of light provided by a tubular lamp with a straight tungsten filament stretched along its axis. Alternatively, the absorption spectrum can be viewed through a pocket spectroscope, and the positions of the absorption bands may be read on the wavelength scale provided in the eye-piece of the instrument.

A striking demonstration of colour changes entirely analogous to those exhibited by the leaves of plants in the course of their growth and development is possible with the acetone extracts of the leaf pigments. The glass cell is filled to about a third of its depth with acetone and then the acetone extract of the leaf pigments (which is itself of a deep green colour) is added a little at a time. The acetone in the cell first turns yellow in colour. Further additions alter the yellow to a greenish-yellow and then progressively to a clear green. These changes correspond to the alterations in the character of the absorption spectrum of the solution. A cut-off of the red beyond 640 mμ appears at the very outset, and this is soon followed by the total extinction of the blue up to 500 mμ. But not until the band of absorption in the yellow between 570 mμ and 586 mμ appears and is fully developed does the solution exhibit a full green colour.

Some finer details observed with the green leaves themselves correspond to the features noticed in the absorption spectra of the leaf extracts. Particular mention may be made of the two *bright* bands noticed in the spectrum of the leaves, one in the green between 550 mμ and 570 mμ and the other in the orange between 586 mμ and 613 mμ. These bands are also noticeable in the spectrum of the transmitted light of the leaf extracts.

LIGHT AND IONISATION CURVES OF METEORS *

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1. Introduction

1.1. Meteors are tiny fragments of stony matter that enter the earth's atmosphere with high velocities which range from 12 to 72 km./sec. During their flight they get heated up and undergo ablation due to impact with the molecules of the atmosphere. The ablated meteor atoms which cascade downwards along the meteor trail collide with the air molecules and produce light and ionisation.

1.2. The majority of visual and photographic meteors appear and disappear between the heights of 120 and 70 km. in the upper atmosphere. The thermal velocities of the molecules of atmospheric gases at these levels are of the order of 0·5 km./sec. which are negligibly small compared with meteor velocities. According to the US Standard Atmosphere (1962), the mean free paths of the atmospheric molecules, the temperature and the scale height of the atmosphere at the meteor levels are as given in Table I.

1.3. The physical dimensions of the meteors are much less than the mean free paths of the atmospheric gases at meteor levels. Hence it is assumed that during its flight through the atmosphere the meteor body is subjected to direct molecular bombardment. The kinetic energy of the impacts gives rise to heating and ablation of the body. The heat of ablation of meteor matter is of the order of 6×10^{10} ergs/gm. while the kinetic energy of a meteor travelling with a velocity of, say 30 km./sec., is $4 \cdot 5 \times 10^{12}$ ergs/gm., which is nearly 80 times the heat of ablation. As a consequence of this, the meteor does not undergo appreciable deceleration and its velocity remains nearly constant all along its flight through the atmosphere. Also, the ablated atoms leave the meteor body with practically the same velocity as the meteor.

1.4. Spectra of meteors reveal lines of neutral Fe, Ca, Mg, Na, Mn, Cr, Ni and Al and of singly ionised Ca, Mg and Si. The H and K lines of Ca^+ are noticed very prominently in the spectra of fast meteors while the D lines of Na are extremely strong in the spectra of slow meteors. The kinetic energy of the ablated meteor atoms

TABLE I

Height (km.)		120	110	100	90	80	70	60	50
Mean free path (cm.)	..	323	82	16·3	3·3	0·5	0·1	0·03	0·008
Temperature (°A)	..	349	257	210	185	181	217	255	271
Scale height (km.)	..	11·00	7·90	6·36	5·56	5·42	7·56	7·60	8·05

* Based on a paper presented at the Symposium on Meteorology held under the auspices of the Indian Academy of Sciences at Poona on 26th December 1964.

travelling with the velocity of the meteor ranges from 100 to 1000 eV. Collisions of the fast-moving meteor atoms with the atmospheric molecules result in the conversion of their kinetic energy into heat, light and ionisation.

2. Ablation and Luminosity

2.1. The equation of meteor ablation follows from the principle of conservation of energy. Considering a spherical meteor of mass m and radius r and velocity v traversing vertically through the upper atmosphere of density ρ, the equation can be written as:

$$\zeta dm = \Lambda(\pi r^2 dz\rho)\frac{v^2}{2} \qquad (1)$$

where dm = mass ablated in traversing the depth dz of the atmosphere;
ζ = heat of ablation per unit mass of the meteor; and
Λ = heat transfer coefficient.

$(\pi r^2 dz\rho)\, v^2/2$ is the kinetic energy of the air mass intercepted by the meteor in traversing the depth dz. The heat transfer coefficient Λ determines what fraction of this energy goes towards heating and ablation of the meteor. The value of Λ is generally much less than 1. It is a very important parameter in the theory of meteor ablation. In general, Λ may be expected to be a function of the meteor velocity v and of the atmospheric density ρ. In the conventional theory of meteor luminosity Λ is supposed to be independent of ρ and hence a constant for a given meteor.

2.2. The luminosity/ionisation equation for the meteor trail is written as:

$$I = \frac{1}{2}\left(\frac{dm}{dt}\right)v^2\tau \qquad (2)$$

In this equation I is the luminous/ionisation intensity at any point of the meteor trail, dm/dt is the rate of ablation of the meteor at that point and τ is the so-called luminous/ionisation efficiency factor that determines what fraction of the kinetic energy of the ablated atoms is converted into energy of light/ionisation. This is a very general equation which does not take into account the specific mechanism of excitation (leading to light emission) and ionisation.

2.3. Making use of the hydrostatic equation $dp = -g\rho\, dz$ and the gas equation, it follows from (1) that:

$$dm = -\frac{\Lambda}{\zeta g}\left(\tfrac{1}{2}\pi r^2 v^2\right)dp \qquad (3)$$

If dr is the decrease in radius of the meteor due to ablation in falling through the height dz we have:

$$dm = 4\pi r^2 dr\,\rho_m \qquad (4)$$

where ρ_m is the density of the meteor.

From (3) and (4) we get

$$dr = -\left(\frac{\Lambda v^2}{8\zeta g\rho_m}\right)dp = -\mathbf{A}dp \qquad (5)$$

where A is a constant for a given meteor.

From (5) it follows that:

$$r = \mathbf{A}(p_e - p) \qquad (6)$$

$$m = \mathbf{A}'(p_e - p)^3 \qquad (7)$$

where p_e is the atmospheric pressure at the level of complete ablation of the meteor and A′ is a constant.

From (7) and (2) it can be shown that:

$$\frac{dm}{dt} = \mathrm{K}(1-x)^2 x \qquad (8)$$

and

$$\mathrm{I} = \mathrm{K}_1(1-x)^2 x \qquad (9)$$

where $x = p/p_e$ and K and K_1 are constants for a given meteor.

From (8) it follows that I is a maximum for $x = 1/3$ and that:

$$\mathrm{I}_{max} = \frac{4}{27}\mathrm{K}_1 \qquad (10)$$

From (8) and (9) we have:

$$\frac{\mathrm{I}}{\mathrm{I}_{max}} = \frac{27}{4}(1-x)^2 x \qquad (11)$$

Equation (11) expresses the luminous intensity at any point of the meteor trail in terms of the luminous intensity at the point of maximum luminosity. It is the equation for the *normalised meteor light curve*. As none of the parameters of the meteor enters into this equation it represents the light curves of all meteors. The same equation holds good for the variation of ionisation along the meteor trail.

In actual practice, the luminous intensity at different points of the meteor trail are estimated in terms of stellar magnitudes. In this case equation (11) can be written as:

$$\Delta\mathrm{M} = \mathrm{M} - \mathrm{M}_{max} = -2\cdot5\log\left(\frac{\mathrm{I}}{\mathrm{I}_{max}}\right)$$
$$= -2\cdot5\left[2\log(1-x) + \log x + \log\left(\frac{27}{4}\right)\right] \qquad (12)$$

In (11) and (12), $x = p/p_e = e^{-h/H}$ where H is the scale height of the atmosphere and h is the height interval between p and p_e (the distance of the instantaneous level of the meteor above the level of its complete ablation).

2.4. The normalised light curve of meteors given by equation (12) is represented by the curve in Fig. 1. The co-ordinates of this curve are ΔM and h. For constructing this curve a uniform scale height of 6·38 km. has been assumed at meteor levels which is nearly the mean value of the scale height between 110 and 60 km.

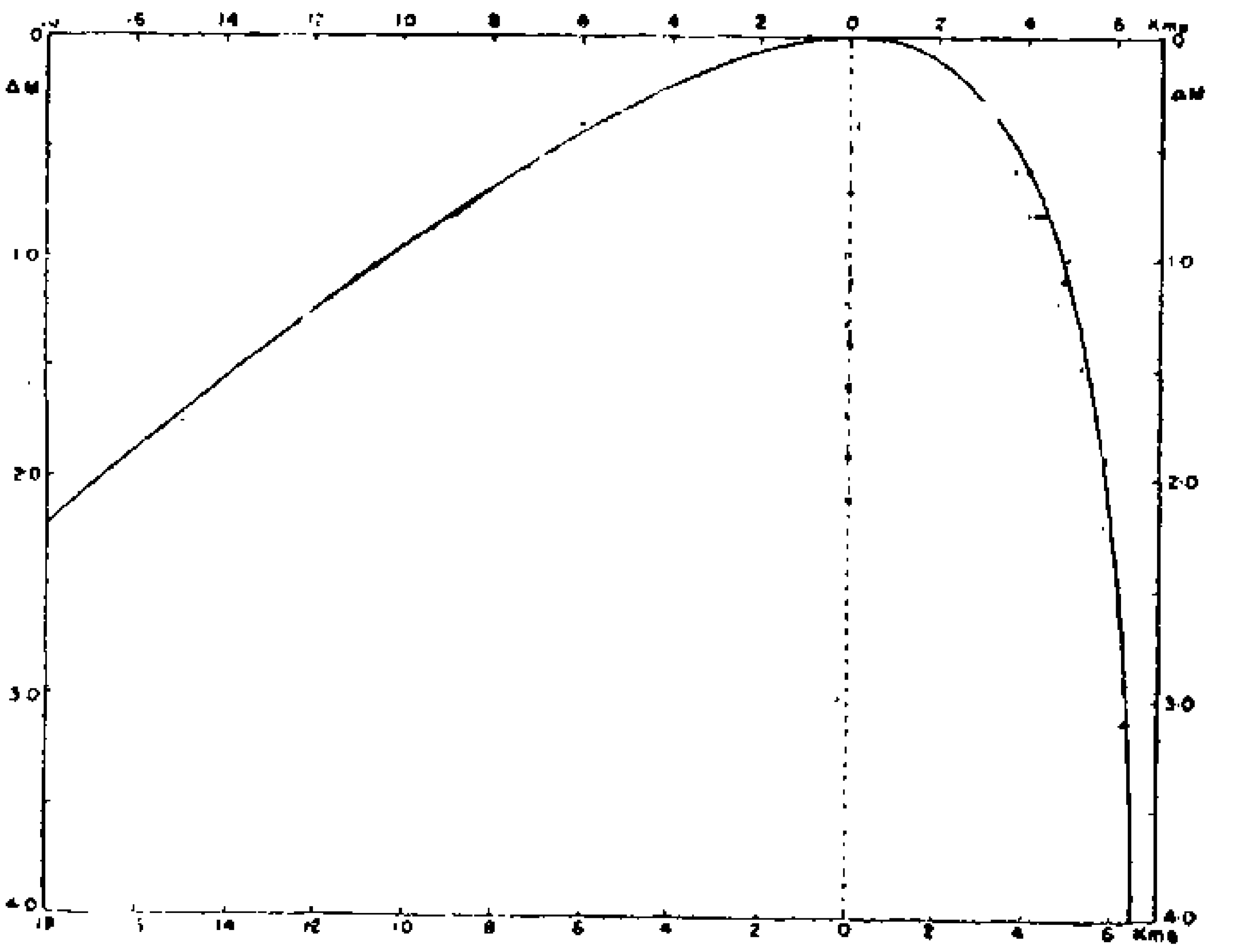

FIG. 1

3. Discrepancy Between Theory and Observation

3.1. Light curves of meteors have been studied by the two-camera photographic technique by Whipple and his collaborators in the U.S.A. In the post-war years high-speed and wide-angle Super Schmidt cameras have been employed for meteor photography yielding a wealth of information. The theory of meteor luminosity outlined in the previous section can be verified by comparing the actually observed light curves against the normal light curve predicted by theory. Such a comparison was made by Hawkins and Southworth (1958) in the following manner. On each meteor trail three points were chosen, two corresponding to the point of just appearance and just disappearance of the trail on the photographic plate and the third corresponding to the point of maximum intensity of the trail (M_{max}). The former points correspond to the limiting plate magnitude (M); $\Delta M = M - M_{max}$. The length of the beginning and end points of the trail from the point of maximum luminosity were evaluated from the photographs. Let these distances be a and b. Then on the normal light curve diagram (Fig. 1) each meteor is represented by two points with abscissæ a and b for the appropriate value of the ordinate ΔM. The two points will thus lie respectively on the ascending and descending branches of the light curve. Pairs of points corresponding to a random sample of 360 Super Schmidt meteors were plotted in this manner. If the theory of meteor luminosity is correct, these points should cluster around the theoretical curve. However, this was not found to be the case. All the plotted points were found to lie inside the curve as shown in Fig. 1.

3.2. This important finding of Hawkins and Southworth brought out conspicuously a serious discrepancy between theory and observation in respect of light curves of meteors. While sounding a note of caution about the validity of results of studies based on the normalised light curves of meteors, these authors also drew attention to the meteor fragmentation theory of Jacchia (1955) as a possible explanation for the discrepancy between theory and observation.

3.3. In two communications published in *Nature* the present writer (Ananthakrishnan, 1960, 1961) adduced reasons to show that the fragmentation theory of Jacchia cannot explain all the features brought by the Hawkins-Southworth diagram (Fig. 1) and that the conventional theory of meteor luminosity would appear to need modification to explain the observed facts. This conclusion was arrived at by eliminating from the Hawkins-Southworth diagram the majority of the fragmented meteors whose light curves are abnormal and examining the behaviour of the remaining meteors which constituted about a third of the total number. The nature of the discrepancy between theory and observation was thus highlighted, and it was shown that if the normalised light curve of the conventional theory is modified by assuming that the luminous efficiency factor τ in equation (2) is proportional to the atmospheric density ρ at every point of the meteor trail, the light curve so obtained shows better agreement with observation. However, no physical reason was adduced to support the assumed dependence of τ on ρ.

4. Modified Theory of Meteor Luminosity/Ionisation

4.1. A physically plausible reason for the modification of the conventional theory of meteor luminosity is found by a careful examination of equation (1) for meteor ablation. As mentioned in para 2.1, the conventional theory assumes that the heat transfer coefficient Λ is a constant for a given meteor throughout its flight. On physical considerations a dependence of Λ on ρ cannot be ruled out and hence it is necessary to enquire into the consequences of such a dependence. Let us assume that:

$$\Lambda = \lambda\rho^{a} \tag{13}$$

where λ and a are constants.

In this case it can be shown that equations (11) and (12) for the normalised light curve

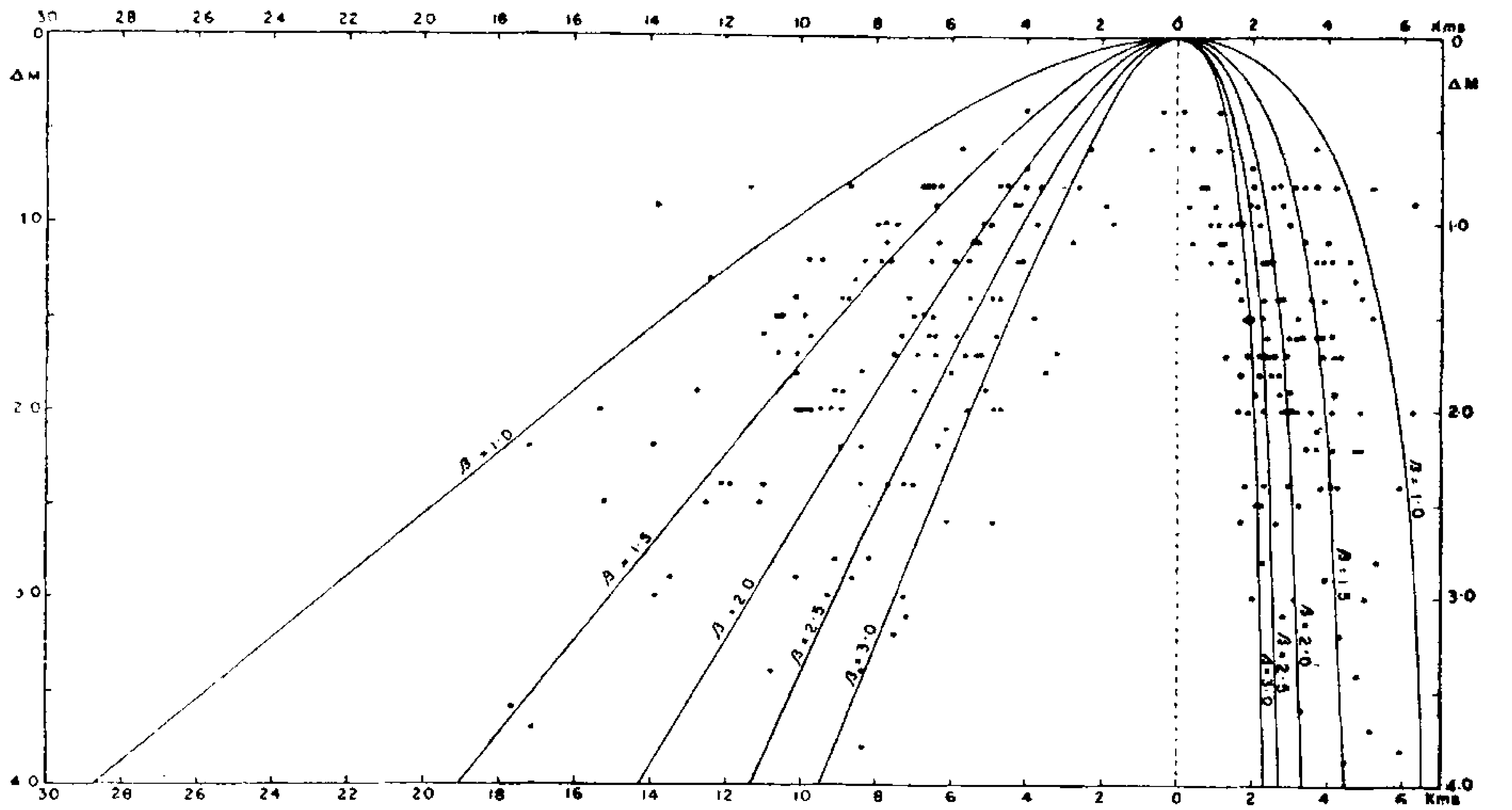

FIG. 2

transform as follows:

$$\frac{I}{I_{max}} = \frac{27}{4}(1-z)^2 \varepsilon \quad (14)$$

$$\triangle M = M - M_{max} = -2 \cdot 5 \log\left(\frac{I}{I_{max}}\right)$$

$$= -2 \cdot 5\left[2\log(1-z) + \log\varepsilon + \log\left(\frac{27}{4}\right)\right] \quad (15)$$

where $z = x^{\beta} = \left(\frac{p}{p_e}\right)^{\beta}$ and $\beta = \alpha + 1$.

Equations (14) and (15) have the same form as (11) and (12) except that z occurs in place of x.

4.2. Since $z = x^{\beta}$ the equations of the modified theory became identical to those of the conventional theory for $\beta = 1$. For values of $\beta > 1$, the ascending and descending branches of the light curve became increasingly steeper. However, for a given value of $\triangle M$ the ratio a/b (ratio of the length of the ascending branch of the meteor trail to the length of the descending branch) is the same for all values of β; the lengths a and b and hence the total length $a + b$ of the meteor trail is inversely proportional to β. Fig. 2 gives the normalised meteor light/ionisation curves corresponding to $\beta = 1 \cdot 0$, $1 \cdot 5$, $2 \cdot 0$, $2 \cdot 5$ and $3 \cdot 0$. These correspond to the cases in which the heat transfer coefficient Λ is independent of ρ and to cases in which Λ varies as $\rho^{0 \cdot 5}$, $\rho^{1 \cdot 0}$, $\rho^{1 \cdot 5}$ and $\rho^{2 \cdot 0}$ respectively. The beginning and end points of the Hawkins-Southworth meteors have also been plotted in the diagram after eliminating the fragmented meteors with abnormal light curves in the manner explained in the author's earlier note (Ananthakrishnan, 1961). A dependence of Λ on ρ is clearly brought out by the diagram. The light curve obtained earlier by the author by empirically assuming that τ is proportional to ρ lies between the curves corresponding to $\beta = 1 \cdot 5$ and $2 \cdot 0$ in Fig 2. This assumption is, however, no longer required to explain the discrepancy between the normalised light curve given by the conventional theory (curve for $\beta = 1$) and the plotted points. The dependence of Λ on ρ can fully account for the observed discrepancy. Although the observational points show a good deal of scatter, it appears that the normalised light curve corresponding to a value of $\beta = 2 \cdot 0$ would represent the light curves of meteors more correctly than that for $\beta = 1$. This would mean that the modified theory gives for meteor trails only half the length given by the conventional theory. This is in accord with the observational fact that observed meteor trails are considerably shorter than predicted by the conventional theory of meteor luminosity.

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