis shows the daily variability along with the visual data reported by the International Meteor Organization (IMO) (plotted in red dots), while the stack plot below the X-axis shows the hourly variability. IMO data for the 2007 Perseids shower peak night was ~ 100 meteors/hour. (b) V_d values during the 2007 Orionids and Leonids showers for frequency equal to 11.850 kHz, IMO data for the 2007 Orionids and Leonids showers peak nights was ~ 80 meteors /hour and ~ 60 meteors /hour respectively. (c) V_d values during the 2009 Perseids shower for frequency equal to 11.850 kHz, IMO data for the 2009 Perseids shower peak nights was ~ 180 meteors /hour. Local time (LT) is equal to UT +2.

When an electromagnetic wave is incident upon a plasma the electrons oscillate. These oscillations are damped by electron-heavy particle (neutral and ion) collisions. The electron-neutral and electron-ion collision frequencies, ν_{en} and ν_{ei} , increase with decreasing altitude and can be in most cases reasonably well approximated by the following expressions [Kelley, 1989]:

$$\nu_{en} = 5.4 \times 10^{-10} n_n T_e^{\frac{1}{2}} \quad (4)$$

$$\nu_{ei} = [34 + 4.18 \times \ln(\frac{T_e^3}{N_e})] N_e T_e^{-\frac{2}{3}} \quad (5)$$

where ν_{en} and ν_{ei} are measured in s^{-1} , the neutral and electron concentrations n_n and N_e in cm^{-3} , and the electron temperature (T_e) in degrees K. At D-region altitudes the electrical properties of the plasma are strongly dominated by collisions with the neutrals, thus the electrical conductivity becomes isotropic, and can be expressed approximately as

$$\sigma \cong \frac{e^2 N_e}{m_e \nu_{en}} \quad (6)$$

Since VLF waves, which are the focus of the present study, are reflected at D-region heights (~ 85 km), their propagation is affected by modifications in the ionospheric conductivity which, in accordance with the term given in (6), are caused by changes in the electron density N_e and/or in electron-neutral collision frequency ν_{en} which, in line with (4), is governed by changes in electron temperature.

5. Conclusions and Discussion

In this paper we have revisited the two hypotheses concerning VLF electromagnetic radiation and meteors. Continuous measurements of VLF electromagnetic waves were performed during the Perseids, Orionids, and Leonids meteor showers during August, October, and November, accordingly, in 2007 and 2009.

In our attempt to objectively isolate VLF pulses related to optical meteor images, we were not successful. Although we did detect VLF pulses associated with 75% of imaged meteors, there are some difficulties in this kind of analysis since we cannot really be sure that what we suspect as electromagnetic pulses from meteors are no more than a series of weak (or distant) lightning discharges. Keay [1980; 1993] predicted that the VLF signal generated by the meteoroid interaction with the geomagnetic field will be sustained, possibly observable over an extended period of time, and it will be distinct from background atmospheric sources. However, Beech and Foschini [2001] pointed out that unless the meteor generated VLF signal has characteristics that clearly distinguish it from background lightning sources, one cannot simply claim that because short-lived VLF transient are observed at the same time that a meteor is seen that the two observations are causally related. This topic needs additional research.

In an attempt to investigate the impact of meteors on the atmospheric ionization and the effects of meteoric dust attachment along with the contribution heavy ions, we have presented the data analysis of atmospheric noise statistics on the nights of 4 meteor shower events. Our results indicate that the V_d parameter, representing the ratio of the strongest VLF noise to the average background noise, is higher on the nights of the meteor showers. V_d values increase up to 2-2.5 dB (20-25%) relative to the background

levels. It is clear from this study that meteor showers do modify the lower ionosphere, and hence the VLF radio propagation characteristics during these events.

We suggest that enhancements in the V_d values are related to a decrease in the VLF background noise reaching our station. This can be explained by either the attachment of ambient free ionospheric electrons on the dust particles which are deposited along the meteor trail and sedimented down, and/or the deposition of large amounts of heavy ions with low mobility, creating sporadic E-layers which are well-defined and limited in space and time. These ionospheric modifications might cause more absorption or inferior reflection conditions for the main VLF noise which is produced by global lightning activity. It should be noted that the ionization effect is seen primarily during local nighttime hours.

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References

- Andrews, A.D., T.W. Rackham, and P.A. Wayman, The meteorite of April 25, 1969, *Nature*, **222**, 727–730 (1969).
- Beech, M., P. Brown, and J. Jones, VLF detection of fireballs, *Earth, Moon and Planets*, **68**, 181–188 (1995).
- Beech, M., and L. Foschini, Leonid electrophonic bursters, *Astrophys.*, **367**, 1056 (2001).
- Blagdon, C., An account of some late fiery meteors; with observation, *Phil. Trans. R. Soc. London*, **74**, 201–232 (1784).
- Boyce, Lee Jr., J. David Powell, Per K. Enge, and Sherman C. Lo., A time domain atmospheric noise level analysis, *Proc. of the International Loran Association, 32nd Annual Meeting*, Boulder, CO (2003).
- Burgess, W. C. , and U. S. Inan, The role of ducted whistlers in the precipitation loss and equilibrium flux of radiation belt electrons, *J. Geophys. Res.*, **98**, (A9), 15,643–15,665 (1993).
- CCIR. World distribution and characteristics of atmospheric radio noise, Report 322, International Radio Consultative Committee, International Telecommunication Union, Geneva (1964).
- CCIR. Worldwide minimum external noise level, 0.1 Hz to 100 GHz, Report 670, in Recommendations and Reports of the CCIR, 1982, 1, International Radio Consultative Committee, International Telecommunication Union, Geneva (1978).
- CCIR. Characteristics and applications of atmospheric radio noise data, Report 322-3, International Radio Consultative Committee, International Telecommunication Union, Geneva (1988).
- Cohen, M., The Stanford University ELF/VLF receiver, <http://solar-center.stanford.edu/SID/AWSOME/> (2006).

- Chakrabarti, S.K., S. Pal, K. Acharya, S. Mandal, S. Chakrabarti, R. Khan, and B. Bose, VLF observation during Leonid Meteor Shower-2002 from Kolkata, *Indian J. Phys.*, **76B**, 686–693 (2002).
- Dubin, M., Meteor ionization in the E-region, *J. Atmos. Terr. Phys., Spec. Suppl.*, **2**, 111–118 (1955).
- Fievet, S., P. Portala, and L. Bertel, A new VLF/LF atmospheric noise model, *Radio Sci.*, **42**, RS3009, doi:10.1029/2006RS003513 (2007).
- Fraser-Smith, A.C., Low-frequency radio noise. in *Handbook of Atmospheric Electrodynamics*, CRC Press, Volume 1, 297–310 (1995).
- Ganot, M., Y. Yair, C. Price, B. Ziv, Y. Sherez, E. Greenberg, A. Devir, and R. Yaniv, First detection of transient luminous events associated with winter thunderstorms in the eastern Mediterranean, *Geophys. Res. Lett.*, **34**, L12801, doi:10.1029/2007GL029258 (2007).
- Gardner, C. S., X. Tao, and G. C. Papen, Observations of strong wind shears and temperature enhancements during several sporadic Na layer events above Haleakala, *Geophys. Res. Lett.*, **22**, 2809–2812 (1995).
- Gelinas, L. J., K. A. Lynch, M. C. Kelley, R. L. Collins, M. Widholm, E. MacDonald, J. Ulwick, and P. Mace, Mesospheric charged dust layer: Implications for neutral chemistry, *J. Geophys. Res.*, **110**, A01310, doi:10.1029/2004JA010503 (2005).
- Grebowsky, J. M., A. Goldberg and W.D. Pesnell, Do meteor showers significantly perturb the ionosphere? *J. Atmos. Solar-terr. Phys.*, **60**, 607–615 (1998).
- Hargreaves, J. K., The Solar-terrestrial Environment, Cambridge University Press, 221–231, 261–266 (1992).
- Hawkins, G.S., Radio noise from meteors, *Nature*, **181**, 1610–1611 (1958).
- Heinrich, D., U. Blum, B. Williams, J. Vance, C.Y. She, W. Singer, and U.P. Hoppe, Observations of wintertime mesopause temperatures with the ALOMAR Weber Na lidar during winter 2004/05, *ESA SP-590*, 133–137 (2005).
- Herlofson, N., The theory of meteor ionization, *Phys. Soc. Rep. Prog. Phys.*, **11**, 444–454 (1948).
- Huntoon, Z. M. and A. A. Giordano, Rms-to-average deviation ratio for interference and atmospheric noise, Proc. 4th Symp. Electromagn. Compat., T. Dvořák, Ed., 33 (1981).
- Kane, T., and C. Gardner, Structure and seasonal variability of the nighttime mesospheric Fe layer at midlatitudes, *J. Geophys. Res.*, **98**(D9), 16875–16886 (1993).
- Keay, C.S.L., The 1978 New south wales fireball, *Science*, **210**, 11–15 (1980).
- Keay, C.S.L., Progress in explaining the mysterious sounds produced by very large meteor fireballs, *J. Sci. Explor.*, **7**, 337–354 (1993).
- Kelley, M. C., The Earth's Ionosphere: Plasma Physics and Electrodynamics, Academic Press, Inc. (1989).
- Kotadia, K. M., Meteors and E_s ionization, *J. Sci. Ind. Research*, **17A**, 46–49 (1958).
- Kulkarni, V. H. and P. Muralikrishna, The role of dusts on the equatorial electrojet currents, *J. Atmos. Solar-terr. Phys.*, **68/2**, 228–235, doi:10.1016/j.jastp.2005.10.007 (2005).
- Leon-Garcia, A., Probability and Random Processes for Electrical Engineers, 2nd Ed., Addison-Wesley Publishing Company, Redding Massachusetts (1994).

- McNeil, W., R. Dressler, and E. Murad, Impact of a major meteor storm on Earth's ionosphere: A modeling study, *J. Geophys. Res.*, **106**(A6), 10447-10465 (2001).
- Merlino, L. and J. A. Goree, Dusty plasmas in the laboratory, industry and space, *Phys. Today*, **57**(7), 32–38 (2004).
- Muralikrishna P. and V. H. Kulkarni, On the height variation of the E-region cowling conductivity – effect of charged dust particles, *Ann. Geophys.*, **24**, 2949 (2006).
- Nicolet, M., Meteor ionization and the nighttime E-layer, *J. Atmos. Terr. Phys., Spec. Suppl.*, **2**, 99-110 (1955).
- Palaniswamy, V. I. and C. M. Purushotham, Stability of shear flow of stratified fluids with fine dust, *Phys. Fluids*, **24**, 1224 (1981).
- Price, C. and M. Blum, ELF/VLF radiation produced by the 1999 Leonid meteors, *Earth, Moon and Planets*, **82-83**, 545–554 (2000).
- Reuveni, Y., C. Price, E. Greenberg, and A. Shuval, Natural atmospheric noise statistics from VLF measurements in the eastern Mediterranean, *Radio Sci.*, doi:10.1029/2009RS004336 (2010).
- Romig, M.F. and D.L. Lamar, Anomalous sounds and electromagnetic effects associated with fireball entry, *RAND Memo. RM-3724-ARPA* (1963).
- Schunk, R. and A. Nagy, *Ionospheres: Physics, Plasma Physics and Chemistry*, Cambridge University Press, Atmospheric and Space Science Series, 2nd edition, 628 pp (2009).
- Udden, J.A., A Texas meteor, *Science*, **46**, 616–617 (1917).

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