Reports

Effects of the Large June 1975 Meteoroid Storm on Earth's Ionosphere

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The June 1975 meteoroid storm detected on the moon by the Apollo seismometers was the largest ever observed. Reexamination of radio data taken at that time showed that the storm also produced pronounced disturbances on Earth, which were recorded as unique phase anomalies on very low frequency (VLF) radio propagation paths in the low terrestrial ionosphere. Persistent effects were observed for the major storm period (20 to 30 June 1975), including reductions in the diurnal phase variation, advances in the nighttime and daytime phase levels, and reductions in the sunset phase delay rate. Large nighttime phase advances, lasting a few hours, were detected on some days at all VLF transmissions, and for the shorter propagation path they were comparable to solar Lyman alpha daytime ionization. Ion production rates attributable to the meteor storm were estimated to be about 0.6 to 3.0 ions per centimeter cubed per second at the E and D regions, respectively. The storm was a sporadic one with a radiant (that is, the point of apparent origin in the sky) located in the Southern Hemisphere, with a right ascension 1 to 2 hours larger than the sun's right ascension.

An exceptionally large meteoroid storm was detected on the moon by the Apollo seismic network between 20 to 30 June 1975, attaining daily impact rates five to ten times larger than the normal steady rates (*1*). The storm has been interpreted as arising from a meteoroid cloud with a diameter of 0.1 astronomical unit and a total mass of 10^{13} to 10^{14} g. Duennebier *et al.* (*1*) have estimated that a total mass of fragments of about 1.8×10^6 g collided with the moon during the event.

To the best of our knowledge, however, no effects on Earth were reported as arising from this large event. Given the cross sections represented by Earth in comparison to the moon, a total meteoroid mass of about 2.4×10^7 g should have impacted Earth during the 10-day period, which corresponds to an average of 2.4×10^6 g/day. This is one order of magnitude larger than the most important regular Geminid meteoroid shower of about 1×10^5 to 3×10^5 g/day (0.1 to 0.3 ton/day) (*2, 3*). These numbers, however, are likely to be larger for Earth because of its larger accretion effect (*4*).

The June 1975 storm was thought to be a very rare event because of its exceptional strength (*1, 5*). The radiant direction was toward the sun. There is a suggestion that it could be an enhancement of the well-known β-Taurid daytime shower (*5*). Brecher (*6*) suggested that the June 1975 meteoroid storm was associated with the "Canterbury Swarm" as a result of the remains of an early Comet Encke fragmentation, which would also include the α-Taurid and β-Taurid showers and two asteroids (2212 Hephestos and 1982 TA). According to Brecher (*6*), the close encounter of such fragments with the Earth-moon system might have produced some extraordinary events in the past, such as the 25 June 1178 flash on the moon, reported by a Canterbury monk, and the 30 June 1908 Tunguska event in Siberia.

The storm might also be the result of a more recent large fragmentation event in space. Such an event was suggested by Halliday (7), in order to explain the first observational detection of multiple meteorite falls from the same orbit (the Innisfree and Ridgedale meteorites, detected on 6 February 1977 and on 6 February 1980, respectively, almost at the same universal time (UT) and falling less than 500 km from each other).

We decided to inspect old data on very low frequency (VLF) propagation obtained in the period. Long-distance VLF transmissions propagate in an Earth-ionosphere spherical waveguide, according to well-known models (*8, 9*). The VLF phase variations are directly related to changes in the height of the upper boundary of the waveguide, located in the low terrestrial ionosphere. The boundaries are set by a certain

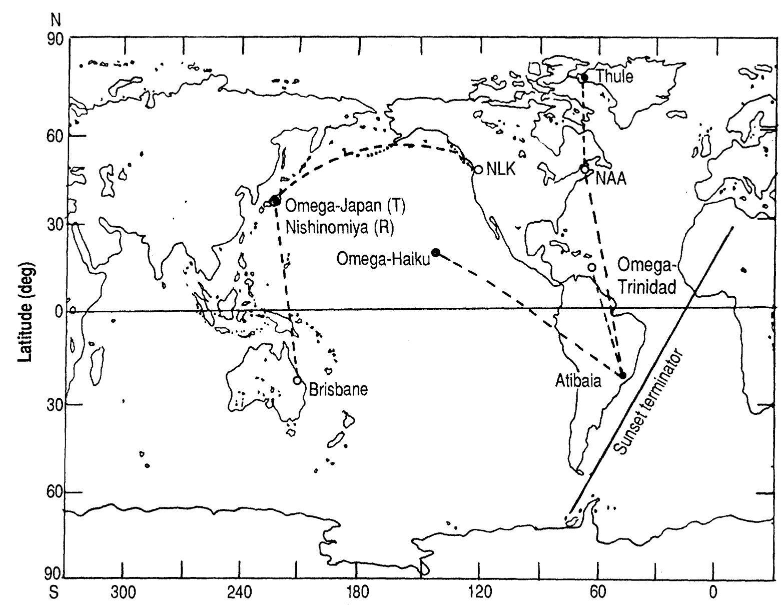

Fig. 1. VLF propagation paths and sunset terminator location in June (at about 1900 UT), considered in the present study. Data for the two high northern latitude paths were reported in the literature (*16, 17*). ○ and T, transmitters; ● and R, receivers.

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electron density. Nighttime height is typically 85 km at the ionospheric E region, whereas daytime height is 70 km at the D region. On the other hand, meteoroids are known to produce ionized trails as the result of conversion of the kinetic energy of the meteors into potential energy of ionization as the meteors are slowed down by collisions with gases in the upper atmosphere (*10*). Observational results and model predictions, assuming a dustball structure for meteoroids, relate their masses to the heights where the trails are defined (*11, 12*). For trails ending at 85 and 70 km, the meteoroid masses should be in the range of 0.1 to hundreds of grams, respectively (these figures should be considered as lower limits). Indeed, for the June 1975 storm, Duennebier *et al.* (*1*) estimated the density of the cloud, for an assumed distribution for the detected objects, and found that 18% of the mass in the observed range (50 g to 50 kg) was in the fraction with mass greater than 5 kg.

The effects of regular meteoroid showers in VLF transmissions have been known for some time (*12–15*). However, the showers are known to produce small 4 to 7σ deviations in nighttime mean phase levels, which can be observed only in the absence of other anomalous propagation effects (caused by particle precipitation and high geomagnetic activity).

We searched for effects of the June 1975 event on the VLF propagation paths shown in Fig. 1. Data were available in strip charts and were reduced every 30 min. The transmissions received at Itapetinga Radio Observatory, Atibaia, Brazil, were from the radio transmitters Omega-Trinidad (at 10.2 and 13.6 kHz), Omega-Haiku, Oahu, Hawaii (10.2 kHz), and NAA, Cutler, Maine (17.8 kHz). Omega-Japan (10.2 and 13.6 kHz) transmissions were received at the University of Queensland, Brisbane, Australia. Propagation data from NLK (18.6 kHz), Jim Creek, Seattle, Washington, obtained at Nishinomiya, Japan, did not show any important anomaly in the period of interest (*16*). NAA (17.8 kHz) signals received at Thule, Greenland, exhibited a smooth change in diurnal phase variation, with a minimum signal late in June (*17*), a normal effect that may be attributed to a seasonal dependence, because that propagation path is under sunlight nearly all the time in the northern summer.

Limited by the observing schedules, the data gathered at Atibaia covered the period 17 to 30 June 1975, and the undisturbed days used for comparison were 17 and 18 June 1975. The data from Brisbane covered a larger period, 3 June to 15 July 1975, with the best undisturbed days 28 June to 13 July. The NAA data received at Atibaia were difficult to analyze and required daily adjustments, because of the phase jumps that occur when the two transmitting antennas are switched. Omega-Japan (13.6 kHz) and other VLF data received at Brisbane were quite noisy and difficult to analyze.

The VLF propagation anomalies, correlated in time with the June 1975 meteoroid storm, have been detected in four ways: (i) a daytime phase advance in the period; (ii) large anomalous nighttime phase advances (lasting a few hours on some days) particularly pronounced on Omega-Trinidad transmissions, where they attained amplitudes comparable to Lyman-α ionization during sunrise; (iii) a phase advance of the mean nighttime phase level and a reduction in the diurnal phase variation, which were partly caused by the important anomalies (ii); and (iv) a pronounced reduction in sunset phase delay time rates, at all transmissions, indicating the presence of an extra ionizing source. In 21 years of VLF observations in Brazil, we had not seen effects (i), (ii), and (iv) before.

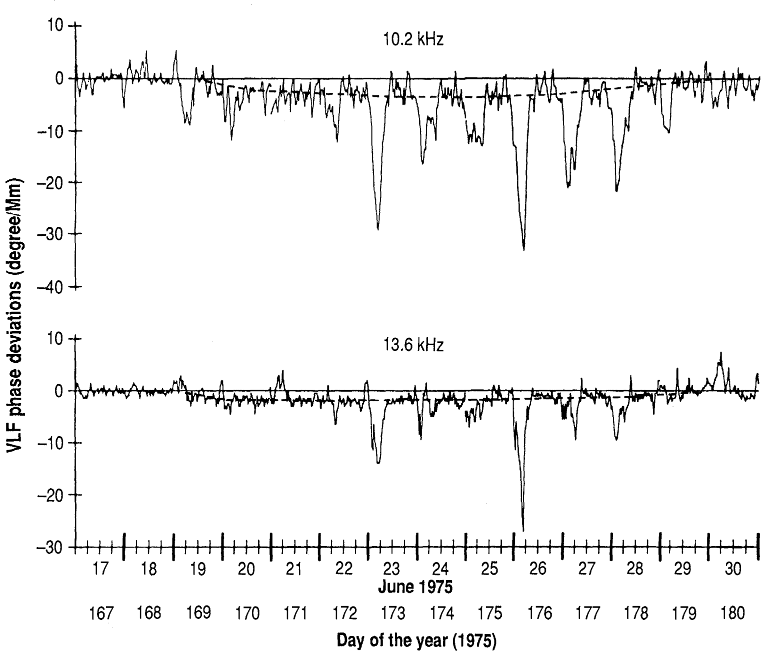

Fig. 2. Phase time behavior of Omega-Trinidad VLF transmissions received at Atibaia, Brazil, at 10.2 kHz and 13.6 kHz, after filtering the typical diurnal variations. Dashed lines indicate the steady phase advance at night and day in the period. The most pronounced anomalies occurred on 23 to 27 June 1975.

The VLF phase behavior in the period of interest, for the shortest southern propagation path (Omega-Trinidad to Atibaia, Brazil), is shown in Fig. 2. We filtered the data, subtracted the normal diurnal phase variation, and used the mean readings from 17 and 18 June 1975 as typical. The most important anomalies are evident, such as the steady daytime phase advance of about 2.9 degrees/Mm (at 10.2 kHz; units are in degrees per megameter of propagation path) and 1.8 degrees/Mm (at 13.6 kHz) from 19 to 28 June 1975; the steady nighttime phase advance and large anomalies, which consequently contributed to the reduction in the mean diurnal phase variation.

These effects were also present in the other transmission, but to a lesser extent relative to the larger normal diurnal phase variations (because of the longer paths). The effects are more pronounced at the lower VLF frequency of 10.2 kHz (Fig. 2), a trend confirmed in all other transmissions analyzed in this study.

The large nighttime phase advances are particularly pronounced on 23 and 26 June 1975. They might be attributed to ionospheric disturbances produced in the daytime side of Earth, affecting the nighttime ionosphere as well through a number of mechanisms, such as traveling disturbances guided by E-region winds (*10*).

On the other hand, in Fig. 3 we show the daily deviations of the diurnal phase variations with respect to the mean in undisturbed days for all transmissions (in degrees per megameter of path length), compared to the meteoroid impact rates on the moon (*1*). The correlation is rather remarkable, especially in the period 22 to 29 June 1975. The Brisbane data, however, suggest that the effects started several days earlier, becoming further enhanced on 20 to 26 June, disappearing afterwards. Similar plots are obtained for the other anomalies.

During the storm period, the sunset phase delay slope with time became considerably smaller than the normal one in most of the transmissions. However, no anomaly was found in the sunrise phase advance slope with time. The sunset phase delay is the result of a combined effect of electron-ion recombination and the terminator movement along the propagation path. The phase delay time rate ($\dot{\varphi}_D$) may be represented as approximately

$$\dot{\varphi}_D = \dot{\varphi}_N - \dot{\varphi}_q \qquad (1)$$

where $\dot{\varphi}_N$ is the normal rate of change of phase at sunset, which is the observed disturbed rate, and $\dot{\varphi}_q$ the change due to the production rate, q, of electrons attributed to the meteoroids. An order of magnitude of the rate of this production may be estimated assuming that in general any phase change is related to the well-known continuity equation ($\dot{\varphi}\ \alpha\ (dn/dt) = q - \alpha n^2$, where n is the electron density and α is the recombination coefficient). After some algebraic manipulations we obtained:

$$q \approx \alpha n^2 \left[\frac{\dot{\varphi}_N - \dot{\varphi}_D}{\dot{\varphi}_N}\right] \qquad (2)$$

We plotted the difference between the mean value for undisturbed days ($\langle\dot{\varphi}_N\rangle$) and $\dot{\varphi}_D$ for each disturbed day (Fig. 4). These are given in units of degrees per megameter per hour. The typical $\langle\dot{\varphi}_N\rangle$ was 5 (Omega-Haiku, 10.2 kHz), 8.3 (Omega-Trinidad, 10.2 kHz), 9.8 (Omega-Trinidad, 13.6 kHz), and 14 (NAA, 17.8 kHz) for the transmissions received in Brazil, and 4.6 (Omega-Japan, 10.2 kHz) for transmission received in Australia. We assumed that both α and n remained close to their typical values at an intermediate daytime and nighttime low-ionosphere height (*18*), that is $n \approx 6 \times 10^2$ cm^{-3}, $\alpha = 4 \times 10^{-6}$ cm^3 s^{-1} at about 80 km. We then obtained an estimate of the electron production rate attributable to the meteoroid storm $q \approx 0.3$ to 0.9 cm^{-3} s^{-1} on the most disturbed days, which is three to nine times larger than estimates given for the large 1946 Giacobinid shower (*2*).

The unusual effect of daytime phase advance (Fig. 2) suggests that the long-lasting ionizing effects of the storm were so strong that they were able to modify significantly the daytime upper boundary of the Earth-ionosphere waveguide (that is the D region). We may also estimate the ion production rate to account for the daytime phase advance, using again the continuity equation and the Earth-ionosphere waveguide theory (*8, 9*). Taking the daytime phase advances at the Omega-Trinidad transmissions received at Atibaia (Fig. 2), we infer a reflection height reduction of 1.5 km. Using

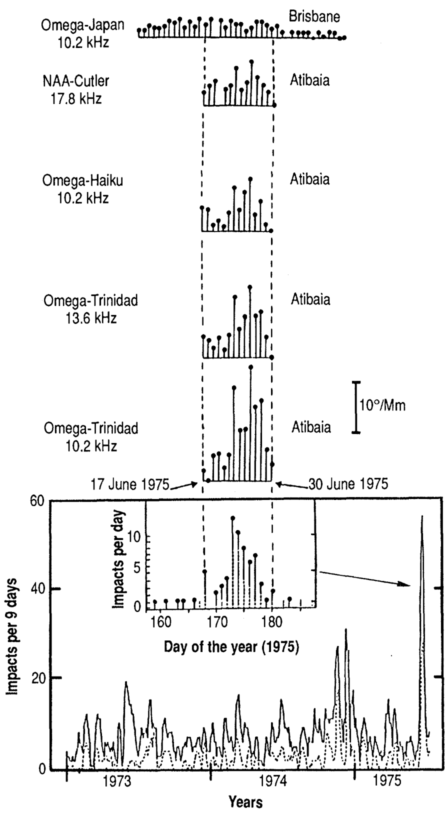

Fig. 3. Daily deviation of the diurnal phase variation with respect to the mean in undisturbed days, for the VLF transmissions analyzed here (**top**) (in degrees per megameter of path length), compared to meteoroid data from Apollo seismographs on the moon in June 1975 (**bottom**) [adapted from (*1*)]. Dashed lines refer only to small impacts that had masses of 50 to 10^3 g).

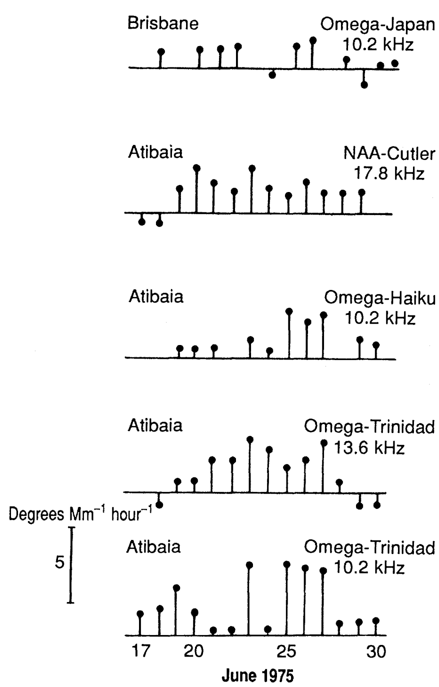

Fig. 4. Changes in phase delay rates (in degrees Mm^{-1} hour^{-1}) compared to undisturbed days, for all VLF transmissions in the period 17 to 30 June 1975, when all data was available.

a relationship for height reduction versus ion production rates, derived for solar flare x-ray effects (*19*), we estimate $q \approx 3$ cm^{-3} s^{-1} attributable to the storm, at an altitude of about 70 km.

Comparing the different VLF transmissions, the effects are considerably larger on the Trinidad-Atibaia path, which extends mostly in the Southern Hemisphere. This might indicate a directional property for the impacting stream of meteoroids. If we assume that the meteoroid storm effects were predominantly a Southern Hemisphere phenomena, we can tentatively reduce the anomalies for the corresponding southern sections of path lengths. The Omega-Trinidad, Omega-Haiku, and NAA paths to Atibaia are 60%, 50%, and 33% in the Southern Hemisphere, respectively. Omega-Japan to Brisbane path is 40% in the Southern Hemisphere. If we normalize the effects for the corresponding fractions of the paths, the magnitude of the effects (such as those shown in Figs. 3 and 4) are no longer so discrepant for the different transmissions. Similar results are found for the other two effects. It is also meaningful that the VLF propagation paths located entirely in high northern latitudes [Jim Creek to Nishinomiya and NAA to Thule (Fig. 1)] (*16, 17*) did not exhibit any anomaly in the period, except for smooth seasonal variations.

On the other hand, it was found that the meteoroid ionization effects remained during sunset hours, although they were not present at the sunrise phase advance period. The sunset effect was measured at the linear part of the phase delay with time, as the terminator moved from the receiver to the transmitter sites (Fig. 1). Depending on the transmission, the effect remained up to 1.5 to 3 hours after sunset at the receiver site. Therefore we suggest that the radiant right ascension was larger than the solar right ascension by about 1 to 2 hours. Since the sun's right ascension was about 90°, the suggested storm radiant was 105° to 120°. None of the well-known meteor showers are located in the Southern Hemisphere, at such right ascension (*20*), except, perhaps, the Corvids shower, which was observed only in 1937 (dec. = −10°, right ascension = 191°). It is likely that the June 1975 event was caused by a genuine sporadic meteoroid storm.

Finally, the peak impact per day rate on the moon, detected on 23 June 1975, does correspond to a large ionization effect on Earth's upper atmosphere (Figs. 2 and 3). However, the largest ionization effect on 26 June 1975, does not show a clear correspondence with impacts on the moon. Interpretations should be made carefully, since the effects on Earth's ionosphere are believed to be complex and largely smoothed out in time, compared to the direct detection of impacts on the moon. However, the lack of strict day to day correlations between data from Earth and moon suggest that the meteoroid stream was not homogeneous in space.

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Phyllosilicate Absorption Features in Main-Belt and Outer-Belt Asteroid Reflectance Spectra

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Absorption features having depths up to 5% are identified in high-quality, high-resolution reflectance spectra of 16 dark asteroids in the main belt and in the Cybele and Hilda groups. Analogs among the CM2 carbonaceous chondrite meteorites exist for some of these asteroids, suggesting that these absorptions are due to iron oxides in phyllosilicates formed on the asteroidal surfaces by aqueous alteration processes. Spectra of ten additional asteroids, located beyond the outer edge of the main belt, show no discernible absorption features, suggesting that aqueous alteration did not always operate at these heliocentric distances.

PRIMITIVE METEORITES OF TYPES 1 and 2 are assumed to be the result of the melting of ice and subsequent aqueous alteration of rocky materials comprising their original parent bodies (*1*). Laboratory reflectance spectra of meteorites that appear to have undergone aqueous alteration and terrestrial rock samples that are products of aqueous alteration show subtle absorption features in the visible and near-infrared spectral regions (*2*); however, telescopic reflectance spectra of asteroids labeled "primitive" have been considered featureless in the same spectral regions (*3*). In this study, we searched 26 high-quality spectra of primitive (C-, P-, D-, F-, and G-class) (*4*) asteroids for weak features in the visible and near-infrared spectral regions. The asteroid sample presented here is composed primarily of the dark asteroids located beyond the outer edge of the main asteroid belt (the outer belt). The main emphasis of the observing program from which these spectra were culled was to understand the nature of asteroids located between the main belt and Jupiter's orbit. We also observed some asteroids classed as P or D in the main belt to search for compositional differences between these objects and the outer-belt P and D asteroids (*5*).

Spectra of asteroids and Hardorp solar analog stars (*6*) were acquired during the years 1984 through 1987. All asteroid data were reduced to relative reflectance spectra scaled to 1.0 around 0.7 μm (*5*). Spectra were selected for this study on the basis of the following criteria: (i) low peak-to-peak noise within a spectrum; (ii) good observing conditions during the nights when these data were obtained; and (iii) comparison of individual spectra with maps of the telluric atmospheric absorptions that could affect spectral shape if the extinction correction insufficiently removed some atmospheric absorptions. In interpretations of the data for asteroids 1162, 1512, and 2357 we have taken account of residual telluric water vapor features in these spectra. For the rest of the asteroids included in this study, such artifacts either were not present or were not sufficiently strong to affect the interpretation (*7*). Each spectrum was treated as a continuum with discrete absorption features superimposed on it. For each object, a linear least-squares fit to the spectral data points defined a simple linear continuum, which was then divided into each individual spectrum, thus removing the sloped continuum and allowing the intercomparison of residual spectral features. The residual features for various groupings of asteroids are shown in Figs. 1 through 4 and can be compared with residual features from laboratory spectra of terrestrial phyllosilicates and carbonaceous chondrite meteorites (*8*).

These diverse features may represent the effect of some asteroidal property (real features), or they could be artifacts from the stellar calibration sources or from the observing or data-reduction procedures. The reality of the slopes and features in the asteroid spectra was tested by a number of criteria. The standard stars can be eliminated as a source of significant features because asteroid data reduced through the same standard exhibit a wide variety of spectral slopes and residual features. No one feature is present in all of the asteroid spectra calibrated with any single standard star, and similar features are seen in asteroid spectra calibrated with different standard stars. If features were not common to all objects observed during any single night and if the observational or reduction procedures provided no explanation for a feature, then we concluded that the features derived primarily from the surface mineralogy of the asteroid.

The strongest of the residual features (Fig. 2) has a maximum absorption intensity of approximately 5%. Most are considerably weaker. Features with intensities below 1% have generally been discounted, without future prejudice, in this study. Thus, a significant subset of these dark asteroids are featureless by this criterion, even though there are variations in their spectra that subsequent study may prove to be real. Asteroid 1 Ceres is the exception to this general rule. This spectrum is a composite of 31 spectra of Ceres obtained at an air mass of 1.00,

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