An explanation for the seasonal dependence of midlatitude sporadic *E* layers

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[1] The midlatitude sporadic *E* layers form when metallic ions of meteoric origin in the lower thermosphere are converged vertically in a wind shear. The occurrence and strength of sporadic *E* follow a pronounced seasonal dependence marked by a conspicuous summer maximum. Although this is known since the early years of ionosonde studies, its cause has remained a mystery as it cannot be accounted for by the windshear theory of E_s formation. We show here that the marked seasonal dependence of sporadic *E* correlates well with the annual variation of sporadic meteor deposition in the upper atmosphere. The later has been established recently from long-term measurements using meteor radar interferometers in the Northern and Southern Hemispheres. Knowing that the occurrence and strength of sporadic *E* layers depends directly on the metal ion content, which apparently is determined primarily by the meteoric deposition, the present study offers a cause-and-effect explanation for the long-going mystery of sporadic *E* layer seasonal dependence.

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1. Introduction

[2] The midlatitude sporadic *E* layers (E_s), which are narrow layers of metallic ion plasma forming at *E* region heights from 90 to 130 km, have been researched extensively over many decades, e.g., see reviews by *Whitehead* [1989] and *Mathews* [1998]. The physics behind sporadic *E* layers relies on the so called ‘‘windshear’’ theory which is now widely accepted as the mechanism responsible for their formation [e.g., see *Whitehead*, 1989, and references therein]. In this theory vertical shears in the horizontal wind can drive, by the combined action of ion-neutral collisional coupling and geomagnetic Lorentz forcing, the long-lived metal ions in the lower thermosphere to move vertically and converge into dense plasma layers. Atmospheric wave dynamics play the key role in this formation process by providing the vertical wind shears needed for ion convergence. Of particular importance are the wind shears in relation with the diurnal and semidiurnal tides which are present regularly in the lower thermosphere [e.g., *Mathews*, 1998; *Haldoupis et al.*, 2006].

[3] Among the properties of sporadic *E* layers that have been studied extensively are those relating to their variability. An important element of E_s variability is the seasonal dependence that is marked by a pronounced summer maximum, which, however, is inexplicable from the windshear theory. In his 1989 review paper *Whitehead* [1989] stated, regarding the E_s morphology that: ‘‘We conclude that the windshear theory is the only viable theory that explains the detailed production of the layers. Nevertheless, it does not explain the overall morphology of sporadic *E*, in particular the large summer maximum.’’ To date, there is not yet a comprehensive explanation, thus the seasonal dependence of sporadic *E* remains an open problem.

[4] The present paper offers an explanation for the longstanding mystery of sporadic *E* seasonal dependence. It relies on the close correlation found between the annual variation of sporadic *E* layer strength and that of meteoric deposition rates. The latter has been revealed by meteor radar interferometers operating over long time periods in Northern and Southern Hemisphere locations. Recent meteor studies established a strong seasonal dependence for the daily meteor counts which, as in sporadic *E*, is marked by a strong summer maximum [e.g., see *Singer et al.*, 2004, *Janches et al.*, 2004; *Lau et al.*, 2006; *Campbell-Brown and Jones*, 2006; P. T. Younger and N. J. Mitchell, Sporadic meteors observed by radar at Arctic, equatorial, and Antarctic latitudes: Sporadic radiants and the distribution of radio meteors in the atmosphere, submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Younger and Mitchell, submitted manuscript, 2007]. This variability has been attributed to the fact that sporadic meteor radiants were not randomly distributed but arrived from well-defined sources located near the ecliptic plane.

[5] The present study shows that there is a good correlation between the sporadic *E* strength and meteor counts,

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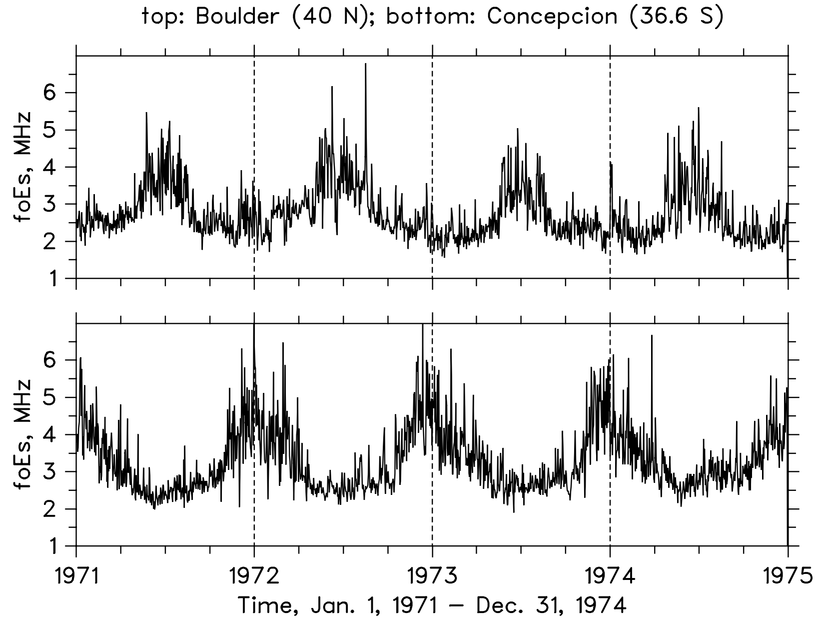

Figure 1. Typical annual variability of sporadic *E* critical frequencies *foEs* measured simultaneously in the Northern (Boulder, 40°N) and Southern (Concepcion, 36.6°S) Hemispheres. This seasonal variation, which is known for many years, is dominated by a strong summer maximum.

which cannot be accidental since the meteoric influx is the main source of the long-lived metal ions needed for the formation and intensification of *Es*. The metal ion content was one of the reasons to be considered in the explanation of sporadic *E* seasonal morphology in earlier papers [e.g., see *Whitehead*, 1989], but it was then excluded because the origin of sporadic meteors in space was thought to be random.

[6] In the following we first summarize our knowledge on sporadic *E* and meteoric influx seasonal dependencies and then compare those dependencies by using simultaneous measurements over several years. We stress that the present study does not aim in examining all the aspects of the problem and there is need for more work.

2. Seasonal Variation of Sporadic *E*

[7] Several statistical studies published over the years [e.g., see review by *Whitehead*, 1989] show that E_s is marked by a strong summer maximum which forms during June–July and December–January in the Northern and Southern Hemispheres, respectively. This is illustrated in Figure 1, which displays times series of critical sporadic *E* frequency daily means over a period of 4 years from 1 January 1971 to 31 December 1974, observed simultaneously in Boulder, Colorado (40°N; 105.3°W) and Concepcion, Chile (36.6°S; 73.0°W). Note that the layer critical frequency *foEs*, is used widely in sporadic *E* studies to quantify the layer's intensity and variability. On the basis of on the simplified form of the magnetoionic theory, *foEs* relates approximately to the maximum electron density in the layer, N_{em}, which can be estimated from the equation: $foEs \approx 9.0\ (N_{em})^{1/2}$, where N_{em} is in m^{-3} and *foEs* in Hz.

[8] As seen in Figure 1, the layers intensify strongly around the summer solstice, in both Northern and Southern Hemispheres, with the mean *foEs* summer increases exceeding on the average 100% relative to the equinoctial and winter months. Although in Figure 1 there are significant shorter period changes present in the seasonal pattern, the most noticeable feature that sticks out clearly is the dominant summer maximum. This is a typical behavior that is also present in sporadic *E* occurrence. The latter is known to be more pronounced for the more intense layers, as shown for example by *Sprenger* [1981] who presented statistics of seasonal *Es* occurrences by using ionosonde recordings from central Europe over a period of 22 years.

[9] The annual *foEs* pattern shown in Figure 1 is characterized in the Northern Hemisphere by a sharp rise during May followed by a fairly flat maximum during June–July and then a more gradual decrease as time moves toward winter which makes the variation somewhat asymmetric about the summer maximum. The same variations prevail also in the Southern Hemisphere but these lag the Northern Hemisphere ones by 6 months. Interestingly, the same annual morphology is also valid for auroral sporadic *E*, as shown for example by *Bedey and Watkins* [1996] who analyzed incoherent scatter radar observations of the high-latitude ionosphere. As well, the same seasonal dependence is present in the occurrence and strength of VHF coherent backscatter at midlatitude [e.g., *Haldoupis and Schlegel*, 1996, and references therein] obviously as a direct consequence of its close relation to sporadic *E* layers [e.g., *Hussey et al.*, 1998].

[10] The *Es* seasonal morphology attracted considerable attention through the many years of sporadic *E* research. The results of several studies on this topic are summarized and evaluated by *Whitehead* [1989] in his comprehensive review paper. It is concluded that the E_s seasonal dependence is inexplicable from windshear theory and remains one of its weakest points.

[11] More recently, *Shalimov et al.* [1999], suggested a possible explanation for the E_s seasonal dependence based

on vortex flows associated with planetary waves which are known to affect the formation of sporadic *E* layers through the modulation of diurnal and semidiurnal tides [e.g., see *Haldoupis and Pancheva*, 2002; *Pancheva et al.*, 2003]. The postulation of *Shalimov et al.* [1999] relied on the apparent association which exists with the seasonal variation of the quasi 2 day planetary wave (QTDW) mean amplitude that also peaks during summer [e.g., see *Jacobi et al.*, 1998]. Given that the QTDW is a small part of the wind system above 100 km that produces E_s (since the major role is played by the 24- and 12-hour tides), and because different planetary wave modes have different seasonal behavior, we suggest that the seasonal QTDW variations hypothesized by *Shalimov et al.* [1999] cannot be the key agent that controls E_s morphology.

[12] Since sporadic *E* layers are mainly due to metallic ions provided by the atmospheric ablation of meteoroids, their mean electron density (intensity) and occurrence are expected to be directly proportional to the metal ion content. The role of metallic ions is recognized widely as being a key factor in *Es* occurrence, and often it has been associated with the sporadic nature of the phenomenon [e.g., see *Whitehead*, 1989]. The metal ion content is determined by the meteoric deposition, the recombination loss by three body reactions that become more efficient at lower *E* region heights, and the photoionization of metal atoms, or during nighttime, charge exchange ionization of the metal atoms, as shown by *MacDougall et al.* [2000].

[13] Although the photoionization by itself provides a clue to the explanation of the seasonal E_s maximum, because during summer the solar radiation will ionize more of the metal atoms, this is far from sufficient to account for the strong E_s summer maximum. Under the assumption that there is no dependence of metal atom ionization on metal ion density, *Whitehead* [1989] concluded that the photoionization should result to a small increase of a few percent, very much in proportion to that in the critical *E* region frequencies, *foE*. This is well below the over 100% increases in *foEs* observed during summer.

[14] With respect to the loss mechanism of metal ions and a possible role on the E_s summer maximum, this again requires a peculiarity of the wind profile during the summer in the context of the windshear mechanism. The metal ions are removed from the formation process by being swept down to lower heights where they recombine by three body collision reactions. Their transport to lower heights is controlled by the downward propagation of wind shear ion convergent nodes associated with the tides [e.g., see *Chimonas and Axford*, 1968]. This has been observed to take place on a routine basis with ionosondes (e.g., see a recent study by *Haldoupis et al.* [2006]) and the Arecibo incoherent radar [e.g., see *Mathews*, 1998]. There might be some seasonal differences in the tidal modes involved in E_s formation, as recommended for example by the ionosonde studies of *Haldoupis et al.* [2006] which favored the presence of diurnal tides with short vertical wavelengths in July. However, there exists no evidence to suggest that something dramatic is happening in the tidal descent of sporadic *E* during summer which traps the metal ions at a height at which they cannot recombine and thus contribute toward a strong summer maximum in sporadic *E*.

[15] Finally, the increase of metal ion content caused by meteoric input increases was also considered in the past (e.g., see again review by *Whitehead* [1989]) as a possible cause of the E_s summer maximum. It was, however, excluded on the basis that meteoric input was sporadic and that no statistical evidence existed that favored a strong seasonal dependence. It now turns out that this was an unfortunate conclusion because, as shown below, the annual changes in metal ion content are significant and likely this is the cause behind the E_s seasonal dependence.

3. Seasonal Variation of Meteoric Input

[16] The meteors entering the atmosphere undergo intense frictional heating that causes light and ionization and rapid evaporation of the meteoric material. The meteoric influx constitutes a continuous source of extraterrestrial metal atoms in the lower thermosphere. These provide through photoionization the reservoir of long-lived metal ions needed for the formation of sporadic *E* layers. The meteors classify as sporadic and shower meteors, with the former being responsible for about 90% of the meteoric material deposited in the upper atmosphere [e.g., see *Ceplecha et al.*, 1998]. The shower meteors move in parallel paths and have radiants originating from a small area on the celestial sphere, whereas the sporadic meteors are dispersed and appear to have a broad distribution of radiants over the entire sphere.

[17] Although radio observations of meteors have been made since the late forties and many aspects of meteor science matured in the sixties, it is only recently that a methodology was developed, using state-of-the-art meteor radar interferometry, which led to the statistical determination of the annual variability of meteoric input in both the Northern and Southern Hemispheres. These studies have shown that the sporadic meteor flux is neither isotropic nor constant. Among other properties they revealed a pronounced seasonal variation in the observed meteor count rates that is characterized by a pronounced summer maximum.

[18] *Singer et al.* [2004] reported a strong annual variation of the mean daily meteor counts, with the largest values observed in summer and the lowest count rates in winter. They arrived at this finding by analyzing SKYiMET 33 MHz interferometer meteor radar measurements from the Northern Hemisphere, first at an upper midlatitude location (Juliusruh, 54.6° N) from November 1999 till August 2001, and then at an arctic site (Andenes, 69.3° N) from October 2001 till February 2004. Their measurements of the daily meteor counts showed that the meteoric input undergoes a strong annual variation, for both Juliusruh and Andenes, which is marked by a peak during June–July and a broad minimum in January–February. It is important to stress that this seasonal variability is particularly pronounced since the summer meteor rates are about 3 times higher than those in the winter months. In addition, they showed the annual variations of meteor rates to increase sharply as time progresses from spring into summer, but to decrease less abruptly as time moves from summer into fall and winter. This makes the variation asymmetric about the summer peak.

[19] *Singer et al.* [2004], who performed a detailed analysis of the Juliusruh and Andenes meteor count data, found no major difference with latitude between the relative changes from maximum to minimum rates. They also

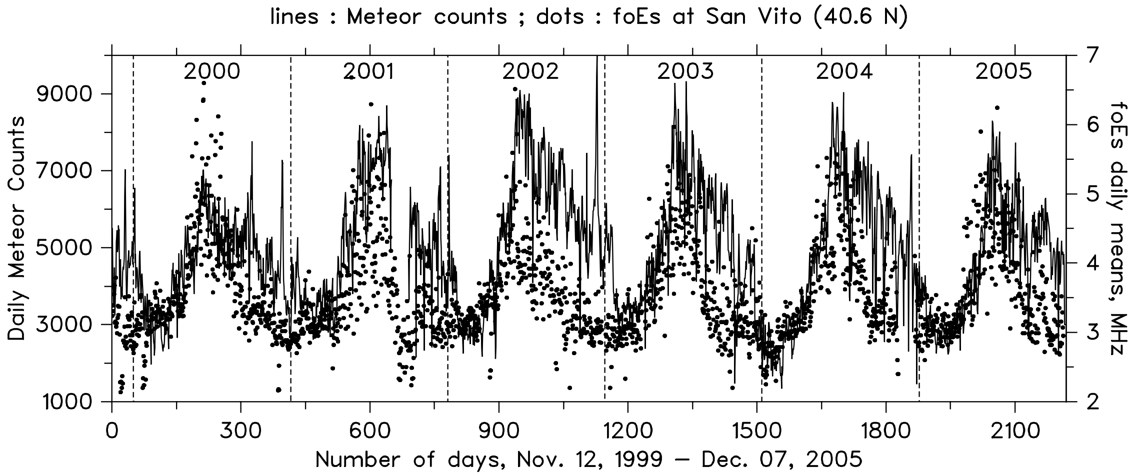

Figure 2. Comparison of the annual variability of daily meteor counts (solid line) measured in the Northern Hemisphere with the mean daily sporadic *E* critical frequency (*foEs*) values measured simultaneously with the San Vito ionosonde at 40.6°N. As seen, there is a good degree of agreement between the annual variations of both parameters.

pointed out that their seasonal meteor rate dependence agreed well with a much earlier study by *Hawkins* [1956] who reported a strong June/July maximum and a February minimum in sporadic meteor counts measured with a 53 MHz radar located at 53.3°N in Jodrell Bank, UK. *Hawkins* [1956] also found that the sporadic meteor radiants are not random in space but directed toward the plane of the ecliptic, and thus explained the summer (winter) maximum (minimum) as a result of the Earth's tilt to the ecliptic plane. Obviously, the study of Hawkins, which would have been quite helpful to the early researchers for understanding the sporadic *E* layer seasonal dependence, must have escaped attention.

[20] Soon after *Singer et al.* [2004] published their paper, *Janches et al.* [2004] reported a similar study based on meteor observations made with a VHF meteor radar deployed near the South Pole in Antarctica. Preliminary results showed that the meteor flux maximizes during the Antarctic summer months and minimizes during winter, in line with what *Singer et al.* [2004] have found for the Arctic. The results of *Janches et al.* [2004] were substantiated further by detailed interferometer measurements of the same Antarctic meteor radar, reported by *Lau et al.* [2006]. They also found that the strong summer peak is because the meteors originate mostly from discrete sources near the ecliptic plane roughly ~20° wide in terms of elevation angle spread.

[21] Finally, a detailed study of sporadic meteor count rates observed with three SKYiMET meteor radars at Esrange, Sweden (68°N), Ascension Island (8°S), and Rothera, Antarctica (68°S), has been carried out recently by Younger and Mitchell (submitted manuscript, 2007). The daily meteor count rates at Esrange cover a total of 6 years from January 2000 to December 2005, and their time series compare very well with the seasonal variations measured by *Singer et al.* [2004] simultaneously in Juliusruh and Andenes. Their observations in Rothera cover only 2005 but show a mirror-like seasonal behavior to that of Esrange that is its geographic conjugate. The Rothera radar observed a pronounced peak in meteor activity during the Antarctic summer in December, in line with the results of *Janches et al.* [2004] and *Lau et al.* [2006]. The equatorial measurements made by an identical equatorial meteor radar in Ascension Island for about a total of 4 years, show in general lower count rates undergoing a semiannual variability. This exhibits maximum count rates in the summer and winter solstices, and minimum count rates, approximately 70% of maximum, in equinoctial months. By applying a careful analysis, Younger and Mitchell (submitted manuscript, 2007) showed that the seasonal dependence of the meteor count rates was due to a number of discrete meteor sources located close to the ecliptic plane.

4. Comparison of Sporadic *E* and Meteor Influx Seasonal Dependencies

[22] The metallic ion concentration in the lower thermosphere is a key parameter that contributes to the strength and occurrence of sporadic *E* layers. The higher the metal ion contents in the lower thermosphere the stronger the sporadic layers become and thus their detection probability increases. Since the metallic ion production is caused by the photoionization of metal atoms, the metal ion content is expected to increase in direct proportion with the amount of meteoric material deposited in the atmosphere. In this way, the strong summer maximum observed for the meteor count rates implies that the ambient metal ion density does follow a similar dependence, most likely dominated also by a pronounced summer maximum.

[23] The above reasoning provides the physical base needed for a comparison between the observed seasonal dependencies of sporadic *E* and meteor count rates discussed in the previous sections. Here we attempt only a qualitative comparison, whereas a more detailed correlative analysis is outside the scope of this paper and is planned to be undertaken in a future study. In this comparison we have used the mean daily meteor counts measured by *Singer et al.* [2004], which cover a period of about 6 years from 1999 to 2005, and concurrent ionosonde *foEs* recordings from the midlatitude European stations in Juliusruh (54.6°N), San Vito (40.6°N), and Athens (38.0°N).

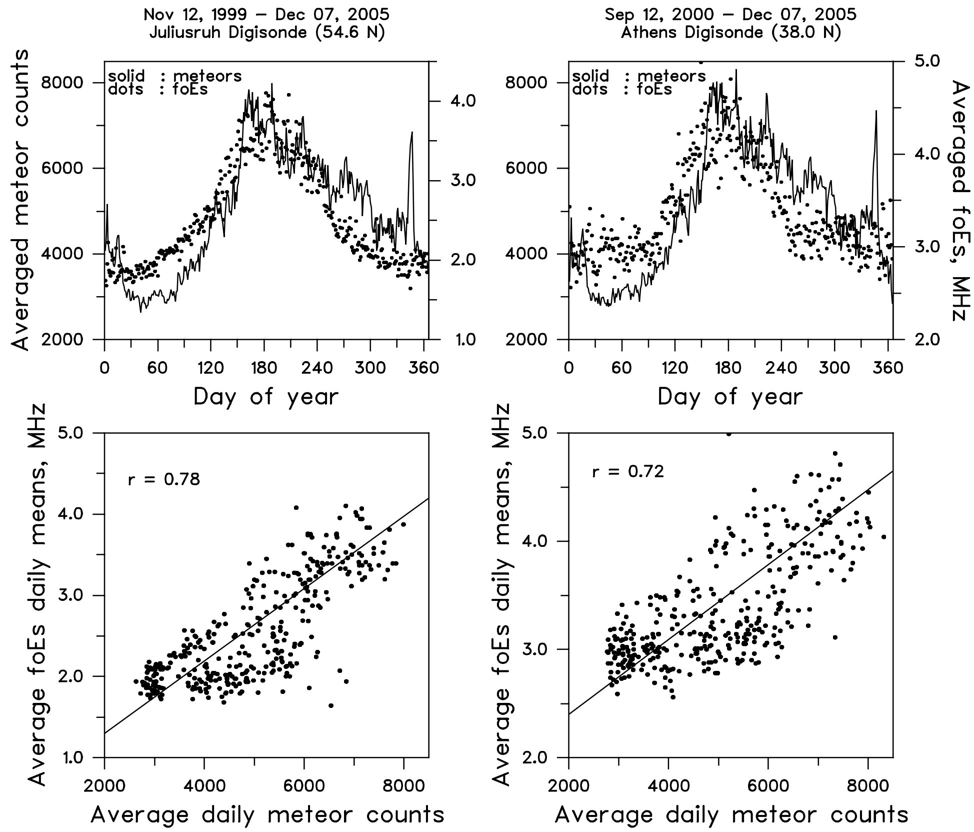

Figure 3. Comparison of the mean annual variation of meteor counts and *foEs* for two cases: (left) for the period from November 1999 to December 2005, using the Juliusruh (54.6°N) ionosonde, and (right) for the period from September 2000 to December 2005 and the Athens (38.0°N) ionosonde. As seen, the correlation between meteor count rates and sporadic *E* strength is quite good.

[24] In Figure 2, superimposed are the time series of daily meteor counts observed by a SKYiMET radar first in Juliusruh and then in Andenes (solid line), and the simultaneous *foEs* daily means recorded at the Italian station of San Vito (dots). Both measurements are nearly continuous and cover the time interval from 12 November 1999 until 7 December 2005. Inspection of Figure 2 shows a good deal of agreement between the seasonal variability of the two parameters, characterized mainly by the coincidence of their summer peaks during June–July and their minima during the winter months. On the other hand, there are differences as well, especially at shorter timescales, for example in relation with count peaks identified with meteor showers, something that has been recognized in previous studies as well [e.g., see *Whitehead*, 1989]. In particular we find poor correlation between the observed *foEs* values and the meteor count peaks caused by the Geminids during 13 to 14 December. Also the meteor count variation seems to be more asymmetric around the summer peak, as compared to *foEs*. Also there are some longer-term (seasonal) differences between *foEs* and meteor counts that appear to be more pronounced around autumn as time progresses from summer to winter.

[25] Note that at least part of the variance seen in Figure 2, between the daily means of *foEs* and meteor count rates, must be due to other causes because, as discussed previously, *foEs* is affected by additional factors. Since we are interested here only on the seasonal variability of sporadic *E*, it is desirable to reduce the variance by comparing the mean annual variations instead of those of individual years, shown for example in Figure 2. The averaged annual variations are shown in Figure 3, for two cases: (1) the Juliusruh ionosonde and meteor count records for the period from November 1999 to December 2005 (Figure 3, left), and (2) the Athens ionosonde and meteor count observations from September 2000 to December 2005 (Figure 3, right). Figure 3 (top) shows the direct superposition of the averaged annual variations for *foEs* and meteoric counts. As expected, there is an improved agreement between the two annual variations as compared to those in Figure 2. Both annual dependencies look very much the same, although some minor differences are still discernible, especially during meteor showers. Figure 3 (bottom) shows x-y scatter plots showing clearly a monotonic functional relationship of *foEs* on daily meteor counts, which may not necessarily be linear. Also shown are lines of linear regression and values of linear correlation coefficient estimates, which are quite high, in excess of 70%.

[26] Finally, besides the good annual correlation shown in Figure 2 and 3, there are also differences between the variations in *foEs* and the meteor counts, seen not only at short but also at larger, and even seasonal, timescales. These may be attributable to various parameters affecting the formation and strength of sporadic *E*, for example system-

atic differences in wind dynamics and climatology, as is for example the annual variation of the quasi-2 day planetary waves [e.g., see *Jacobi et al.*, 1998; *Shalimov et al.*, 1999]. Also, some of these differences may be due to seasonally dependent meteor count biases. For example, radar meteor counts may not be representative of all meteors or may not be representative of all metallic meteors; thus there might be count uncertainties relating to seasonal discrepancies in composition and metal content, as well as in latitudinal meteor count differences. In addition the metal ion content, on which apparently *foEs* depends, may not necessarily be proportional to the measured meteoric input at a given time. This is not only that we lack knowledge on the exact nature of the relationship between metal ion densities and meteor counts but also because no transport effects by neutral winds were considered here, which can alter the local concentration of the long-lived metallic ions deposited by the meteoric input. In view of all these uncertainties, the observed discrepancies between *foEs* and meteor counts are not unexpected, but also on the other hand they are not sufficient to obscure the good deal of agreement seen in their annual and overall seasonal variability.

5. Summary and Concluding Comments

[27] This paper provides convincing evidence showing that both the sporadic *E* critical frequency, *foEs*, and the meteoric influx (radar daily meteor count rates) follow a similar seasonal dependence marked by a strong summer maximum. It is shown that the annual variation of both parameters are on the average closely related, having linear correlation coefficients in excess of 0.7. In view of the anticipated dependence of sporadic *E* layer strength and occurrence (quantified by *foEs* through its relation to E_s electron density maximum) on the metal ion content, the present study has identified a cause-and-effect relation as a likely explanation for the long-known annual morphology of sporadic *E*, which so far has remained a mystery.

[28] Although there was an old study [*Hawkins*, 1956] pointing to a strong annual dependence in sporadic meteor deposition in the atmosphere, its importance for understanding the E_s annual morphology must have escaped attention. The unequivocal presence of a strong seasonal dependence for the meteoric influx was established only recently by the systematic analysis of massive data of underdense meteor echoes observed with routinely operating MLT radars in the Northern and Southern Hemispheres. These meteor studies employed interferometric techniques to measure the sporadic meteor radiant distributions. This led them to the conclusion that the vast majority of sporadic meteors come from a discrete number of sources situated near the ecliptic plane. Therefore the reason for the sporadic meteor influx seasonal dependence and its pronounced summer maximum seems to be the obliquity of the ecliptic, that is, the inclination angle relative to the ecliptic plane of the Earth's rotational axis.

[29] Finally, since our purpose here was to report only on the likely explanation of the seasonal dependence of sporadic *E*, no attempt was made to correlate in detail the simultaneous measurements of meteoric influx and E_s critical frequencies. This could include a search for establishing an approximate functional relation between the metal ion density and the meteoric influx and/or investigate the relationship of *foEs* and meteor counts at shorter timescales. The latter has been tried in several past studies which led to inconclusive results suggesting that at short term there is a more complex relation between sporadic *E* and meteoric deposition (e.g., see review by *Whitehead* [1989] and a recent paper by *Chandra et al.* [2001]). This may not be unexpected given that sporadic *E* depends critically, particularly at shorter timescales, on atmospheric wave dynamics providing the favorable wind shears needed for E_s formation. Such effects may also contribute to longer time scale sporadic *E* variability, but on the average these short-term influences are filtered/reduced when it comes to long-term seasonal changes.

[30] In view of the present findings, the seasonal variations in sporadic *E* can now be understood in terms of the metal ion content variability that is governed by the seasonal dependence of the meteoric influx into the upper atmosphere. The identification of a cause for the *E*s seasonal dependence on sporadic meteor deposition should lead to more detailed studies in order for it to be fully substantiated and properly quantified.

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