VARIATION OF RADIO STAR AND SATELLITE SCINTILLATIONS WITH SUNSPOT NUMBER AND GEOMAGNETIC LATITUDE

By

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ABSTRACT

A simple semi-empirical equation is developed for the variation, with sunspot and with geomagnetic latitude, of the annual mean of the scintillation amplitude index S_4, where $S_4 = [\overline{(\Delta P/P)^2}]^{1/2}$. Mercier has shown that $S_4 = [1 - \exp(-2\Phi^2)]^{1/2}$ in the far zone, and Briggs and Parkin have shown that $2\Phi^2 = K\lambda^2 \sec(i)$, where $K = 2\sqrt{\pi}\, r_e^2\, \Delta\overline{N^2}\, \Delta h\, r_o$ for isotropic irregularities, λ is wavelength, and i is ionospheric zenith angle. Experimental data on scintillation obtained by other authors is used to deduce that $K \doteq L(\Phi_{sm})\, \overline{R}$, where $\overline{R}$ is the average sunspot number and $L(\Phi_{sm})$ is a latitude variation factor which is given by a graph. The most important feature of $L(\Phi_{sm})$ is that it increases by a factor of fifty between sub-ionospheric geomagnetic latitudes (Φ_{sm}) of 51° and 63°. It is shown that the resulting semi-empirical equation

$$S_4 = (1 - \exp(-L(\Phi_{sm})\, \overline{R}\, \lambda^2 \sec(i)))^{1/2}$$

is in good agreement with experimental data obtained by Aarons, Mullen and Basu; by Castelli, Aarons and Silverman; by Little, Reid, Stiltner and Merritt; by Lansinger; and by Lawrence, Jespersen and Lamb.

INTRODUCTION

Scintillations are the random fluctuations of a radio wave (from an artificial earth satellite or a radio star) caused by its passage through irregularities in the electron density of the ionosphere. This paper considers the variation of the annual mean of the scintillation amplitude index (S_4) with geomagnetic latitude and sunspot number. A simple semi-empirical equation for S_4 is developed which provides a good fit to available experimental data.

Definitions of, and the relationships between, the four quantitative scintillation indices are as follows:

$$\begin{aligned} S_4 &= \left[\overline{(R^2 - \overline{R^2})^2}\right]^{1/2} / \overline{R^2} \\ S_3 &= \overline{|R^2 - \overline{R^2}|} \;/\; \overline{R^2} \doteq 0.73\, S_4 \\ S_2 &= \left[\overline{(R - \overline{R})^2}\right]^{1/2} / \overline{R} \doteq 0.52\, S_4 \\ S_1 &= \overline{|R - \overline{R}|} \;/\; \overline{R} \doteq 0.42\, S_4 \end{aligned} \tag{1}$$

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where R is the amplitude of the wave [*Briggs and Parkin,* 1963]. Other subjective scintillation indices are often used (such as $F = 0, 1, \ldots, 5$) but the relationship of these indices to S_4 has not been established.

Theory [*Briggs and Parkin,* 1963] gives the mean-square phase deviation (Φ^2) for isotropic irregularities as

$$2\phi^2 = 2^{3/2} r_e^{2} \overline{\Delta N^2} \Delta h \, r \, \lambda^2 \sec(i) \tag{2}$$

where: r_e is the classical radius of the electron; ΔN^2 is the mean-square deviation of the electron density in the ionosphere; Δh is the effective thickness of the ionosphere; $r = (\pi/2)^{1/2} r_0$, where r_0 is the scale of the irregularities (the distance at which the correlation coefficient falls to $1/e$); λ is the wavelength in meters; and i is the zenith angle at the ionosphere. The geometry of the problem is illustrated in Figure 1. For small Φ^2 the Briggs and Parkin theory gives

$$S_4 = (2\Phi^2)^{1/2} (1 + (r^2/\lambda z)^2)^{-1/2} \tag{3}$$

where $z = z_1 z_2/(z_1 + z_2)$ and z_1 is the slant range from the ground to the irregularity layer and z_2 is the slant range from the irregularity layer to the radio source. For a radio star z_2 approaches infinity and therefore z equals z_1. In the far zone where $r^2/\lambda z << 1$

$$S_4 \doteq (2\Phi^2)^{1/2}, \tag{4}$$

in the transition zone where $r^2/\lambda z \cong 1$ equation three holds, while in the near zone where $r^2/\lambda z >> 1$

$$S_4 = (2\Phi^2)^{1/2} \lambda z/r^2 \tag{5}$$

The effect of the finite height of a satellite is to make z smaller which: (a) reduces the scintillation index in the near zone but not in the far zone; and, (b) makes the transition from the far zone to the near zone occur at a smaller value of r^2/λ. *Mercier* [1962] has shown that the limiting value for S_4 in the far zone is given by

$$S_4 = (1 - \exp(-2\Phi^2))^{1/2} \tag{6}$$

For small phase deviation, $\Phi^2 << 1$, this reduces to equation four.

The finite source size problem has been discussed by *Briggs* [1961] and by *Aarons and Guidice* [1966]. Artificial earth satellites and the radio star Cygnus are effectively point sources, but the diameter of the radio star Cassiopeia is sufficiently large so that this source often demonstrates a lower scintillation index than Cygnus under the same conditions. According to arguments presented by Briggs this reduction in the scintillation index is a function of the mean-square phase deviation

(Φ^2). Therefore, it is possible to include this effect in the equations by replacing $2\Phi^2$ by $\varepsilon(2\Phi^2)\ 2\Phi^2$ with the appropriate source size factor (ε). For satellites and Cygnus, $\varepsilon = 1$; while for Cassiopeia, $\varepsilon \leqq 1$.

It is known that the scintillation index varies with many parameters, such as wavelength, zenith angle, local time, magnetic index, geomagnetic latitude, and sunspot number. The primary emphasis in the literature has been on the variation of the scintillation index with wavelength and zenith angle. The basic premise of this paper is that the most important parameters influencing the scintillation index are wavelength, sunspot number and geomagnetic latitude. To date, equations for the scintillation index have not included explicitly a dependence on either sunspot number or geomagnetic latitude.

Experimental data reported by *Koster* [1958], *Chivers* [1960], and *Briggs* [1964] has shown that a definite correlation exists between scintillation index and sunspot numbers. It is also known that many characteristics of the ionosphere can be expressed by an empirical linear equation, $a + bR$ for $c < R < d$, where R is the mean Zurich sunspot number. Such characteristics include: the total electron content N_T, the equivalent slab thickness τ, and the critical frequencies $(foE)^4$, foF_1 and $(foF_2)^2$ [*Bhonsle et al.,* 1965; *Davis,* 1965]. Therefore, the relationship between scintillation index and sunspot number should be investigated further.

Experimental data reported by *Aarons et al.* [1964] has shown that there exists a "cliff" in geomagnetic latitude; that is, a sudden large increase in scintillation index is observed as the auroral zone is approached. Similar results have been reported by *Kent* [1959], *Beynon and Jones* [1964], *Yeh and Swenson* [1964], and the *Joint Satellite Studies Group* [1965]. While no experimental data exists for the variation of scintillation index above 73°N, it has been shown that a definite correlation exists between scintillation activity and auroral activity [*Benson,* 1960; *Little et al.,* 1962; *Moorecroft and Forsyth,* 1963; *Aarons et al.,* 1963; *Ryan,* 1965]. The incidence of visual auroral forms at geomagnetic latitudes from 60°N to 90°N has been given by *Davis* [1962], and this data exhibits a cliff in geomagnetic latitude similar to that exhibited by scintillation index. Therefore, the relationship between scintillation index and the incidence of visual aurora should be investigated further.

THE SEMI-EMPIRICAL EQUATION

Assumptions. The North geomagnetic (dipole) pole is at 78.3°N, 69.0°W. The height of the irregularities (h) is assumed to be 400 km [*Aarons et al.,* 1964]. Although it is known that the irregularities are not isotropic [*Spencer,* 1955; *Jones,* 1960], isotropic irregularities are assumed. Although it is known that transition zone conditions prevail for some of the experimental data used in this paper, far zone conditions are assumed. In this paper, the more sophisticated assumptions of anisotropic irregularities and transition zone conditions would yield only a relatively small improvement in the fit between the resulting semi-empirical equation and the experimental data, and these assumptions would seriously complicate the entire analysis.

Because of the far-zone assumption, Mercier's equation (which has the advantage of being valid for all values of Φ^2) is appropriate. In this paper the collection of parameters, $2^{3/2}\ r_e^2\ \overline{\Delta N^2}/\Delta h\ r$, is replaced by a function (K) which is to be determined. Thus

$$2\Phi^2 = K\ \lambda^2 \sec(i) \tag{7}$$

A finite source size factor (ε) which is a function of $2\Phi^2$ is included for Cassiopeia. For satellites and Cygnus, $\varepsilon = 1$. Therefore, the scintillation index is given by:

$$S_4 = (1 - \exp(-\ \varepsilon\ K\ \lambda^2 \sec(i)\ )\ )^{1/2} \tag{8}$$

The function K (and ε) will be determined from experimental data by:

$$\varepsilon\, K = -\ln(1 - (S_4)^2)\ /\ \lambda^2 \sec(i) \tag{9}$$

The function of K/2 is the mean-square phase deviation with its dependence on frequency and zenith angle removed. The function K will be examined for its dependence on mean sunspot number (R) and on sub-ionospheric geomagnetic latitude (Φ_{sm}).

Experimental data. The experimental data used in this paper was taken from papers published by other authors. The criteria for selection of this data were as follows. First, the scintillation index must have been a long term average, including averaging over local time and magnetic indices. Second, the scintillation index must be recognizable as S_1, S_2, S_3 or S_4. Third, in order to avoid near zone conditions, data based on satellite sources is limited to satellites which have a height of at least 800 km, i.e. twice the assumed height of the ionosphere (therefore $z_1/2 < z < z_1$). Figure 2 illustrates the range of values of sunspot number and subionospheric geomagnetic latitude associated with each set of experimental data.

Little's data refers to Figure 9 of *Little, Reid, Stiltner and Merritt* [1962] which gives S_3 as a function of zenith angle for Cygnus and Cassiopeia observed from College, Alaska at a frequency of 223 MHz and at an average sunspot number of 196. The data taken at 456 MHz cannot be used because it was not calibrated in terms of S_3.

Castelli's data refers to Figure 6 of *Castelli, Aarons, and Silverman* [1964] which gives S_3 as a function of zenith angle for Cygnus observed from Boston at frequencies of 63, 112 and 225 MHz and at an average sunspot number of 48. Castelli noted that their data taken at 63 MHz failed to exhibit the wavelength dependence predicted by theory and discussed this point. The 63 MHz data has not been used in this paper.

The variation with zenith angle of the Castelli data is transformed to a variation with sub-ionospheric geomagnetic latitude.

Lansinger's data refers to data taken by *J. M. Lansinger* of Boeing Scientific Research Laboratories (private communication) which gives S_3 for Cassiopeia observed from College Alaska at a frequency of 68 MHz and at an average sunspot number of 16 (February 1965 to January 1966). This data is plotted in Figure 11.

Aaron's data refers to Figure I of *Aarons, Mullen and Basu* [1964] which gives S_3 as a function of sub-ionosphere geomagnetic latitude for the satellite Transit 4A observed from Boston at a frequency of 54 MHz and at an average sunspot number of 46. The Fredericksburg magnetic indices [*Lincoln,* 1962] for July 1961 to June 1962 are given by $K_{F_r} < 2$, 70.5%; $K_{F_r} = 3$, 18.3%; $K_{F_r} > 4$, 11.2%. This data was used to remove the variation with K_{F_r} present in Aaron's data, and the result is plotted in Figure 8. The relationship between ionospheric zenith angle (i) and sub-ionospheric geomagnetic latitude (Φ_{sm}) was calculated by assuming the "typical pass" for Transit 4A illustrated by Figure 4 of *Aarons et al.* [1963].

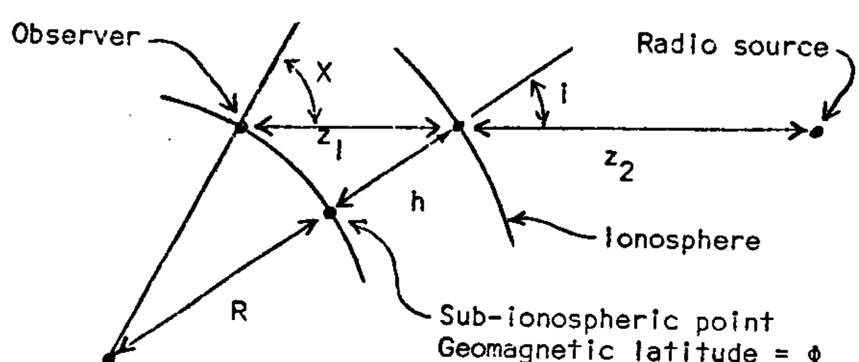

FIG. 1.—Geometry of the problem.

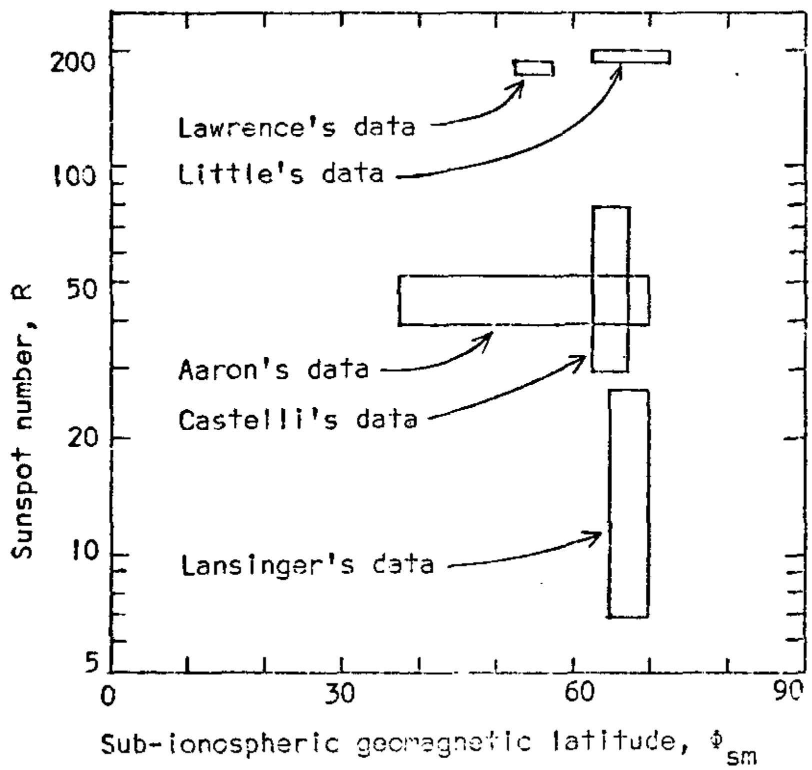

FIG. 2.—Semilog plot of the values of sunspot (R) and sub-ionospheric geomagnetic latitude (Φ_{sm}) associated with each set of experimental data.

Lawrence's data refers to Figure 12 of *Lawrence, Jespersen and Lamb* which gives $(S_2)^2$ as a function of zenith angle for Cygnus observed from Boulder, Colorado at frequencies of 53 and 108 MHz and at an average sunspot number of 181. This data is expressed in terms of S_3 in order to be consistent with the other data.

The following data is used only to illustrate certain trends. Koster's data refers to Figure 3 of *Koster* [1958] which gives the average night-time scintillation index for several radio stars observed from an equatorial station during the period 1953-1957. Brigg's data refers to Figure 7 of *Briggs* [1964] which gives the scintillation index for Cassiopeia at upper and lower transit observed from Cambridge, England for the period 1950-1961. The relationship of either Koster's or Brigg's scintillation index to S_3 has not been established. Davis' data refers to Figure 13 of *Davis* [1962] which gives the incidence of auroral forms at geomagnetic latitudes 60°-90° during the IGY, 1957-58.

Variation with sunspot number. Little's data, Castelli's data and Lansinger's data were all taken within a narrow range of subionospheric geomagnetic latitudes, $63° < \Phi_{sm} < 73°$. This data provides no evidence of a variation of S_3 with Φ_{sm}; zenith-angle variations in the far zone adequately explain this data. Therefore, it is assumed that the function K does not vary with sub-ionospheric geomagnetic latitude (Φ_{sm}) in this range. The data of Little, Castelli and Lansinger were taken at average sunspot number (R) of 196, 48, and 16 respectively. This data is to be examined for the variation of the function K with R (and for the effect of finite source size).

The value $_{\varepsilon}K$ is calculated by equation 9 for each experimental value of S_3. Figure 3 plots the average of K as a function of the average sunspot number ($\overline{R}$) for: Little's Cygnus data, Little's Cassiopeia data, Castelli's Cygnus, and Lansinger's Cassiopeia data. Note that K is averaged over the experimental data, while R is averaged over a year's time. It can be seen from Figure 3 that the average of K varies linearly with $\overline{R}$ for the Cygnus data.

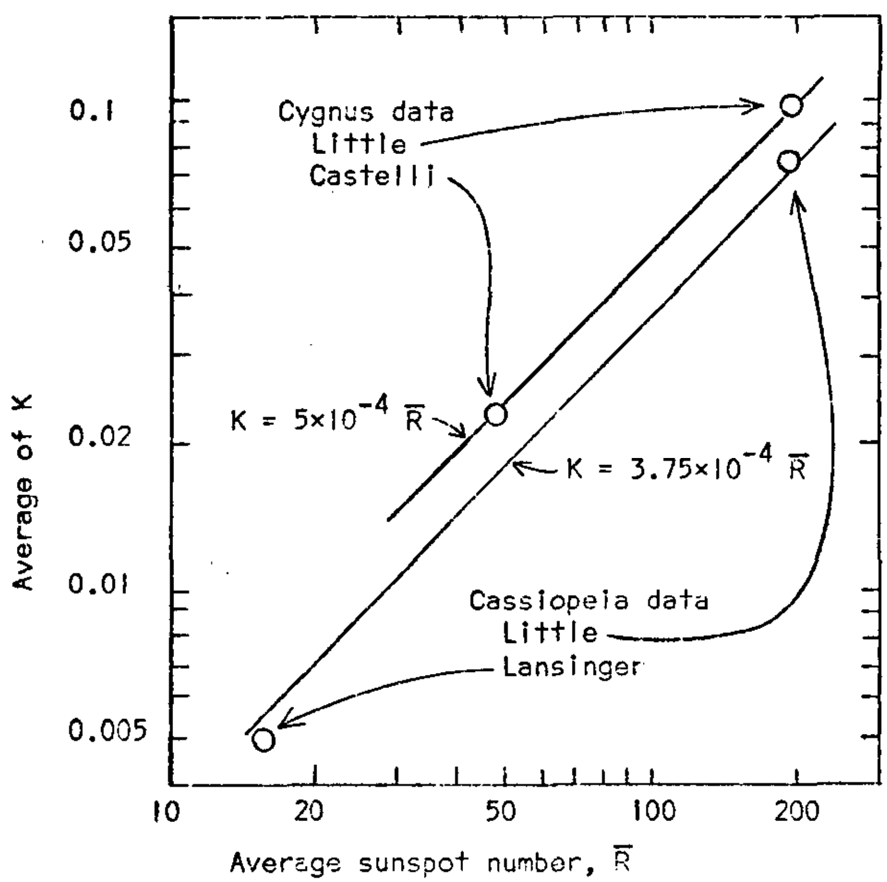

FIG. 3.—Log-log plot of the average of K as a function of the average sunspot number $\overline{R}$ for $63° < \Phi_{sm} < 73°$.

The difference in the average value of K between Little's Cassiopeia data and his Cygnus data must be assigned to the finite source size factor (ε). The average value of S_3 for Little's Cassiopeia data and Lansinger's Cassiopeia data is almost the same. Therefore, both sets of data should have almost the same source size factor ε. It is assumed that both sets of data have the same ε. It can be seen from Figure 3 that the average of K varies linearly with $\bar{R}$ for the Cassiopeia data, and that when S_3 is approximately equal to 0.30, ε equals 0.75 for Cassiopeia.

It has been shown that K is proportional to $\bar{R}$ for $63° < \Phi_{sm} < 73°$. A partial check on the validity of this relationship at other values of Φ_{sm} can be obtained by using the data of Koster and Briggs. Koster's data was taken at a geomagnetic latitude of 12°N and therefore at low values for Φ_{sm}. Brigg's data was taken at $\Phi_{sm} = 55.1°$ and $\Phi_{sm} = 61.6°$. (It will be shown in the next section that the region $51° < \Phi_{sm} < 63°$ has a special significance). Let the scintillation indices of Koster and Briggs be denoted by F. It is assumed that F is proportional to S_4. Equations 4 and 7 give $S_4 = (K \lambda^2 \sec(i))^{1/2}$. If K is proportional to $\bar{R}$, then F is proportional to $\bar{R}^{1/2}$. Figure 4 shows that Koster's data and Brigg's data roughly agree with this last relationship. Therefore, it is reasonable to conclude that K is approximately proportional to $\bar{R}$ for all Φ_{sm}.

Variation with geomagnetic latitude. Aaron's data was taken with $38° < \Phi_{sm} < 68°$, and Little's data was taken with $63° < \Phi_{sm} < 73°$. This data is to be examined for the variation of the function K with Φ_{sm}. In the last section it was shown that K is proportional to $\bar{R}$. This dependence must be removed. Figure 5 shows a plot of $K / \bar{R}$ as a function of Φ_{sm} for this data. It can be seen that the solid line in Figure 5 adequately represents the variation of $K/\bar{R}$ with Φ_{sm}. Let

$$K = L(\Phi_{sm})\ \bar{R} \tag{10}$$

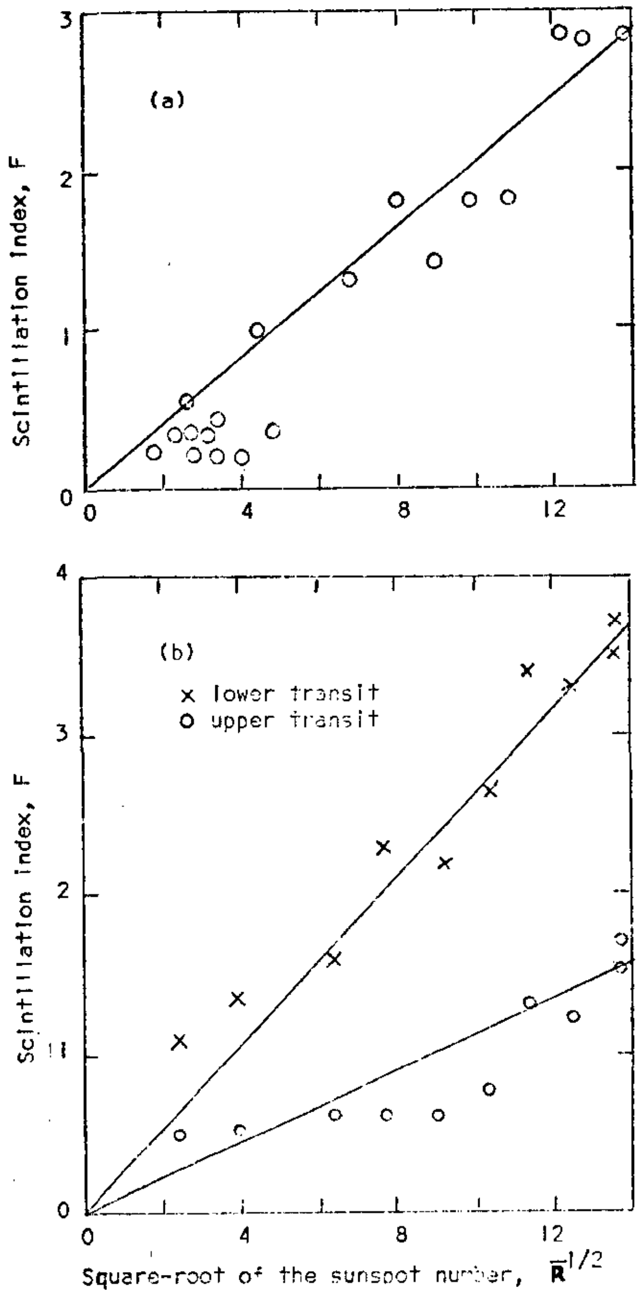

FIG. 4.—The scintillation index (F) versus the square-root of the average sunspot number for: (a) Koster's data; (b) Briggs' data.

where $L(\Phi_{sm})$ is a latitude variation factor and Φ_{sm} is the sub-ionospheric geomagnetic latitude. Therefore, for $38° < \Phi_{sm} < 73°$, $L(\Phi_{sm})$ is given by the solid line in Figure 5.

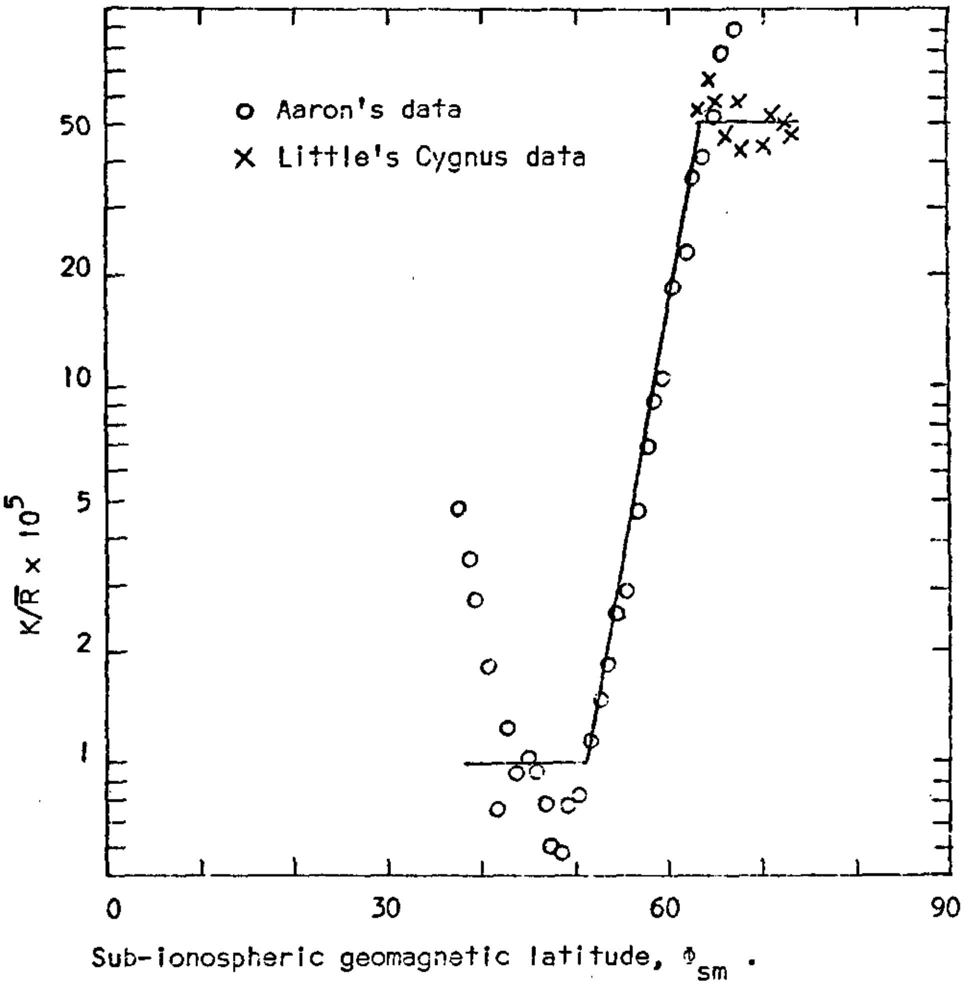

FIG. 5.—Semilog plot of $K/\overline{R}$ as a function of sub-ionospheric geomagetic latitude, Φ_{sm}.

The definite correlation between scintillation activity and auroral activity was discussed in the introduction. Figure 6 plots the solid line of Figure 5 and Davis' data for the occurrence of visual auroral forms (multiplied by an arbitrary constant, 4 x 10^{-4}). It can be seen that the dotted line in Figure 6 is a reasonable estimate for the latitude variation factor $L(\Phi_{sm})$ for $73° < \Phi_{sm} < 90°$. No adequate data exists for the region $0° < \Phi_{sm} < 38°$. Therefore, it is reasonable to conclude that the latitude variation factor $L(\Phi_{sm})$ is given by Figure 7.

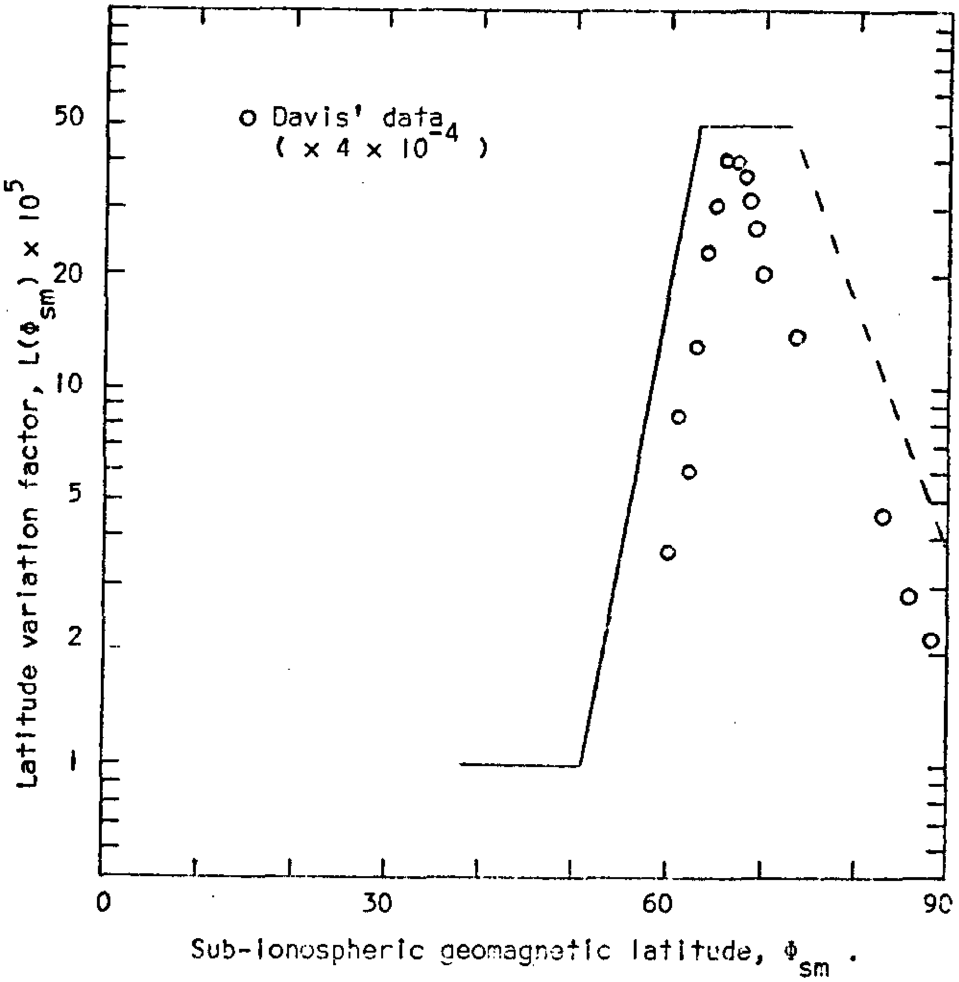

FIG. 6.—Semilog plot of the latitude variation deduced from Figure 5 and of Davis' data for the incidence of auroral forms. Dashed line is estimate for the latitude variation in the region $73° < \Phi_{sm} < 90°$.

Comparison with experimental data. Substituting equation 10 into equation 8 gives the scintillation index as

$$\overline{S}_3 \doteq 0.73(1 - \exp(-\varepsilon\, L(\Phi_{sm})\, \overline{R}\lambda^2 \sec(i)))^{1/2} \quad (11)$$

where the latitude variation factor $L(\Phi_{sm})$ is given by Figure 7, $\overline{R}$ is the average Zürich sunspot number, superscript bar denotes annual mean, and the finite source size factor ε is given by $\varepsilon = 1$ for satellites and Cygnus and $\varepsilon = 0.75$ when $S_3 \cong 0.30$ for Cassiopeia.

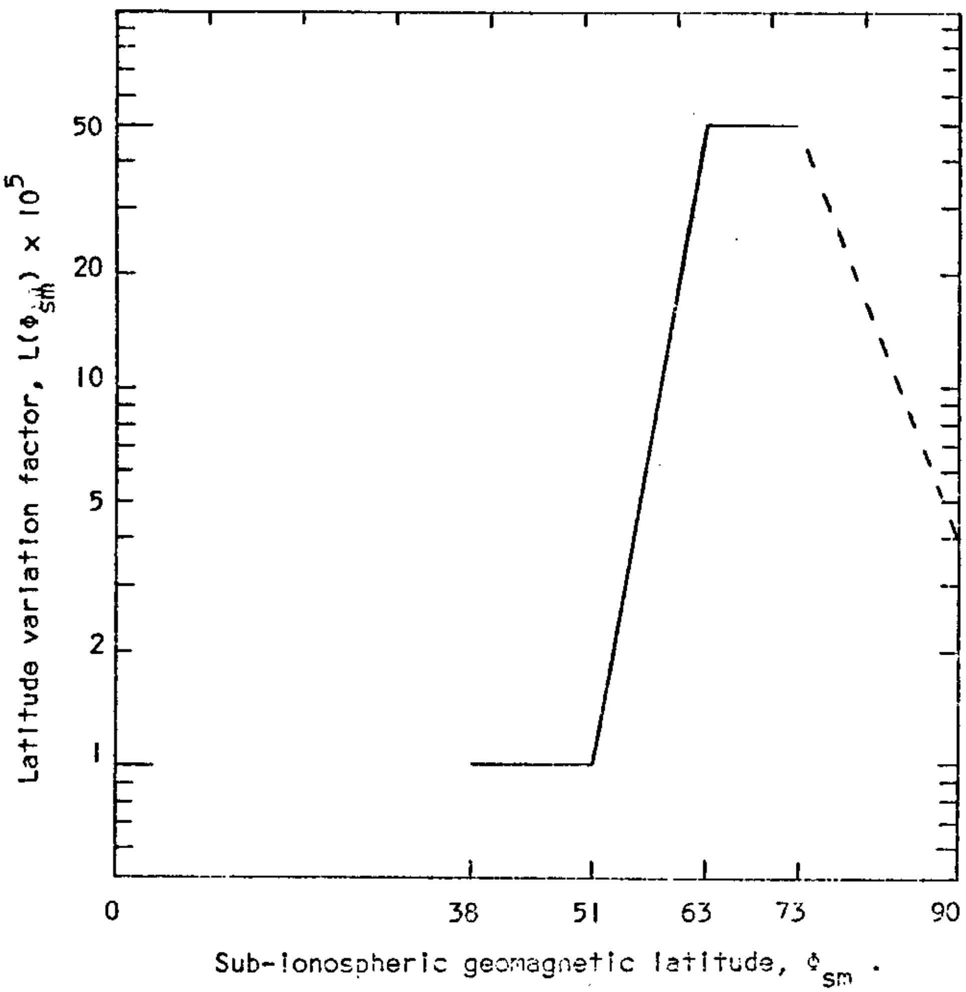

FIG. 7.—Semilog plot of the empirical latitude variation factor, $L(\Phi_{sm})$, as a function of sub-ionospheric geomagnetic latitude, Φ_{sm}. Dashed lines are estimates.

It is necessary to determine how well equation 11 agrees with experimental data. Equation 11 has been used to calculate $\overline{S}_3$ for the conditions appropriate for each set of data. Figures 8 through 12 compare the values of $\overline{S}_3$ given by equation 11 with the experimental data of Aarons, of Castelli, of Little, of Lansinger, and of Lawrence. It can be seen that the results obtained by equation 11 agree closely with the experimental data.

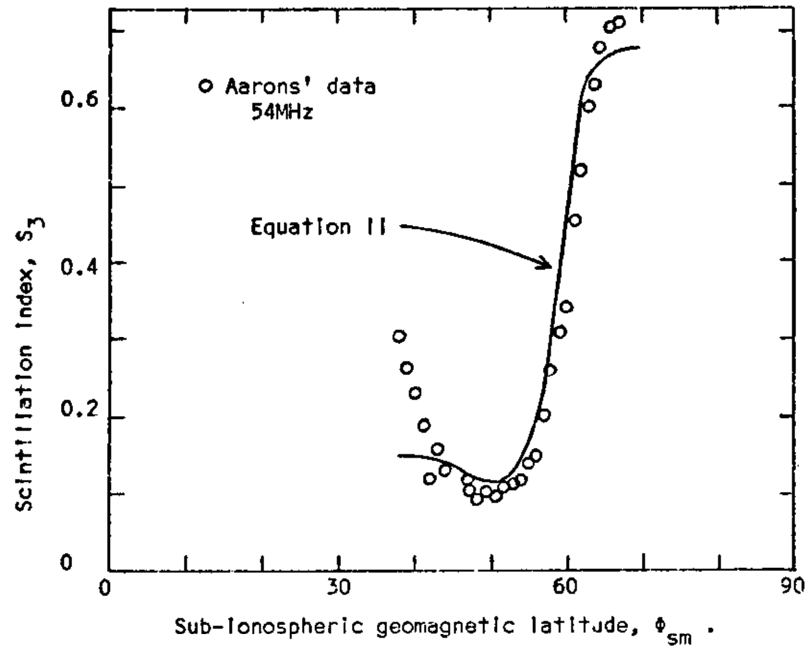

FIG. 8.—Comparison of values given by equation 11 with Aarons' experimental data.

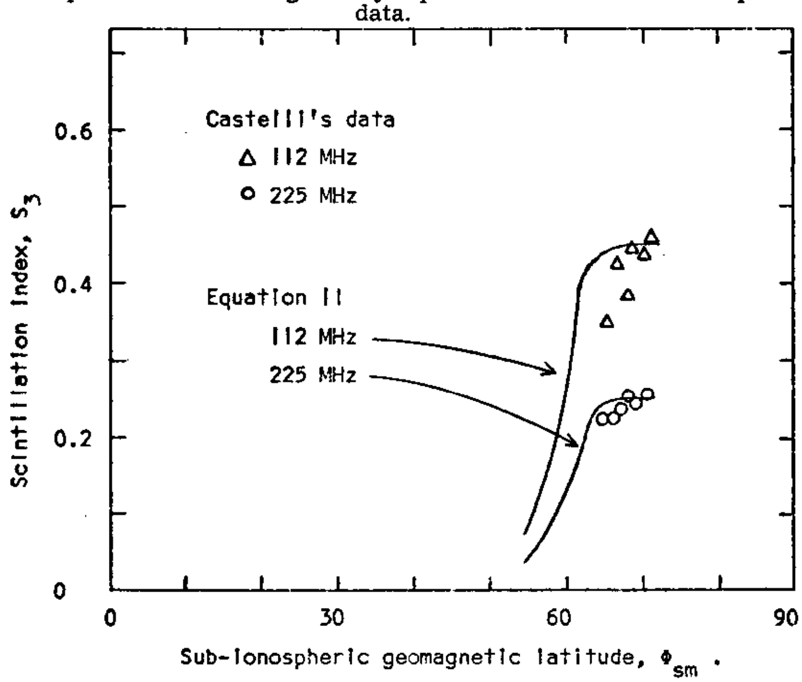

FIG. 9.—Comparison of values given by equation 11 with Castelli's experimental data.

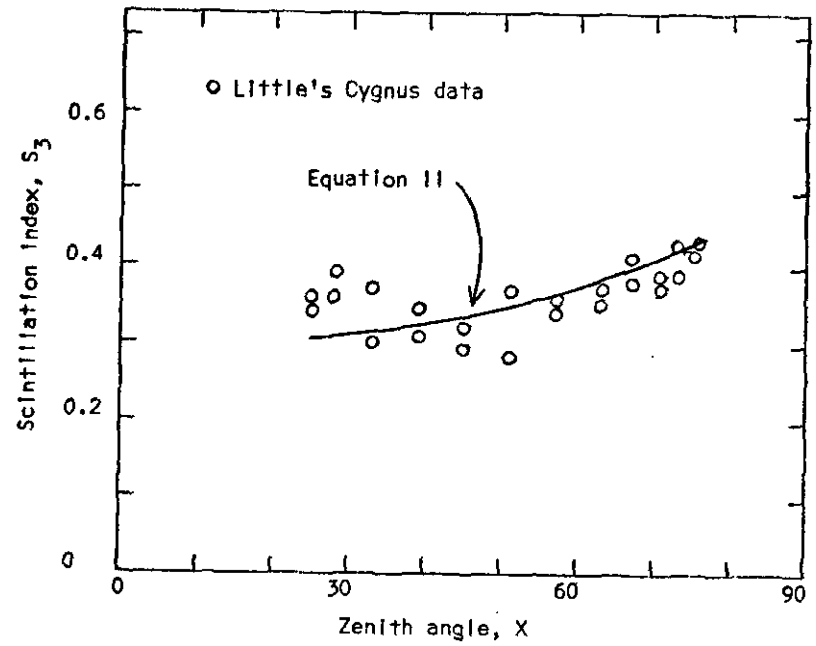

FIG. 10a.—Comparison of values given by equation 11 with Little's Cygnus data.

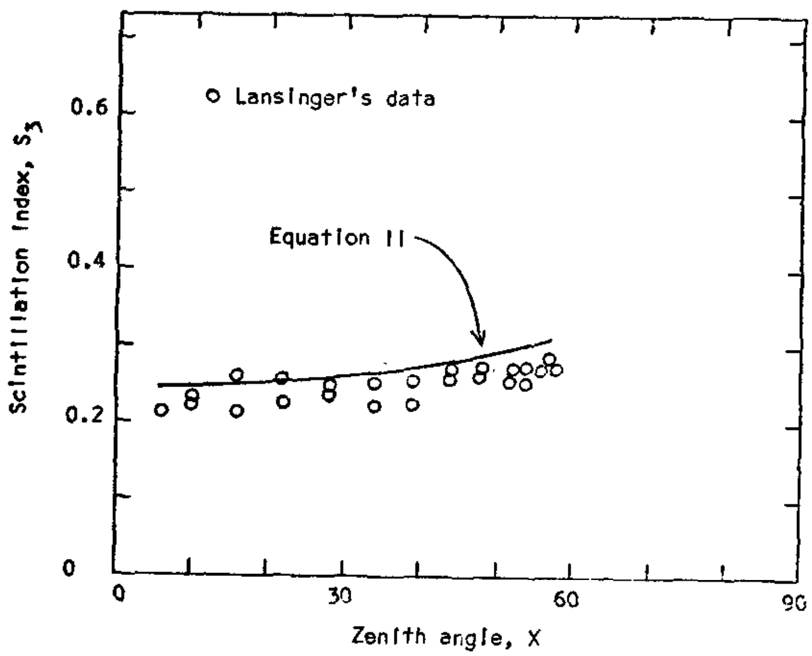

FIG. 10b.—Comparison of values given by equation 11 with Little's Cassiopeia data.

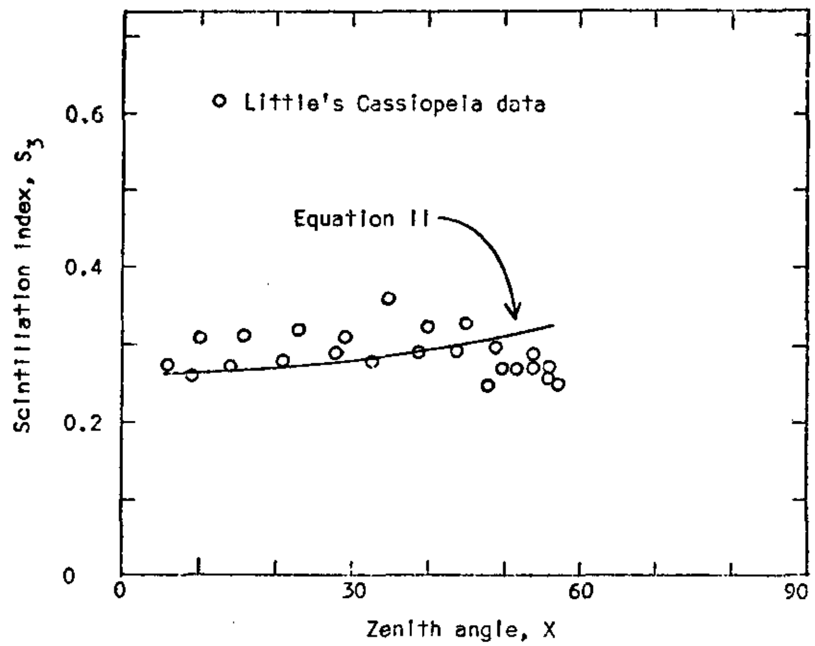

FIG. 11.—Comparison of values given by equation 11 with Lansinger's data.

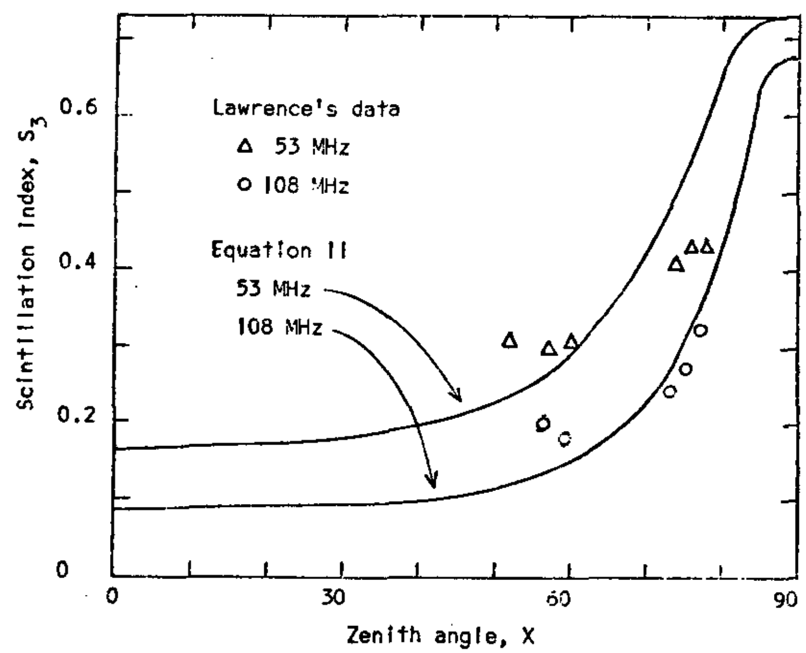

FIG. 12.—Comparison of values given by equation 11 with Lawrence's data.

Discussion. The principal conclusion of this paper is that the mean-square phase deviation (Φ^2) equals the product of the average sunspot number ($\overline{R}$) and the latitude variation factor $L(\Phi_{sm})$ given in Figure 7. This conclusion was reached on the basis of a limited amount of experimental data. Clearly, additional experimental data is necessary to further verify this conclusion. Equation 11 can be used to determine appropriate experiments. For example, Figures 9 and 12 illustrate that data taken from Boston and Boulder tracking Cygnus from horizon-to-horizon would yield useful data on the important region $51° < \Phi_{sm} < 63°$, the "face of the cliff".

Cassiopeia has often been used as the source because it is the strongest radio star. In this paper the finite source size factor has been determined for only one point on the curve, $\varepsilon(0.40) \doteq 0.75$. The finite source size factor $\varepsilon(2\Phi^2)$ for Cassiopeia should be determined for all Φ^2, in order that Cassiopeia data can be compared with data from Cygnus and satellites.

It is well known that the scintillation index is also a function of the magnetic index K and local time T. While the extension of equation 11 to include the dependence of S_4 on K and T is beyond the scope of this paper, a few comments are in order. The correlation between scintillation and auroral activity has been noted by many workers. In addition, comparison of Aaron's data, which gives the variation with magnetic index of scintillation as a function of geomagnetic latitude, with the data of *Gartlein et al.* [1960], which gives the variation with magnetic index of the occurrence of aurora as a function of geomagnetic latitude, reveals a striking similarity. Therefore, it seems logical to examine the variation of the occurrence of aurora with local time for clues to the behavior of scintillation in the arctic regions as a function of local time. *Feldstein* [1966] has shown that the frequency of auroral appearances is a complex function interrelating "geomagnetic latitude," local magnetic time, and planetary magnetic index.

It should be noted that the study of scintillations now has an engineering aspect as well as a basic research aspect. There exists current interest in designing communication systems employing terminals in the auroral regions and satellites. Equation 11 is useful in calculating the fading which can be expected due to scintillation.

Conclusion. The plausibility of the following conclusion has been demonstrated. The annual mean of the scintillation index S_4 is given by the semi-empirical equation

$$\overline{S_4} \doteq (1 - \exp(- \varepsilon\, L(\Phi_{sm})\, \overline{R}\, \lambda^2 \sec(i)))^{1/2} \qquad (12)$$

where the latitude variation factor $L(\Phi_{sm})$ is given by Figure 7 as a function of the sub-ionosphere geomagnetic latitude Φ_{sm}, and R is the average Zürich sunspot number. Superscript bar denotes an annual mean, λ is the wavelength in meters, i is the ionospheric zenith angle, and the finite source size factor ε is given by $\varepsilon = 1$ for satellites and

Cygnus and by $\varepsilon = 0.75$ when $S_4 \cong 0.40$ for Cassiopeia. It has been shown that this semi-empirical equation yields results which agree closely with experimental data obtained by *Aarons et al.* [1964], *Castelli et al.* [1964]; *Little et al.* [1962], *Lansinger,* and *Lawrence et al.* [1961]. However, additional experimental data is required to further verify this semi-empirical equation.

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