11. The Auroral Green Line in Perseid Spectra Near Sunspot Maximum

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Thirty-one spectra photographed during the Perseid showers of 1969 and 1970 are found to exhibit greater ionization and stronger, more frequent appearance of the forbidden oxygen line at 5577 Å than Perseid spectra obtained with the same instrument in 1961. Data from 13 Perseid showers indicate a relationship between the frequency of occurrence of the oxygen line and solar activity. In 1969–70, near sunspot maximum, the strength of this so-called auroral green line is greatest near shower maximum, as though the nature of the meteoroids were a function of their distance from the core of the stream, or, alternatively, the strength of the green line were a function of the altitude of the radiant.

SINCE 1948, A SPECTROGRAPHIC STUDY of the annual Perseid meteors has been conducted by the University of Southern California, generally at an observing site in the Sierra-Nevada range in northern California (Russell, 1959). An earlier summary of the results of this project showed the shower of 1961, during which 10 spectra were obtained with one prism spectrograph, to be the most productive of spectra of any shower observed by U.S.C. through 1963 (Russell, 1964). In 1969 and 1970, 31 spectra were recorded with the same instrument used in 1961. The distribution in time of the spectra from the 1969 shower has already been discussed (Russell, 1969). In this paper the spectral features will be considered.

The spectra from the 1961 shower were classified into four groups on the basis of the presence of certain spectral lines as follows:

Group 1—The *H* and *K* lines of ionized calcium

Group 2—The magnesium triplet at 5175 Å, the auroral green line of neutral oxygen at 5577 Å, the *D* line of sodium, and a calcium-iron blend near 6170 Å

Group 3—Only the *D* line of sodium and the blend at 6170 Å

Group 4—Only the *D* line of sodium

In 1961 these four categories sufficed, as the green line was present in or absent from all spectra in a given category. For the spectra of 1969 and 1970 this was not the case, and all groups except number four were bifurcated, a prime following the group number indicating the presence of 5577 Å. The results are shown in table 1. It will be noted that in 1969 and 1970, compared to 1961:

(a) The *H* and *K* lines appeared almost four times as often.

(b) Lone occurrences of the *D* line were ⅟₁₂ as frequent.

(c) The green line appeared with nearly twice the frequency.

It is clearly evident from item (a) that the level of ionization of calcium was higher in the

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TABLE 1.—*Number of Spectra in Defined Groups for 3 Perseid Showers*

Group	1	1′	2	2′	3	3′	4	Total	Percent with *H* and *K*	Percent with *D* only	Percent with 5577 Å
1961	0	1	0	2	3	0	4	10	10	40	30
1969	3	4	1	4	5	4	0	21	33	0	57
1970	2	2	0	3	1	1	1	10	40	10	60

1969–70 spectra than in those of 1961. Item (b) indicates indirectly that the same was true for silicon. The observation in 1969–70 of only one questionable spectrum in group 4 may be attributed to the nearly equal densities of the *D* line and the blend at 6170 Å, whereas in 1961 the *D* line was distinctly the stronger of the two, and in very faint spectra could be seen alone. Compare figures 1 (a) and (b). The two features were also closer together in 1961 as indicated in table 2.

The blend to the red of the *D* line in the 1961 spectra was attributed principally to neutral calcium. Figure 1(c) shows the one 1969 spectrum, recorded at the plate edge where the focus is better in the red, in which the feature is resolved into what are probably the calcium blend at 6170 Å and the SiII doublet at 6360 Å. The increased strength and greater wavelength of this blend in 1969–70 may be attributed to a stronger SiII component. This interpretation is supported by the observation of Hirose and his co-workers (1968) that where the plate sensitivity is favorable, the SiII lines are the strongest lines to be found in Perseid spectra. It is interesting to note that this near equality in the density of the *D* line and the red blend is so consistent in the 1969–70 Perseid spectra that the meteor in figure 1(d), whose path missed the Perseid radiant by 8°, was easily judged to be sporadic because of the additional evidence provided by the weakness of the red blend.

The added strength of the SiII feature appears unrelated to plate sensitivity. The same emulsion was used all three years, and no difference in the location of the red cutoff could be observed by comparing spectra of the same stars recorded in 1961 and in 1969–70. As the SiII component in the resolved 1969 spectrum in figure 1(c) is stronger than the calcium component, the lower photographic density in 1961, the result of less efficient development, would suppress the calcium component and make the blend farther from the *D* line than in 1969. The reverse of this is observed. Hence the increased strength of SiII in 1969–70 is believed to be real.

Millman, Cook, and Hemenway (1971) using an image orthicon tube in place of a photographic emulsion, observed the auroral green line in all 14 of the 1969 Perseid spectra studied. With our more conventional techniques, the line at 5577 Å is totally absent from some spectra whereas in others it is the most prominent feature. The irregularities of appearance of the green line have been well covered. Halliday (1960) was the first to suggest that the velocity of the meteor and the extent of solar activity were likely contributing factors. Velocity differences cannot be invoked to explain differences in spectra from the same shower, but there is evidence in these data that the sunspot cycle is involved. In figure 2, the percentage of spectra showing the green line is plotted for 13 Perseid showers from 1948 through 1970. The 13 points are joined by the dashed line. Through each point is a vertical line, the length of which is inversely proportional to the square root of the number of spectra represented by the point. The longest lines indicate single spectra; the shortest line, 21 spectra. Average daily sunspot numbers, plotted by the year, are joined by the solid line. If the numbers on the percentage scale are multiplied by two, they serve as sunspot numbers. Despite the absence of data for several showers, the correlation is clearly evident.

Lindblad (1968) found several meteor parameters to be correlated with solar activity, explaining the correlation as the result of the Earth's atmosphere, at the critical height, having a maximum density at solar minimum and vice

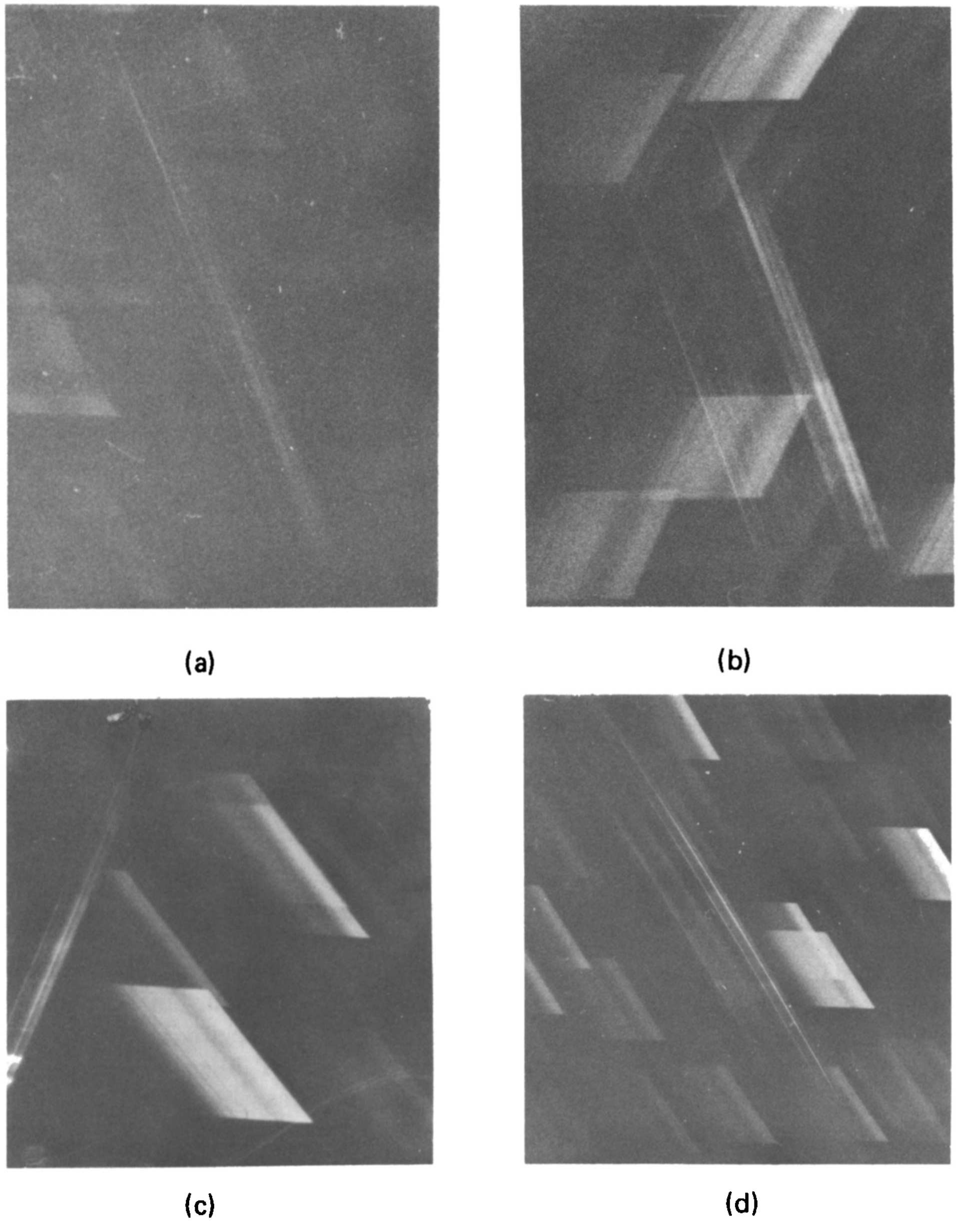

FIGURE 1.—The D line of sodium is the marked line. Violet is to the left throughout. (a) 1961 Perseid spectrum showing strong D line. (b) 1969 Perseid spectrum showing the D line and blend at 6170 Å of nearly equal density. (c) 1969 Perseid spectrum showing resolution of the blend to the red of the D line. (d) Sporadic spectrum showing very weak radiation to the red of the D line.

versa. Increased ionization and green line strength in Perseids near sunspot maximum may both be fostered by this density effect. It is well known that ionized lines are enhanced in the spectra of giant stars whose atmospheres are of lower density than those of stars on the main sequence. The low density may also favor the oxygen atom's remaining in the excited state until the forbidden line is emitted.

The appearances of the auroral green line in figure 2 were recorded without taking account of the strength of the line. In figure 3, the relative

TABLE 2.—*Linear Separation of the* D *Line and the Feature to the Red thereof for Different Years*

Year	Separation (cm)	Probable error (cm)
1961	0.0234	±0.00076
1969	0.0264	±0.00030
1970	0.0257	±0.00062

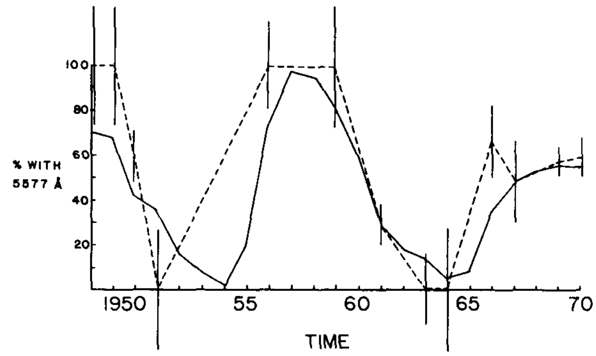

FIGURE 2.—Percentage of spectra from each of 13 Perseid showers showing the forbidden oxygen line at 5577 Å. The solid line delineates sunspot numbers for the same period.

density of the line, on a scale of 5, is plotted against the time of appearance for the spectra of 1961, 1969, and 1970, using circles, dots, and triangles respectively. The ordinates are defined as follows:

0. No oxygen green line observable
1. Green line present but very faint
2. Green line easily seen but well below *D* line density
3. Green line approximately as dense as the *D* line
4. Green line is the densest feature in the spectrum.

The consistent strength of the oxygen line on the night of 1969 August 11–12 until 1^h PST is not likely a statistical fluctuation. The line was generally weak the balance of the night as well as on the previous and following nights. The single strong oxygen line observed on the night of 1969 August 10–11 is in the spectrum of a sporadic meteor, another example of the consistently similar appearance of Perseid spectra compared to those of sporadic meteors.

The *Monthly Bulletin of the American Association of Variable Star Observers* for August 1969, shows sunspot activity in a state of decline during the shower and quite unrelated to the behavior of the green line. The planetary magnetic 3-hr range indices of the International Union of Geodesy and Geophysics, published by the Institut für Geophysik in Göttingen, Germany, look more promising. The night of August 11–12 activity was consistently three times what it was the previous night and twice what it was on the following night. However, unless rapid and significant variations in geomagnetic activity are masked by the three-hour means, solar activity provides no explanation for the strong green line August 10–11, for the sudden change in the middle of the second night, or for the presence in a weak Perseid spectrum of the green line with greater intensity than it possessed in a stronger spectrum obtained four minutes later on the same film. Moreover, the magnetic range indices seem uncorrelated with the green line activity in 1970!

Figure 3 indicates that all of the green lines in Perseid spectra with strength rated 3 or 4 appeared on the night of maximum both in 1969 and in 1970. If the strength of the green line is in any way related to the position of the Earth in the meteor stream, the peak of green line activity would be expected about 6 hr later from year to year. Maximum in 1969 occurred about 11 p.m. PST on August 11. In 1970 it occurred about 5 a.m. PST August 12. In 1969 the green line activity was clearly on the decline during the night, whereas in 1970 it was increasing, as one would expect if the position of the Earth in the stream were a factor. Also, the three green line spectra of 1961 behave much like those of 1969, as they should, since two 4-yr calendrical cycles intervene, resulting in maxima on the same day and nearly the same hour.

Variations in the density of meteoroids in the same or different streams have been discussed by Ceplecha (1967), Jacchia (1963), Kresák (1968), Russell (1964), and Verniani (1967), but I am aware of no evidence of variations in a given stream that are a function of distance from the stream center.

Millman (1968) points out that when a shower

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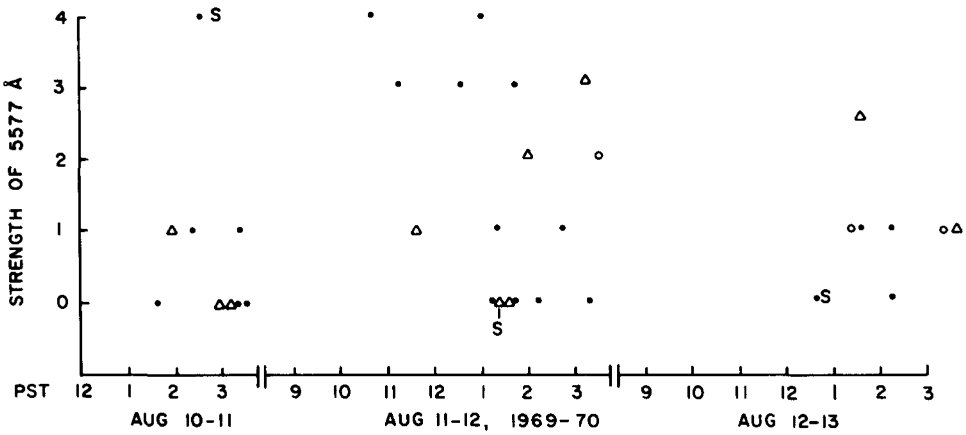

FIGURE 3.—Strength of the forbidden oxygen line relative to the sodium *D* line. Spectra from 1961, 1969, 1970 are plotted as circles, dots, and triangles, respectively. Sporadic spectra are marked *S*.

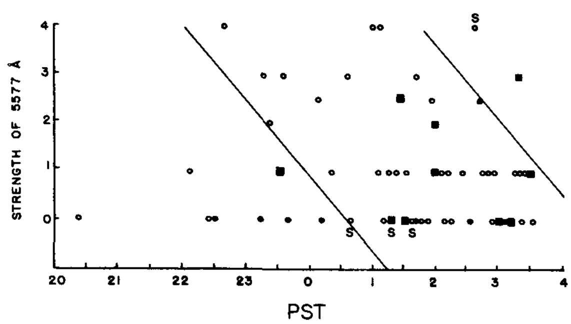

FIGURE 4.—Green-line strength as a function of local time for the Perseid showers in figure 2. The 1970 data are shown as squares. See text for other details.

radiant is at low elevation, bright meteors observed by radar may have a range spread of over 100 km, as they remain in the meteor echo height zone for several seconds. This suggests, as an alternative explanation for the concentration of strong green lines in 1969, that a low radiant could likewise allow a meteor to remain in the green-line producing zone for a longer period. During the Perseid shower, the radiant is rising throughout the hours of darkness, the value of cosec Z at 21^h being about twice what it is at midnight and three times its value at $2^h\ 30^m$. Thus the strong green lines in 1969 were occurring when the radiant was lowest as well as at shower maximum, since the two events were nearly simultaneous.

Figure 4 shows the green line data for all showers included in figure 2 in which at least one green line appearance was noted, plotted against the PST of appearance of the meteor. The 1970 data are plotted as squares, while 1961 spectra in groups 3 and 4 are plotted as filled circles. Sporadics are marked *S*. The decline in green line strength after shower maximum, or with decreasing zenith distance, in 1969 and the increase toward shower maximum in 1970 are muddied by the inclusion of all of the data. If one is willing to eliminate sporadic meteors, meteors observed in 1970, the single-line group 4 meteors of 1961, a spectrum consisting of only the *H* and *K* lines in terminal burst, and a meteor that was barely in the camera field, only the meteor plotted at $22^h\ 25^m$ lies outside the arbitrarily drawn diagonal lines, and those remaining within indicate a tendency for green line strength to decline with increase in the altitude of the radiant during the night. The contrary behavior of the 1970 data may be related to an effect noted by Hajduk (1968) who showed that whereas for Orionids, long duration echoes decrease in frequency with decreasing zenith distance of the radiant, for Geminids the reverse is true. Possibly an anomalous variation in 1970 of the height of the layer producing the green line resulted in the same type of reversal that Hajduk observed for different showers in a layer presumed to be at a fixed altitude.

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