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Sporadic *E* ionization associated with meteor events

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Abstract. Two meteor events which were sighted in the Gujarat skies of India, were accompained by the visibility of sporadic *E* ionization on the ionograms recorded at Ahmedabad (Geog. Lat. 23·2°N, long. 72·30°E). The first event was the Dhajala fireball which flashed into the geoatmosphere along an E–N to W–S trail at about 20·40 h IST on 28 January 1976; the closest distance of the ground projection of meteor trail from Ahmedabad was 50 km. The other event was a possible meteor group sighted over Ahmedabad on 28 May 1978, at about 21·10 h IST. This work describes the nature of the sporadic *E* ionization observed on Ahmedabad ionograms during the two events. Features of the *Es* echo during the Dhajala event which indicate that it could be of meteoric origin are discussed . Meteor theory is used to relate the observed ionization with the physical dimensions of the Dhajala meteorite as obtained by other workers.

Keywords. Meteoric ionization; sporadic *E*; line electron density.

1. Introduction

The possibility of extra-terrestrial objects being ionized on entry into the earth's atmosphere was first realized in 1904 when a spectrophotograph of a meteor event revealed ionized calcium.

Trowbridge (1907) compared the appearance of an optical meteor to the afterglow caused in electrical discharges in low-pressure gases, and suggested the similarity to be due to meteoric ionization. The work of Lindemann and Dobson (1923) and Sparrow (1926) showed that ionization could result from the impact of meteors with gas molecules of the upper atmosphere. The neutral atmospheric density of about 10^{-12} g/cm^3 existing at around 150 km altitude is sufficient to cause intense frictional heating of the meteor surface. The meteor material becomes incandescent and leaves a visually observable trail. At this stage it breaks into several pieces, the sizes of which are decided by the initial structure of the body (Lal and Trivedi 1977). Incandescence causes the surface material of the meteor to vaporize and to subsequently get ionized. The thin column of ionization thus left behind finally moves with the velocity of the meteor-head reflecting radio waves in all directions. Atmospheric diffusion and turbulence act on the cylindrical trail of ionization, and these forces continuously expand and deform the trail. It was initially believed that the kinetic energy of the incoming object is dissipated in producing heat, light, and ionization in the ratio 10^4:

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10^2:1 (Herlofson 1948). Later work replaces these figures by 10^4:10^2:10 for bright meteors and 10^4:10:10 for faint meteors (Greenhow and Hawkins 1952).

Between 1929 and 1930, ionospheric workers often noticed short-lived echoes from the *E* region, on night-time records from ionospheric sounders, which suggested the sudden passage of some transient source of ionization. The observations of Schafer and Goodall (1932) on radio frequencies of 2·4 MHz, 3·3 MHz and 4·8 MHz, definitely associated intermittent *Es* echoes at altitudes between 100 and 200 km with the Leonid meteor showers. Skellett (1935) showed a sudden increase in abnormal *E* layer ionization coinciding with the passage of visual meteors. The field strength records of Pierce (1938) on 10 MHz at a distance of 30 km from the transmitter showed small volumes of dense ionization in the *E* region to be caused by the transit of a single large meteor. The contribution of meteoric ions to the formation of sporadic *E* was studied by Appleton and Naismith (1947), and amongst others by Whitehead (1970) and Ellyet amd Goldsborough (1976).

Sinno (1979) found the intensity of ionospheric scattering to be correlated with the rate of meteor bursts observed by VHF (49·68 MHz) oblique propagation experiment conducted in Japan during the IGY years. Sinno (1980) also found a good correlation of the activity of sporadic *E* layer with a time lag of about one week. Electron density profiles obtained over Thumba using rocket borne Langmuir probes also show sporadic *E* layers to be present only on days with meteoric activity (Gupta 1990). These studies suggest that the sporadic *E* layers generated by meteor activity contain a large number of metallic ions.

2. Observation of sporadic *E* ionization

The Physical Research Laboratory operated a C_3/C_5 ionospheric sounder at Ahmedabad, transmitting radio pulses at frequencies 1–20 MHz with peak power of 10 kW and operating on a quarter hourly basis. It has delta type transmitting and receiving antennae with a large beam-width (approximately 45°). Sporadic *E* ionization at altitudes approximating 100 km to 130 km with maximum reflection frequency in the vicinity of 3·4 MHz was observed during both the meteor events described below. The characteristics of the two events are listed in table 1.

2.1 *The Dhajala meteorite event*

This meteor was sighted in Ahmedabad on the night of 28 January 1976 at approximately 20:40 hr (IST) and its entry velocity *V* was estimated by Ballabh *et al* (1978) to be about 21·5 km/s. Reports indicate that it plunged in from the north-east skies at an angle of 75° to the vertical within 100 km of Ahmedabad, as pieces of the meteor-debris were recovered from the village of Dhajala, 140 km south-west of Ahmedabad city. It was one of those rare events in which a meteor survives the fiery passage through the atmosphere and leaves visible evidence of itself on earth. Figure 1 is a map drawn to scale from Ballabh *et al* (1978) showing the azimuthal angles of the meteor trail and the meteor fall-out; these are N 32°E and N 47°E respectively. The shortest distances from Ahmedabad to the ground projections of the meteor trail and the axis of the elliptical meteor fall-out are 67 km and 34 km respectively. This gives the average closest distance to be 50 km, and any meteoric ionization would therefore be within the range of detectability of the ionosonde at

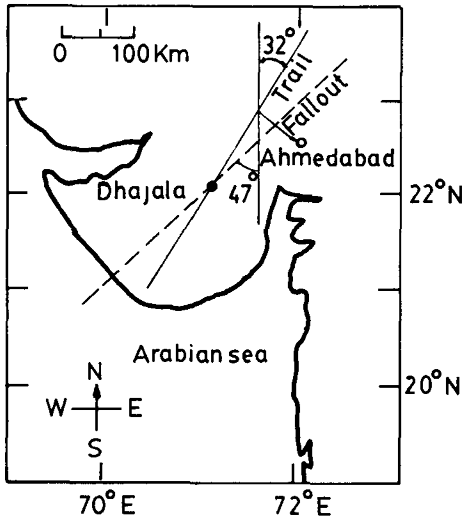

Figure 1. Projected path of the Dhajala Meteor trail and the meteorite fall-out, and their nearest perpendicular distance from Ahmedabad (modified from Ballabh *et al* 1978).

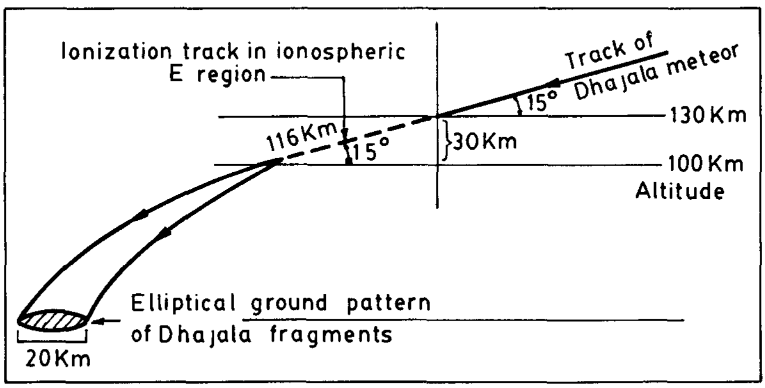

Figure 2. Entry of Dhajala meteorite into atmosphere, its fall on the ground, and the ionization track of 116 km created between the altitudes 100 km and 130 km.

Ahmedabad because of the large field-of-view of its antenna. Figure 2 shows the possible geometry of entry of the Dhajala meteor in a vertical plane, and the ellipse on the ground within which the fragments were strewn. The figure is drawn to scale, and the relevant path-lengths are indicated. The length of the cylindrical ionization track of the meteor between 100 km and 130 km works out to be 116 km. It is this large length of ionization trail at a mean distance of 50 km from Ahmedabad which leads the authors to believe that the *Es* ionization seen on the Ahmedabad ionograms at the time of the meteor event was caused by the Dhajala meteorite.

The Ahmedabad ionosonde records taken at 2000 h, 2015 h and 2030 h showed only the normal night-time *F*-region trace at about 230 km altitude, typical of this location. Reproduced in figure 3 are the tracings of the ionograms for 2045, 2100 and 2115 hr. Tracings, rather than actual ionograms, are shown because 'noise' from several SW

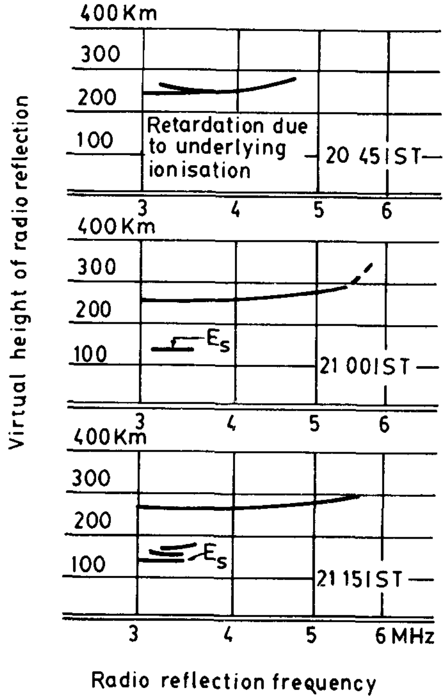

Figure 3. Tracing of Ahmedabad ionogram of 28 January 1976 showing faint *Es* ionization observed during entry of the Dhajala fire-ball into the geo-atmosphere. Note the three-layer *Es* structure at 2115 hr IST.

broadcast stations had 'cluttered' the ionograms, rendering photographic reproduction difficult. At 2045 h the *F*-region trace at 250 km shows developed extra-ordinary (*X*) and ordinary (*O*) components at the lower frequency end, although no ionization trace is seen at lower heights. The presence of *X* and *O* traces at different virtual heights indicates retardation caused by ionization existing at a lower height (Titheridge 1959). In the record of 2100 h a short reflection trace is seen at about 130 km commencing at 3·1 MHz, and extending to over 3·4 MHz. This corresponds to reflection from an ionization layer containing slightly more than $1{\cdot}24 \times 15^5$ el/cm.

The observations of the record of 2115 h are interesting. The *E*-region reflection appears to have split into at least 3 strata separated by roughly 6 km. The same feature with one more stratification was seen in the ionogram of 2130 h. By 2145 h the stratified appearance disappeared leaving a single short trace near 3 MHz. At 2200 h two strata at 120 km and 135 km, again in the neighbourhood of 3·2 MHz were seen, but nothing was observed on subsequent records. To summarize, this irregular *E*-region ionization remained at a height of about 120–140 km throughout a period of one hour with plasma reflection frequencies ranging from 3·1 MHz to 3·4 MHz, and occasionally stratified into several layers.

2.2 *The Meteor group event of 28 May 1978*

The UFO event (more correctly referred to as a meteor group event) was sighted over Ahmedabad on 28th May 1978 at approximately 2110 h. It appeared to be a

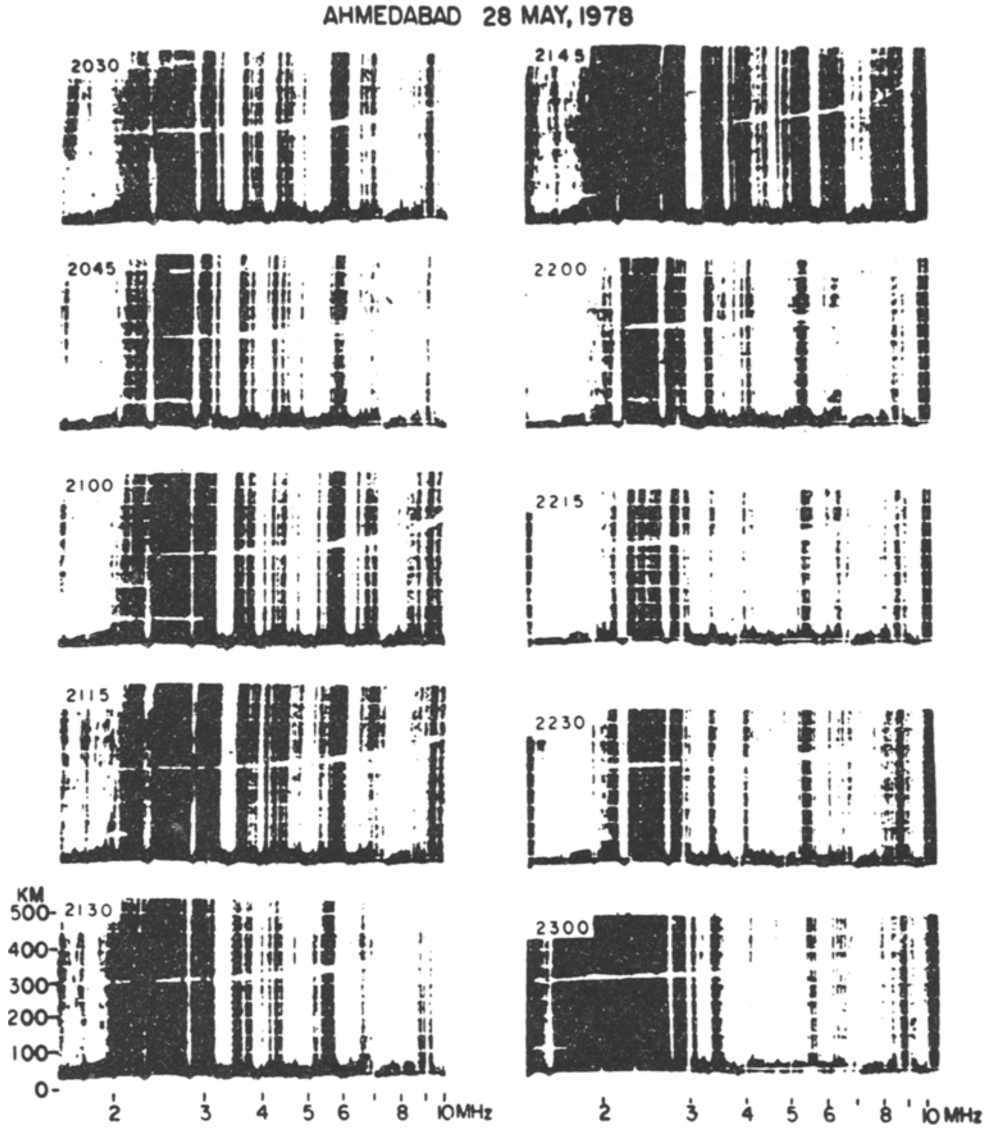

Figure 4. Ahmedabad ionograms of 28 May 1978 showing clear *Es* ionization observed at the time of entry of a meteor group event.

point-like object, and from various eye-witness accounts from Ahmedabad as well as from other places like Surat and Rajkot, it was possible to visualize its trajectory. The orbit was approximately overhead and trajectory was along the line joining Rajkot to Surat. Since the object was visible for about 50 seconds, a rough estimate of the velocity was 10 km/s. From eye-witness accounts the declination was estimated to be about 50–70° and the nearest distance from Ahmedabad one expected from these estimates was around 100 km. Apparent magnitudes were likely to be about -3 to -4, as the visual estimates were put between the brightness of Jupiter and Venus.

The ionograms obtained at Ahmedabad on this day are shown in figure 4. At 2100 h there is no *Es* trace. At 2115 h there is *Es* trace with a maximum frequency about

3 MHz. At 2130 h there is strong *Es* trace with second multiple also present. The *Es* trace is much fainter at 2145 h. There is no *Es* trace at 2200 h but at later times viz 2215 hr and 2230 h there are again *Es* traces which are probably not related to the meteor event. The occurrence frequency of sporadic *E* for night-time at Ahmedabad during summer months is very high and exceeds 80% for a low or medium sunspot year (Chandra 1978). Judging from the strength of the *Es* echo it appears the sporadic *E* ionization due to the meteoric group was closest to Ahmedabad at 2130 h.

3. Discussion

While evidence for the *Es* ionization of 28 May 1978 being definitely caused by the meteor group is not very strong due to the frequent occurrence of night *Es* during summer, this is not the case for the Dhajala event. A series of arguments is presented here in support of the hypothesis that the *Es* ionization seen on the Ahmedabad ionograms between 20:45 h and 21:30 h was caused by the Dhajala meteorite.

(i) The appearance of clearly separated *O* and *X* traces on the ionogram for 2045 h discussed is § 2·1, beyond doubt proves the existence of an underlying layer of ionization which manifested itself on the 2100 h ionogram as *Es*, at a virtual height of 130 km. The *Es* layers on this night differed in character from the *Es* of other nights. A systematic examination of the Ahmedabad ionograms during $\pm$ 15 nights centred around the Dhajala event showed that any *Es* which occurred during the relevant hours between 2000 h and 2200 h was of a clear, bold type often extending to over 5 MHz, unlike the faint stratified echo traces in the frequency range 3·1 MHz to 3·4 MHz seen on the Dhajala night.

(ii) A large fireball like the Dhajala could leave an "overdense" ionization trail in which the electron density could be high enough to prevent complete penetration of the incident radio wave, and hence cause "ionospheric layer-like" reflections (Davies 1966). Greenhow and Lovell (1960) explain how for large fireballs, the ionization remains packed densely in a cylindrical trail. When the line electron density of the trail exceeds 10^{16} electrons/cm (which was the case for the Dhajala meteorite as shown in § 3), the diffusion of the trail may not occur easily and the only process by which the trail weakens is through chemical loss of ionization.

(iii) Figure 2 shows that for the Dhajala fireball there would have been at least 116 km cylindrical length of ionization with cross-sectional diameter exceeding 1 meter which is the diameter of this meteorite. The longevity of the cylindrical ionization trail of a fireball can be understood thus. A meteoric trail is rich in metallic ions such as Ca^+, Fe^+, Mg^+, Si^+. Such ions show an inability to undergo simple dissociative recombination. They can recombine with free electrons only by the process of radiative recombination in which photons are emitted (Greenhow and Lovell 1960; Biondi 1969). This radiative recombination coefficient for such metallic ions in the *E* region is $\sim 10^{-12}$ cm/s which is about 5 orders lower than the dissociative recombination rate for normal NO^+ ions in the *E* region (Brown 1973). It is this very low recombination coefficient of the metallic ions which enables meteoric ionization to maintain its shape and structure for periods of time exceeding 1–2 hours in the *E* region. Sinno (1979) worked out chemical recombination and loss processes to show that metallic ions caused by meteor entry into the lower ionosphere are rather long-lived, and they possibly contribute to the formation of sporadic *E* layers.

(iv) The apparent height of the sporadic *E*, 120 km to 135 km (the corresponding 'true' height of reflection will be slightly less) over the time-interval of over 1 h and seems reasonable according to the observations of Gazley (1959) that large meteors tend to appear higher and persist through a thicker stratum of the atmosphere. A massive meteorite like the Dhajala would fit well into this category.

(v) Normal *Es* ionization seen on ionograms for other nights did not show a tendency to stratify into layers at separation intervals of 5 to 6 km as the night of 28 January 1976 did. This feature adds credence to the meteoric origin of the *Es* ionization in the ionograms shown. Other workers have reported their observations of ion layers during meteor showers being stratified at 5 km altitude intervals between 100 km and 125 km (McKinley and Millman 1949; Whipple 1952) Gupta (1990) notes from rocket flights carried out during meteor shower days at the equatorial location Thumba that the Langmuir probe detects distinct multiple layers of sporadic *E* with semi-thickness about 5 km, and separated by about 10 km. Gallet's (1955) interpretation is that turbulent mixing causes *Es* to stratify at 3 preferential levels, one at the level of peak *E*-region electron density, and the other two at roughly one scale height above and below this peak. Another interpretation of the layer structure is that the cylindrical trail of ionization could have been broken into irregular blocks by the dynamic forces of diffusions. In that case the apparent stratification would be due to differences in slant range to the blocks rather than due to differences in height between well-defined horizontal layers.

4. Estimates of ionization expected from the Dhajala meteorite

The physical theory of meteors, and the luminosity and ionization arising from their interaction with the earth's atmosphere, have been treated in detail by McKinley (1961), and several other workers (Verniani and Hawkins 1964; Fiocco 1967; Verniani 1969). Using the relationships given by these workers between expected or observed meteoric ionization, and the probable physical parameters of a meteor, an attempt is made to deduce the one from the other as follows:

(a) It is possible to obtain the 'line electron density' (the total number of electrons per unit length of the cylindrical meteor trail) from the zenithal magnitude of the Dhajala meteorite. This can be done from the revised theoretical relationship between two parameters given by Greenhow and Hawkins (1952); the relationship is shown extrapolated in figure 5. The Dhajala fireball is given an apparent magnitude of -20 (Bhandari *et al* 1976) as it was brighter than the moon. This corresponds to zenithal magnitude-19 (Greenhow and Hawkins 1952) which from the revised theoretical line of figure 5 gives a line electron density of 5×10^{18} el/cm. This figure seems reasonable in the light of observations by other workers that the visual magnitude of meteors which survive atmospheric ablation and fall on the ground, must exceed $-12{\cdot}5$, with an associated electron line density exceeding 10^{16} el/cm, and an initial mass exceeding 10 kg.

(b) The line electron density can also be obtained from the probable radius of the meteor, following the relationship of Herlofson (1948):

$$N_e/\mathrm{cm} = 2 \times 10^{15} r_0^3. \tag{2}$$

Bhandhari *et al* (1978) estimated from ^{26}Al activity a radius of about 50 cm for the

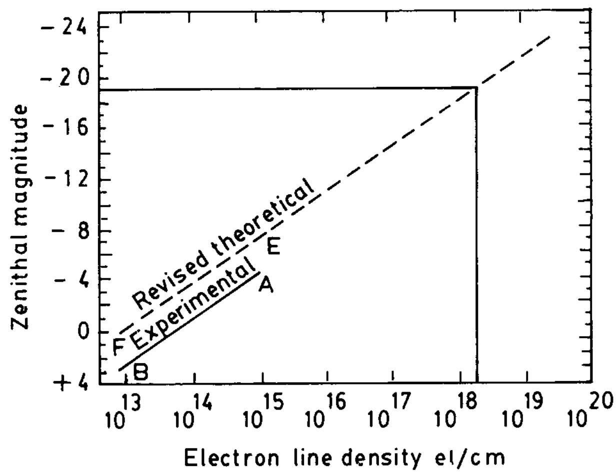

Figure 5. Theoretical and experimental relations between the zenithal magnitudes and electron line densities of meteor trails (modified from figure 2 of Greenhow and Hawkins 1952).

Dhajala meteorite, which yields a line electron density of 10^{20} el/cm. This is not too far off from the figure obtained in (a).

(c) We next try to obtain the line electron density from the mass M and velocity V, using the relationship of Verniani (1969):

$$M_\infty = (3{\cdot}8 \times 10^5) Q V^{-4}, \tag{3}$$

where M_∞ is the mass of the meteorite before ablation, V, the velocity of entry of the meteorite into atmosphere at time of ablation and Q the total number of electrons produced by the meteorite. Assuming a mass of $(1{\cdot}4 \pm 0{\cdot}4)$ tons and an entry velocity of 21·5 km/s for the Dhajala meteorite (Ballabh *et al* 1978), and using cgs units, Q works out to be 10^{26} electrons. Since figure 2 suggests the cylinder of ionization to have a length of about 116 km, the electron line density (number of electrons produced per unit path length) works out to be 10^{19} el/cm. This tallies very well with the line electron density obtained from the zenithal magnitude of the Dhajala meteorite, suggesting that the length of cylinder of ionization obtained in figure 2 is indeed of the right order.

(d) Verniani and Hawkins (1965) suggested a relationship between the initial mass of the meteor and the maximum line electron density to be:

$$\log M_\infty = \log q_m - 16{\cdot}6. \tag{4}$$

Again with Mks, units, putting $M_\infty = 1425$ kg yields the line electron density $q = 5{\cdot}7 \times 10^{19}$ el/m which works to be $5{\cdot}7 \times 10^{17}$ el/cm. This tallies well with the value of line electron density obtained in (a) for the Dhajala meteorite.

(e) Finally we try to estimate the rate of influx of ionizable material of the Dhajala meteor from the electron concentration observed in figure 3 from the Ahmedabad ionograms, using a relationship of Fiocco (1967)

$$N_e = \left[\frac{\phi \cdot I(Z)}{\alpha}\right]^{1/2} \tag{5}$$

Here N_e is the electron concentration/unit volume, $I(Z)$ the ion production rate per kg of meteor material per unit length of trail, ϕ the influx of meteorite mass per square meter per second and α the recombination coefficient for the ionospheric E region.

The Ahmedabad ionograms for the Dhajala event gave $N_e = (2 \times 10^5)\,\mathrm{el/cm^3}$ which is $(2 \times 10^{11})\,\mathrm{el/m^3}$. Following Fiocco (1967) if we take

$$\alpha = 10^{-14}\,\mathrm{m^2/s}$$
$$I(Z) = 10^{17}\,\mathrm{ions/kg\,m}$$

the influx rate ϕ for the Dhajala meteor works out to be $(4 \times 10^{-9})\,\mathrm{kg/m^2\,s}$. This works out to be almost 2 orders of magnitude larger than the density of the ambient neutral atmospheric medium at E region altitudes.

5. Conclusion

It is possible to obtain the mass of the Dhajala meteorite from the ionization equation which expresses the number of electrons created per unit length of the path in terms of τ_q, the ionization efficiency factor (McKinley 1961); as also from the ionization equation which expresses the ionization in terms of the ionizing probability factor (Verniani 1969), but we do not deal with this here.

The converse approach of inferring the ionization produced from the physical characteristics of the Dhajala meteorite, has yielded slightly varying values of line electron density when various relationships were used; these are shown in tabular form in table 2. If one takes the line electron density of $(5 \times 10^{18})\,\mathrm{el/cm}$ obtained in §4·1 from the zenithal magnitude of the Dhajala meteorite as the standard, it will be seen that the two relationships which yield values closest to this, are those of Verniani and Hawkins (1965) and Verniani (1969).

Meteoric ionization can thus be used to yield knowledge on the composition, structure, and of the size and trails of meteor-like objects coming from space and the ionosonde can prove a useful tool in this.

Table 1. Probable characteristics of Dhajala meteorite and Meteor group.

Event	Date of observation	Time of observation (h IST)	Apparent Magnitude	Direction of body	Nearest approach to Ahmedabad	Fragments recovered	Estimated mass of body	Estimated velocity of body (km/s)	Angle of entry
Dhajala Meteorite	28 Jan 1976	20:40	−20	E–W to W–S	Within 100 km south-west	Yes. In an elliptical area roughly 140 km south west of Ahmedabad	1425 kg	~21·5	75° with respect to vertical
Meteor group event	28 May 1978	21:10	−3 to −4	N–W to S–E	About 100 km south	None	Not available	10	—

Table 2. Estimates of ionization from physical characteristics of Dhajala meteorite using various relationships

Source	Relationship used	Value of q (line electron density)
Greenhow and Hawkins (1952)	From Zenithal magnitude	(5×10^{18}) el/cm
Herlofson (1948)	$N_e/\mathrm{cm} = 2{\cdot}10^{15} r_0^3$	$2{\cdot}5 \times 10^{20}$ el/cm
Verniani (1969)	$M_\infty = (3{\cdot}8 \times 10^5) Q V^{-4}$	10^{19} el/cm
Verniani and Hawkins (1965)	$\log M_\infty = \log q_m - 16{\cdot}6$	$(5{\cdot}7 \times 10^{17})$ el/cm

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