## No. 7 ON THE SPECTRUM OF LIGHTNING IN THE ATMOSPHERE OF VENUS

*by* A. B. MEINEL *and* D. T. HOXIE

PHENOMENA in the Venus atmosphere are apt to be unusual in comparison with the terrestrial atmosphere owing to the lack of water vapor. Yet a phenomenon as familiar as lightning may occur on Venus with such violence that it might be detectable from the earth. Atmospheric mixing on that planet is evidenced by the perpetual cloud layer and the uniformity of the temperature observed on the sunlit and dark hemispheres. Early spectroscopic attempts to measure the presence of water vapor or oxygen were unsuccessful. Adams and Dunham (1932), however, observed $CO_2$ to be an abundant constituent of the Venus atmosphere, photographically detecting the 7820-7882A band. Kuiper (1947, 1948) has observed the presence of 19 additional $CO_2$ bands from 1.0$\mu$ to 2.5$\mu$. These observations lead to the conclusion that Venus must have an atmosphere consisting almost exclusively of $CO_2$ and $N_2$, the latter being undetectable in any accessible spectral region.

The absence of $H_2O$ and $O_2$ in a planet of similar mass to the earth has been puzzling. Among the explanations several have evolved which explain both the cloud layer and the absence of $H_2O$. The first of these, by Wildt (1940) involved the reaction under ultraviolet light of

$$CO_2 + H_2O \rightarrow CH_2O + O_2,$$

producing formaldehyde. The formaldehyde would in turn react with water vapor to produce solid polyoxymethylene, a white substance forming chains of the form

$$nCH_2O + H_2 \rightarrow HO\text{-}(CH_2O)\text{-}H.$$

This, in the presence of an over-abundance of $CO_2$ in an originally moist atmosphere would both deplete the water vapor content of the Venus atmosphere and produce abundant clouds.

A second photochemical reaction that might operate in the Venus atmosphere was proposed by Kuiper (1957). The original presence of both $CO_2$ and CO, which are natural volcanic products, will lead to the formation of carbon suboxide by several reactions such as

$$CO_2 + 2CO \rightarrow C_3O_2 + O_2.$$

This molecule also readily polymerizes under heat or in the presence of ultraviolet radiation forming a linear polyatomic molecule of the form $(C_3O_2)_n$. Although both the carbon suboxide and the formaldehyde reactions produce oxygen, the planet must be grossly oxygen-deficient and the oxygen produced would be rapidly removed from the atmosphere.

Both $CH_2O$ and $C_3O_2$ produce a strong absorption spectrum in the 3000-3300A region. Spectra have been published by Henri and Schou (1928) for $CH_2O$ (also see Pearse and Gaydon, 1950), and by Thompson and Healey (1936) for $C_3O_2$. Observations by Wildt (1940, 1942) and by others confirm that there are no detectable spectral features in this region in the photographic spectrum of Venus other than the terrestrial ozone bands. Sinton (1960) also indicates that the $C_3O_2$ monomer is not present in the 8-12$\mu$ region. The spectrum of the polymer forms would not be expected to show the same absorption bands as the monomers. One could expect, however, that the electronic transition responsible in the monomer for these bands would be evidenced in the polymer as a broad absorption feature in that part of the spectrum. The observed yellowness of Venus in the ultraviolet could be a result of this absorption. To our knowledge no laboratory observations have been published of the reflection or transmission spectrum of $nC_3O_2$ or $nCH_2O$ in either the near infrared or the ultraviolet, although Kuiper has obtained photographic reflection spectra of a high polymer mixture of $C_3O_2$. A laboratory study of both is indicated since the addition of balloon and satellite-borne telescopes will soon make it possible to examine the spectrum of Venus from the vacuum ultraviolet to the far infrared. If either carbon suboxide or formaldehyde is present, Venus would show a low albedo in the 3000-2500A region and in some intervals in the 2-4$\mu$ regions. Laboratory measurements do not exist for these polymer substances in either the ultraviolet or the infrared.

The presence of either or both $nC_3O_2$ and $nCH_2O$ in the Venus atmosphere could be the equivalent of $H_2O$ on the earth. Their vapor pressure at the elevated temperature of the atmosphere of the planet could lead to strong convection and condensation at suitable altitude above the surface of the planet. Violent convection could produce atmospheric electrical activity of major importance. The presence of such activity, if intense enough and of sufficient spatial character, could contribute to the radio flux of the planet as well as the optical flux. A spatial distribution of only one event per 100 square kilometers per second could yield a total of $2.3 \times 10^6$ events per hemisphere per second.

Kozyrev (1954) and Newkirk (1959) have taken photographic spectra of the dark hemisphere of Venus and reported emissions of rather dubious certainty. Newkirk and Weinberg (1961) now report that a re-examination of the spectra do not show any evidence for emissions from the dark side of Venus. T. C. Owen (1962) of this Laboratory has made similar observations with the 36-inch Cassegrain spectrograph at the Kitt Peak National Observatory, also with negative results. The presence of a strong scattered solar spectrum characterizes the spectra of each observer.

The photographic spectrograph is not particularly well suited for the measurement of small intensity differences. The search for emissions from Venus is complicated by the richness of the absorption features in the solar spectrum and the intensity of the light scattered from the illuminated hemisphere of the planet which saturates the spectrograph in exposures of the order of 5 minutes. The spectrogram published by Kozyrev (1954) illustrates the problem presented by the solar spectrum. It would be difficult to detect emissions against the solar spectrum on an Eastman Kodak 103a-0 plate if the relative contribution is much less than 10%.

A photoelectric measurement will afford a significantly improved detection limit, and with photon-counting techniques the effective exposure time can be extended indefinitely to achieve the required signal-to-noise ratio. The photoelectric method, however, is effective only when one wishes to examine for the presence or absence of certain definite spectral features. Kozyrev and Newkirk were looking for evidence of night airglow or auroral activity on Venus. The physics of an airglow are complex and the spectrum of the Venus airglow would be hard to predict. The absence of $O_2$ and $H_2O$ in the Venus atmosphere would mean that the prominent features of the terrestrial airglow, the [OI] lines and the OH Meinel bands would probably be absent, although photodissociation of $CO_2$ and $CH_2O$ in the high atmosphere might yield sufficient OI, HI, and $O_3$ for the airglow reactions. Since Venus must be expected to have considerable $N_2$ in its atmosphere, the auroral spectrum would certainly show the intense negative bands of $N_2^+$, with the (0, 0) band at 3914A being the strongest. In the red, the first positive bands of $N_2$ would be strong.

Since we are interested in the presence or absence of lightning activity on Venus, we must select criteria that will be independent of either airglow or auroral activity. This selection is not difficult by analogy to the terrestrial situation. The airglow exhibits neutral atomic forbidden lines. The aurora exhibits strong molecular bands and permitted and forbidden lines of neutral atoms. In comparison to other features lightning exhibits strong lines of ionized atoms. It is true that the 5001-5A lines of N II appear in the aurora (Chamberlain and Meinel, 1953), but they are quite weak in comparison to the $N_2^+$ and $N_2$ bands. Lightning also occasionally has weak to moderate molecular bands. We therefore can reasonably predict that the presence of ionized atomic lines in the spectrum of the dark hemisphere of Venus would be an unambiguous indicator for lightning activity on Venus.

In preparation for a search for evidence of lightning we have produced high-voltage discharges in air and in air enriched with $CO_2$. In air, the laboratory spectrum is quite similar to terrestrial lightning with most of the strong emissions being produced by N II. Plate 7.1 shows the spectrum of lightning taken by Salanave (1961). The laboratory spark spectrum in air is shown for comparison. In the en-

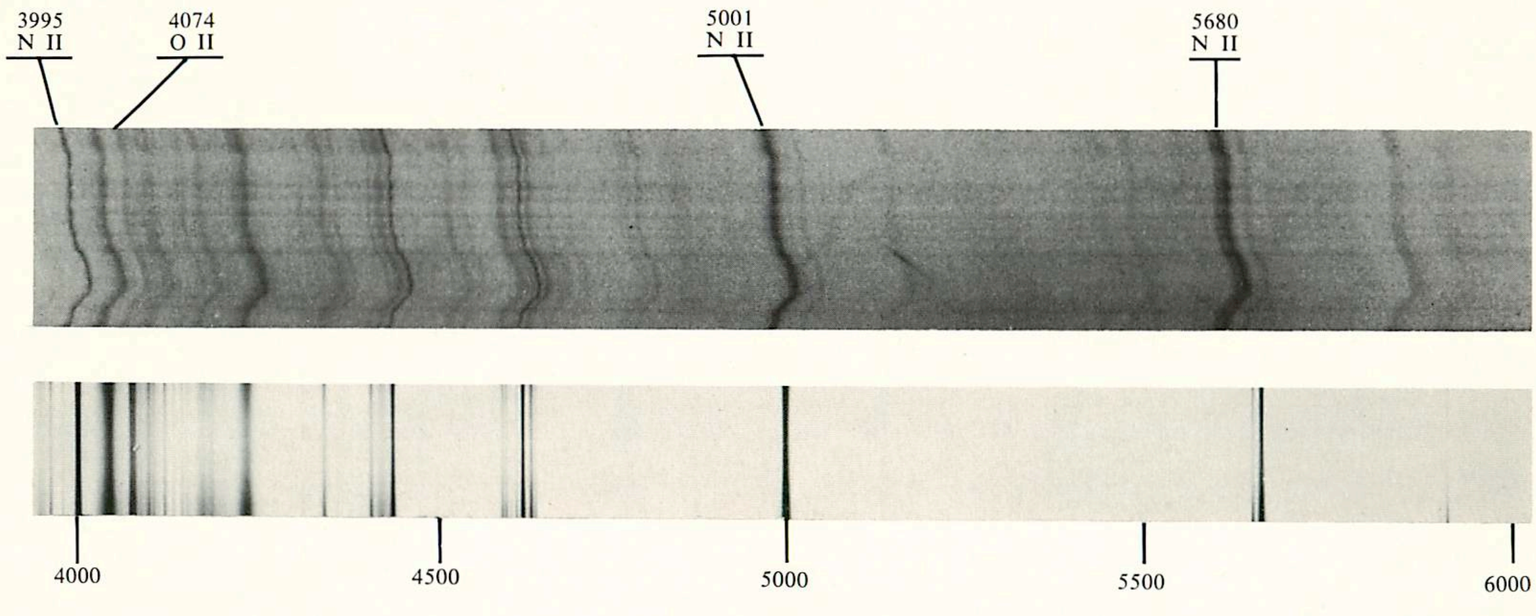


Plate 7.1. The spectrum of lightning obtained with an objective grating camera at Tucson, Arizona, by Salanave, 1961. Other reproductions of lightning spectra are given in the above reference. The background density of this spectrum is produced by the light of the lightning bolt as reflected by the background clouds.

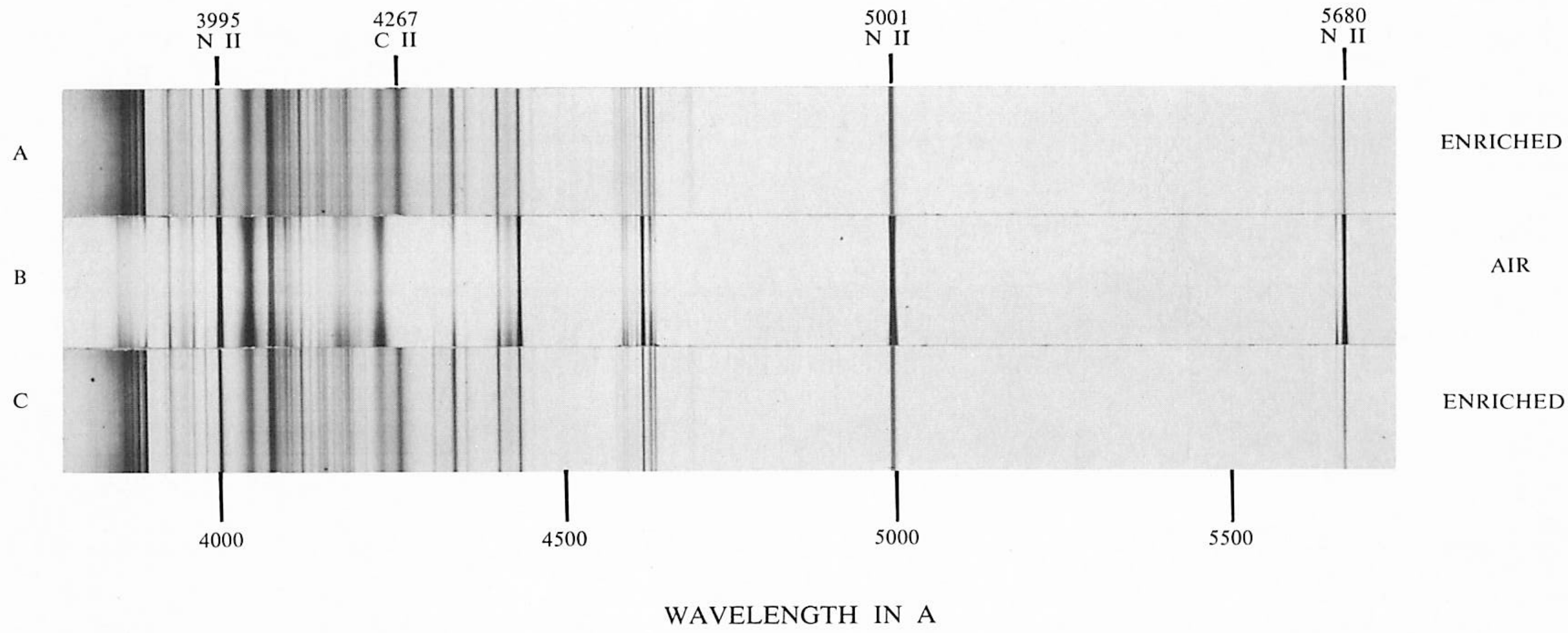


Plate 7.2. The spark spectrum of air, *B*, and of air enriched with $CO_2$, *A* and *C*. The progressive variation of intensity of the numerous nitrogen features along the length of the spectrum is a consequence of the focussing of the spark by the lens upon the slit of the spectrograph.

riched spectrum we note the addition of a single intense emission line from C II at 4267A and the (0, 0) CN band at 3888A as shown in Plate 7.2.

In the laboratory spectrum the principal difference is the presence of a strong line of O II at λλ4075.9 and 4072.2A. This double line is weak in the spectrum of lightning. One could therefore question whether the CII line would be intense in lightning in the Venus atmosphere. If we examine the energy levels producing the emissions, we note that the OII lines have an excitation potential of 28.7 ev whereas the NII lines have a value of 23.1 ev. Natural lightning must occur upon the occurrence of a slight excess in the minimum electric gradient field strength. Laboratory lightning discharges on the other hand are always operated at considerable excesses in the field strength; consequently the natural spectrum would tend to be one of lower excitation. In the case of CII, the λ4267A emission arises from an excitation potential of 20.9 ev and the emission should be prominent in a $CO_2$ abundant atmosphere.

The total flux in the 3000-6000A region to be expected from a single lightning bolt is somewhat uncertain. Assuming a 1 $cm^2$ column of ionization over a total path length of 5 km and a mean particle density of $2 \times 10^{18}$ per $cm^3$ with each particle emitting one photon, we obtain a total flux for the single event of approximately $10^{24}$ photons.

$$F_o = 1 \times 10^{24} \text{ photons/event.}$$

If we further assume that 5% of the flux is in the 4267A CII emission and that 10% of this flux emerges from the Venus atmosphere, then the flux of this line would be

$$F = 1.1 \times 10^{27} \text{ C II photons/sec.}$$

The intensity at the earth with a distance to Venus of $6 \times 10^{12}$ cm would be

$$I = \frac{F}{4\pi r^2} = 2.5 \times 10^1 \text{ C II photons/cm}^2 \text{ sec.}$$

A 36-inch telescope photometer would then collect a flux, allowing a 40% net efficiency of the telescope of

$$I = 6 \times 10^4 \text{ C II photons/sec.}$$

The brightness of Venus is approximately –4.0 mag. at this observational distance. It has been observed that the flux from a 22.5 mag. star with an 82-inch telescope is 2.5 photons/sec in a 1000A spectral interval. The brightness of Venus as observed with a 36-inch telescope will therefore yield a flux of $2 \times 10^{10}$ photons/sec per 1000A spectral interval. An interference filter can be used to admit approximately 50A including the 4267A CII line. While the total Venus flux is the order of $1.0 \times 10^9$ photons/sec through a 50A filter, the fluctuations should be statistically small enough to detect the C II emission of the above magnitude even though it is only 0.016% of the total signal. Improvement of a factor of 100 (1.6%) could be obtained by excluding the illuminated face of Venus, but scattered light within a conventional reflecting telescope would preclude much further improvement. Coronographic techniques as employed by Newkirk would afford a greater improvement and would be the best way to establish a low upper limit to the amount of lightning activity on Venus.

It would also be desirable to monitor Venus for the presence of either the strong N II line at λλ5001-5A or at λ5680A. These lines are outstanding in the spectrum of terrestrial lightning, and if detected on Venus in conjunction with the C II line, could yield the only direct evidence for the existence and amounts of $N_2$ on its atmosphere. Plate 7.2 strips *A* and *C* show the laboratory spectra of a spark discharge in air enriched with 50% (approximate) of $CO_2$ and strip *B* shows normal air. The search for emissions should probably be extended with a filter to isolate the 3914 (0, 0) $N_2^+$ band since the photon counting technique will enable one to establish a lower limit to auroral activity than is possible by the observations by Kozyrev and Newkirk.

The principal uncertainty in the above estimates is perhaps the opacity of the Venus cloud layers. The diffusion may be such that the estimate of an emergent flux of 10% may be too large by a factor of 10 or 100. An upper limit to the flux will, however, be of sufficient importance to warrant the search, for the existence of lightning would require a re-examination of the significance of radio flux measurements from Venus.

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