METAL LINE BLANKETING AND OPACITY IN THE ULTRAVIOLET OF ALPHA^2 CANUM VENATICORUM

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ABSTRACT

Ultraviolet photometry by OAO-2 was made of α^2 CVn covering the entire $5^d.5$ period of this magnetic Ap variable. The light curves ranging from 1330 Å to 3320 Å indicate the dominant role of rare-earth line-blanketing in redistributing flux. In a broad depression of the continuum covering 2300-2600 Å, scanner observations possibly identify strong lines of Eu III as major contributors to this feature. At maximum intensity of the rare-earth lines, the ultraviolet continuum shortward of 2900 Å is greatly diminished while the longer wavelength regions into the visual become brighter. Thus, the light variations in α^2 CVn are due to the variable strong line-blanketing by the abundant rare-earth elements.

In addition, there is evidence that the hydrogen line opacity is variable and the photoionization edge of Si I at 1680 Å is identified. These ultraviolet observations suggest the importance of metal line-blanketing and opacity in the redistribution of flux in Ap variables.

I. INTRODUCTION

α^2 Canum Venaticorum is one of the brightest ($2^m.9$) and most studied members of the anomalous group of Ap stars whose spectra are characterized by strong and profuse metal lines. This star is well-known for its periodic ($5^d.47$) spectral variations of line intensities and radial velocities of overabundant rare-earths and iron-peak elements as well as other metals. In addition, there are with the same period a strongly variable magnetic field (-1000 to +2000 gauss) and small variations in light and colors.

Many models have been proposed for α^2 CVn and the most successful at present are the oblique-rotator models advanced by Deutsch (1958), Böhm-Vitense (1966), Kodaira and Unno (1969), Pyper (1969) and Cohen (1970). These models describe the observed periodic phenomena as due to the rotation of the star. A magnetic dipole field inclined to the axis of rotation and concentrations or "patches" of metals on the surface will rotate with the star causing the observed periodic changes. The mapping of these surface metal concentrations for α^2 CVn has been extensively carried out by Pyper (1969) and with her model most of the observed spectral changes can be understood.

These models were made, however, to describe the magnetic and spectral variations neglecting for the most part, or failing to explain, the perplexing problem of the light and color variations. The UBV photometry of Pyper (1969) and scanner observations of Cohen (1970) both show α^2 CVn being reddest and brightest at rare-earth maximum at phase E = 0.0, while it is bluest and faintest at rare-earth minimum at E = 0.5. Such light and color variations cannot be easily explained as the result of a change in temperature. The fact that the equivalent width ratio, Dy II/Dy III, remains constant over the period (Pyper, 1969) gives further support that a temperature change is not the cause of the light and color variations. Cohen (1970) shows that differential line-blanketing (in the visual), as well, cannot explain the changes in light and color.

In this investigation the nature of the light and color variations will be examined using extensive far ultraviolet data from the Wisconsin Experiment Package on board the Orbiting Astronomical Observatory, OAO-2. The design and operation of the spacecraft and experiments are described by Code, Houck, McNall, Bless and Lillie (1970).

II. PHOTOMETRY OBSERVATIONS

The OAO photometry data presented here was obtained by observing α^2 CVn every orbit of 100 minutes for six consecutive days completely covering the $5^{d}.47$ period. A standard photometry sequence was used which consists of dark readings at the start and conclusion of the filter and calibration source readings. This serves as a check for any changing background radiation from the South Atlantic Anomaly (SAA); however, during this observing run, the SAA never coincided with the spacecraft nighttime when the observations were made. This gave continuously high-quality data uninterrupted by the SAA throughout the six days of observing.

Table 1 gives the pertinent information concerning the photometry. Only the highest unsaturated gains were used; these are listed along with the number of times each orbit the measurement was made. In addition, the digital counts, minus sky and dark backgrounds and prescaled by 1/64, are given for phase E = 0.0. The relative statistical fluctuations indicate the good quality of these data.

Table 1. OAO Photometry Statistics for α^2 CVn

Filter Wavelength (Å)	Gain (Exposure) (sec)	Observations /Orbit	Signal Counts minus Background × 1/64 Phase E = 0.0	Statistical Fluctuation (±%)
3317	1/8	2	631.3	0.41
2985	1/8	2	533.1	0.44
2945	1/8	2	258.9	0.63
2462	1	1	1403.	0.39
2386	1/8	2	113.5	0.95
1913	8	2	2797.	0.19
1554	8	1	471.5	0.66
1430	8	1	190.5	1.05
1332	8	1	40.5	2.26

Also in this table are the effective wavelengths of the filters for a uniformly flat energy distribution. Note that not all of the available filters were used. The 4250 Å filter was ruinously saturated even at the lowest gain; the 2050 Å filter has severe "pinholes" and the 1680 Å filter has apparently developed opaque patches. The data from these filters were discarded after verifying that they could not be used.

One final note concerning these observations is that the companion, α^1 CVn, was always included in the 10 arc-minute diaphragm because these stars are separated by only 20 arc-seconds; however, its MK type is F0 V and m_V = 5.60. A faint late-type star such as this relative to α^2 CVn is overwhelmed in the far ultraviolet so that, for all intents and purposes, it contributes nothing to the signal.

III. FAR ULTRAVIOLET LIGHT CURVES

The far ultraviolet curves are given in Figure 1 which shows the data for each filter relative to phase E = 0.0 in units of 10%. The phase, E, is calculated from the elements of Farnsworth (1932)

$$\text{J.D.(Eu II maximum)} = \text{J.D. } 2419869.720 + 5.46939E.$$

The most striking feature about these light curves is that the two curves near 2960 Å remain relatively flat while the 3317 Å curve varies nearly in antiphase with the curves around 2300 Å. If we compare the variations of the light curves in the 2300 Å region with the spectral line variations, we find that these curves match remarkably well the curves of the rare-earths in that minimum light occurs at maximum intensity of the rare-earth elements. Upon examining the spectra of the singly and doubly ionized rare-earths, we find that their lines, which are exceedingly numerous, fall heavily between 2000-2900 Å (Dieke, Crosswhite and Dunn 1961). Thus, the filters in this region see strong line-blanketing which is the greatest at maximum intensity of the rare-earths at phase E = 0.0. The evidence strongly suggests so far that the 3317 Å curve is reflecting the redistribution of flux from rare-earth blanketing around 2300 Å; however, the 3317 Å curve peaks at E = 0.1, not at rare-earth maximum at E = 0.0. As we will see later, the 3317 Å light curve is due to another effect.

The three lowest wavelength light curves, 1554, 1430 and 1332 Å, are different than those around 2300 Å. They all have a very strong minimum at E = 0.1 and a second smaller minimum at E = 0.5; however, this feature is not very evident at 1554 Å. Although we can correlate the 2300 Å region light curves with the rare-earths, we encounter great difficulty with these curves. The strong minimum at E = 0.1 cannot be correlated with spectral variations of any metal lines. The secondary minimum, however, does occur at the maximum intensity of the iron-peak elements. In order to discuss the light curves further, the scanner data must be examined.

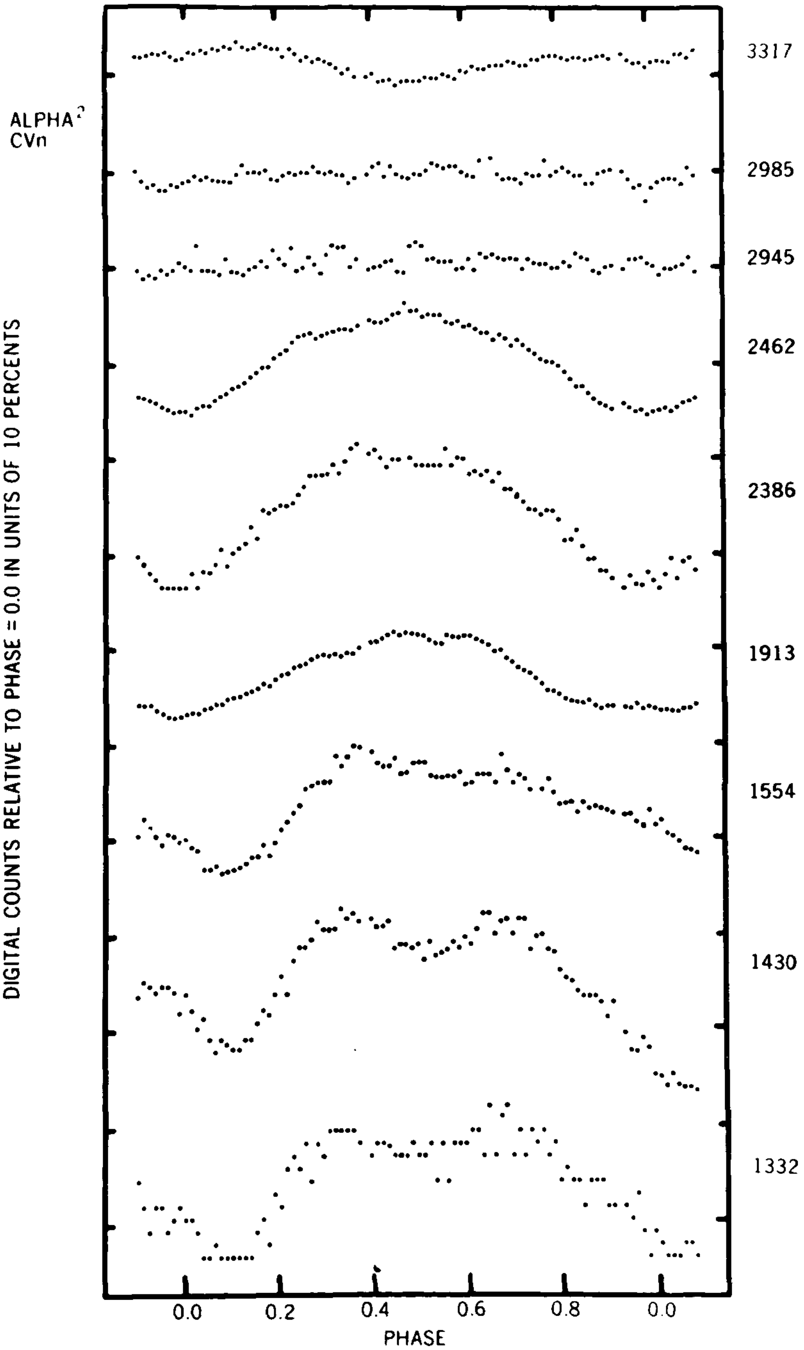

Figure 1.—Far ultraviolet light curves of α^2 CVn in digital counts relative to phase E = 0.0 in units of 10%.

IV. SCANNER OBSERVATIONS

Spectrometer #1 covers the wavelength interval ~1900~3700 Å in 20 Å steps. When these observations were made, the sensitivity had degraded to where the digital output was non-usable even for a star as bright as α^2 CVn. The analog signal can be used, however, so the analog output from six scans at phases near E ~ 0.1 and ~0.5 was averaged and smoothed. These two mean scans are shown in Figure 2 relative to η UMa.

These scans were made with the intention of identifying any large features due to strong line-blanketing by the rare-earths or the iron-peak elements (Underhill 1972). It appears that at E = 0.1, near rare-earth maximum, many features appear stronger; and the strongest feature corresponds, perhaps fortuitously, to the strongest lines of Eu III which is the most overabundant of the rare-earths (Cohen 1970). Although these scans indicate strong blanketing, the higher resolution of OAO-C or SAS-D will be needed to identify some of the numerous lines contributing to the extensive blanketing in this region.

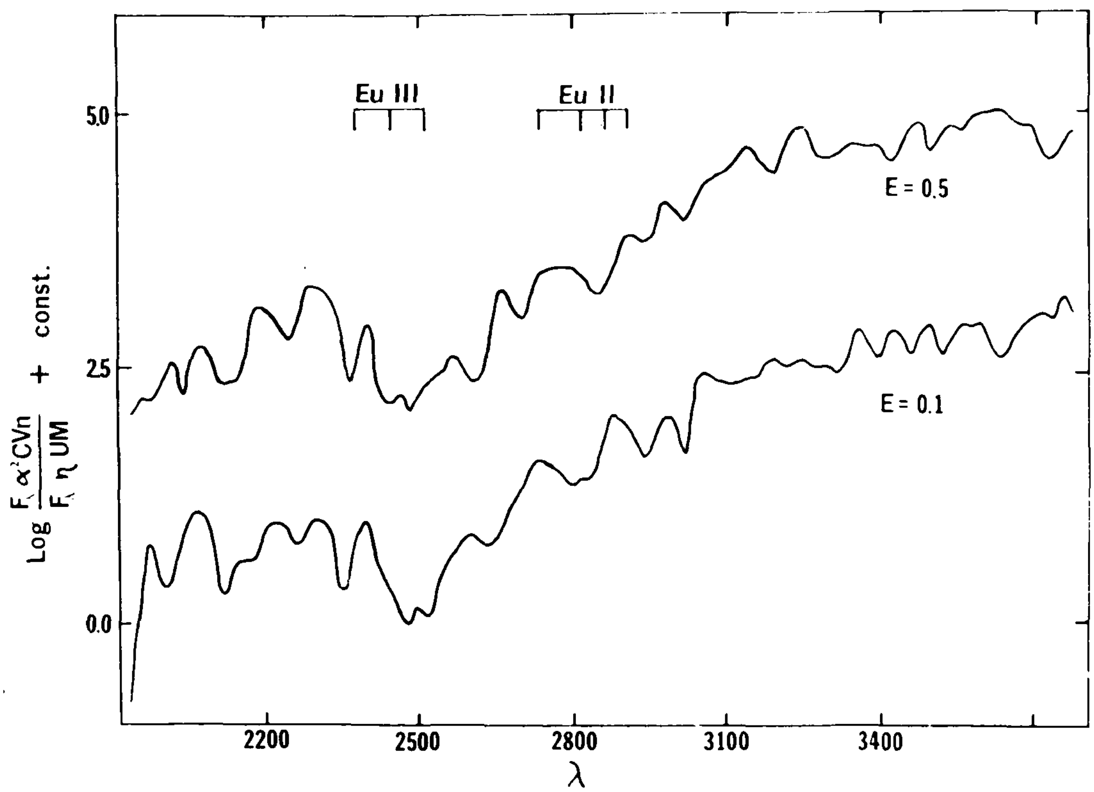

Figure 2.—Mean of six analog scans relative to η UMa for Spectrometer No. 1 at phases E ≈ 0.1, ~0.5.

Spectrometer #2 scans from ~1100~1800 Å in 10 Å steps and Figure 3 shows relative to η UMa two scans averaged together. The dashed line indicates the continuum derived from a scan made with the spacecraft offset from α^2 CVn which shifted the effective wavelength (Code, et al. 1970). No strong spectral variations with phase were noticed in spectrometer #2, so only one mean scan is illustrated.

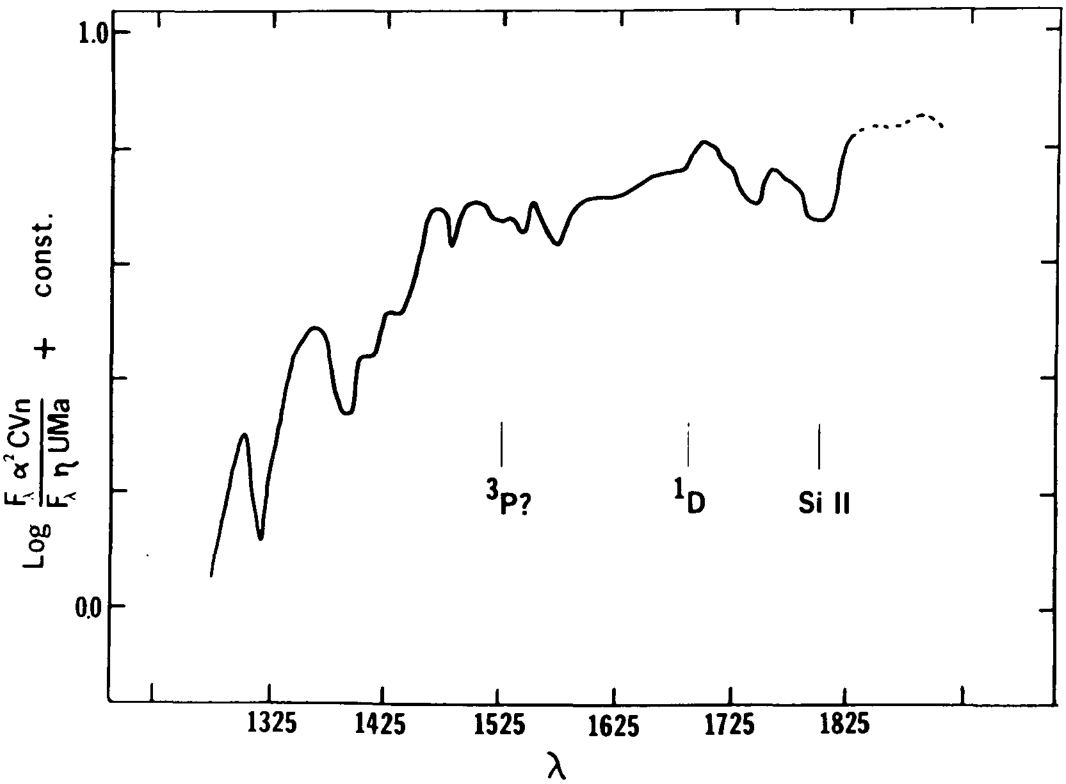

Figure 3.—Mean of two digital scans relative to η UMa for Spectrometer No. 2. Broken line is derived from an offset scan.

The most striking feature is an ionization edge corresponding to the ^{1}D level of Si I which lies 0.04 volts above the ground level at 1680 Å. Strong silicon edges would be expected in α^2 CVn since silicon is about 50× overabundant (Cohen 1970). It is disappointing, though interesting, not to find the ground level ^{3}P edge at 1520 Å; however, there may be several reasons why it is not seen. First, if there is a discontinuity, there are lines of Si II and other metals which will mask or "wash out" the edge. Second, Praderie (1969) has shown that as the silicon abundance is increased, the 1680 Å edge grows while the 1520 Å edge is diminished due to a saturation effect of the silicon opacity. We can then expect for α^2 CVn that the 1680 Å edge will be much larger than the 1520 Å edge which might even be too small to be detected. The last important effect to consider is that the continuum opacity in this region is heavily dominated by the confluence of the Lyman lines and notably the broad wing of Lyman-α to such a degree that any additional opacity due to silicon is insignificant (Klinglesmith 1971). This indicates that the edges would be diminished due to the Lyman-α opacity and the 1520 Å edge would be affected more than the upper 1680 Å edge. It is plausible that some combination of these three effects will explain the absence of the 1520 Å edge.

V. DISCUSSION

With these far ultraviolet light curves and scans we can begin to understand the visual light curves. Recently, Wolff and Wolff (1971) have correctly proposed that the photometric variability results from a redistribution of flux, which is caused by variable absorption below 3000 Å. In this work we find that at phase E = 0.0 the rare-earths are at maximum intensity and the line-blanketing around 2300 Å is the strongest. The flux from this region is redistributed into the visual region making the star appear brighter notably in the V filter (Pyper 1969). The V filter photometry shows, in fact, a curve that is exactly in antiphase with the 2300 Å region. The reason that the star is reddest at this phase can be better understood if we first discuss the farthest ultraviolet light curves.

It is noted above that the three lowest wavelength curves are different than the 2300 Å light curves. They have a strong minimum at E = 0.1 which does not correlate with any metal line variations. The secondary minimum at E = 0.5 is much weaker and cannot be attributed to an increasing silicon opacity since the Si II lines are maximum at E = 0.4 (Pyper 1969) rather than E = 0.5. This minimum may be due to the numerous lines of the iron-peak elements in this region which in general reach maximum intensity at E = 0.5. Line-blocking may also explain the minor differences in the 1554 Å light curve from the lower light curves.

Since no metals apparently cause the strong minimum at E = 0.1, we propose that these three light curves are due primarily to variations in the wings of Lyman-α which is the most important opacity source in this region for late B and A type stars. If we are truly seeing variations in the large wing, it might be expected that the amplitude in the 1332 Å curve would be larger than at 1554 Å which is less affected being farther out in the wing. In examining the relative depth of the minima of the curves, a 3% increase in the minimum for the 1332 Å curve is noted with a probable error of 1%.

We further note that the U and B filters, as well as the 3317 Å filter, lie on or near the confluence of the Balmer lines. The ground level for the Balmer lines is the upper level, n = 2, for Lyman-α and we might expect coupling of any Lyman-α variations with the Balmer lines. The U, B (Pyper 1969) and 3317 Å light curves closely resemble the reflection or inverse of the lowest light curves except for the secondary minimum at E = 0.5 which is probably due to lines of the iron-peak elements. These lowest curves are at minimum at E = 0.1 while the light curves in the Balmer confluence are then at maximum which strongly suggests that this is a variation in the strength of the hydrogen lines where the Balmer confluence is in antiphase with Lyman-α. If the amplitudes of the U and B light curves are any indication of the size of the Balmer line variations, they must be on the order of a few per cent or less.

The V light curve is less influenced, if at all, by the confluence of Balmer lines and, as we noted above, it reflects the redistribution of flux from the rare-earth line-blanketing. On the other hand, the U and B light curves are strongly influenced by the Balmer lines and are much less influenced by the redistribution of flux. Thus, the star appears redder, as well as brighter, at E = 0.0 due to a flux redistribution and not a changing temperature. Figure 4 shows the far ultraviolet continuum for 14 CVn, an unreddened B9 V star, and α^2 CVn at two phases which illustrates the severely suppressed continuum of this anomalous star. If energy is to be conserved, the flux removed by blanketing must be redistributed longward which will distort the slope of the Paschen continuum. Scanner observations of the Paschen continuum by Cohen (1970) show, in fact, that the amplitude in the light variation increases proportionately away from the Balmer discontinuity. In the infrared α^2 CVn might have very large light amplitudes. However, we point out that temperatures derived from the continuum slope are adversely affected by the flux redistribution.

VI. SUMMARY

We have seen strong evidence that the light and color variations in α^2 CVn are due to the effects of variable line-blanketing by the rare-earths which is consistent with the oblique-rotator models. Furthermore, the ultraviolet and visual continua are severely distorted by line-blanketing and the redistribution of flux, so that colors will indicate erroneous temperatures.

We have also seen evidence that there may be variations in the hydrogen lines. In addition, it appears that the influence of the hydrogen lines is important in affecting the light curves. On the other hand, the Si I opacity has apparently no

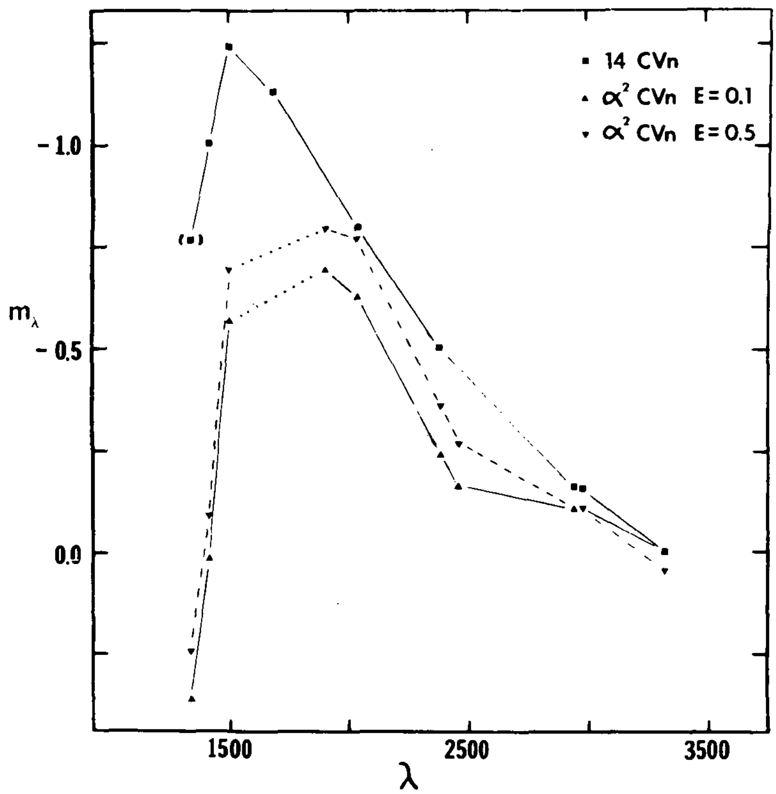

Figure 4.—Far ultraviolet continua of 14 CVn, B9 V and α^2 CVn at phases E = 0.1, ~0.5.

effect on the curves, although an ionization edge is found.

Based upon these observations, we can predict that the other Ap variables will probably also have variable line-blanketing. The lines of Cr, Fe and Sr are also effective (Underhill 1972) and variations in these should cause light and color changes.

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