SPECTROSCOPIC PROOFS FOR EXISTENCE OF VOLCANIC PROCESSES ON THE MOON

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A CONCEPT of the Moon devoid of internal energy, sufficient for volcanic and mountain-forming processes, is widely accepted at the present time. Therefore, it is generally assumed that the relief formation of the Moon is due to external actions on its surface. However, such a viewpoint is not sufficiently substantiated. In fact, the history of Earth's relief shows that the period of telescopic observations of the Moon is too short to enable us to observe changes in whole sections of the crust. Catastrophic changes, apart from actions of water and atmosphere, occur on the Earth only in a very restricted area, and the size does not exceed a few kilometres. Therefore, we must not expect on the Moon any sudden changes over an area exceeding appreciably one square second. The reality of such minute effects in the relief could hardly be established on the basis of available cartographic data.

Whereas it is impossible to establish morphologically in exact manner the consequences of mountain-forming processes, we may attempt to detect the existence of these processes from the accompanying physical phenomena. The luminescence of gases escaping from the lunar interior may constitute an example of such a phenomenon. A flame, i.e. the luminescence of the gases themselves, can hardly be observed because of the absence of atmosphere and free oxygen on the Moon. However, a luminescence of gases must occur under the action of solar radiation. After the observations had proved the fluorescence of rocks constituting the lunar surface, it became evident that the fluorescence of gaseous cloud should be observable much more distinctly near the terminator—due to to the geometric effect of illumination—than the fluorescence of the surface; indeed, it should even produce the effects of atmospheric mist, veiling the lunar surface. From general concepts of light absorption on the photodissociation of molecules, we may assume that 10^{15} molecules above cm^2 of the surface should be sufficient for a complete absorption of the short-wave solar radiation and, consequently, for obtaining the maximum luminosity of fluorescence. The temporary existence of such a local atmosphere of pressure, smaller than one-billionth of the terrestrial atmosphere, is quite possible.

The American astronomer, D. Alter, was the first to secure an objective proof attesting to the temporary appearance of the mist which can obscure certain regions of the lunar surface. On the basis of a comparison of photographs taken in violet and infrared rays, Alter arrived at the conclusion that he had observed a blurring of the features in the crater Alphonsus. However, only the spectral analysis can provide a direct and rigorous proof of the existence of such physical processes on the Moon. Only by this method can we establish and investigate additional spectral peculiarities, which the physical phenomenon on the Moon adds to the usual solar spectrum reflected from the lunar surface.

We must not expect the number of active regions on the Moon to be great. Therefore, to solve the problem of lunar activity, it is quite sufficient to prove the existence of just one active area. In these spectral investigations it is important that the width of spectrograph slit be not greater than one second of arc with a sufficient focal-ratio of telescope. The 50-in. reflector of the Crimean Astrophysical Observatory with the scale of 8″ per mm fully satisfies these requirements.

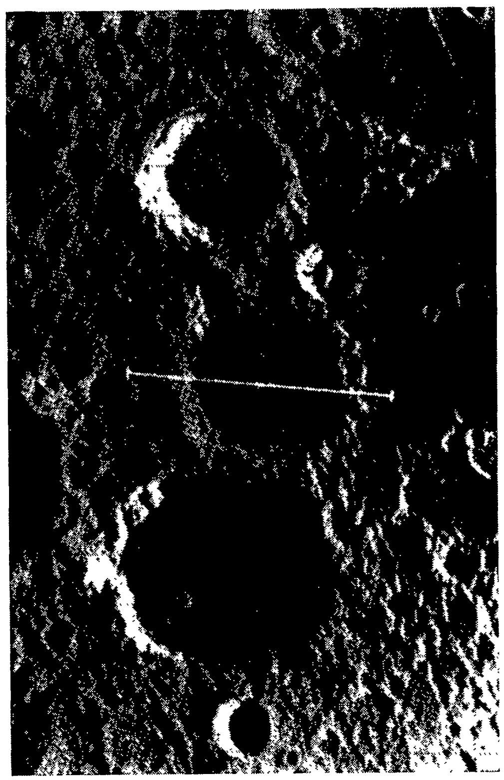
Beginning in 1955 up to the present, I have conducted spectral examinations of many sections of the lunar surface by means of this reflector. In 1958, after D. Alter had published his interesting photographs of Alphonsus, I decided to pay particular attention to this crater.

On 3 November 1958, with exposure lasting from 3 hr 00 min to 3 hr 30 min (UT), a spectrogram was obtained, showing the luminescence of gases escaping from the central peak of Alphonsus. During the time of exposure the central peak on the spectrograph slit appeared to be brighter and whiter than usual. Suddenly, the brightness of this peak dropped to normal during the time on the order of tens of seconds. Then I terminated the exposure immediately and started a new one lasting from 3 hr 30 min to 3 hr 40 min with the same position of the slit. This spectrogram confirmed the reality of the visual impression; it showed the spectrum of the quite normal state of the crater. In addition to these pictures, I obtained during the same night, at about 1 hr (UT), one more spectrogram through clouds; this spectrogram was also completely devoid of any symptoms of gaseous emission.

I pointed out in my preliminary reports that the central peak on this spectrogram appears to be noticeably weaker in violet rays, and that this phenomenon can be explained by the ejection of dust, i.e. volcanic ashes. However, a detailed study of this spectrum, carried out at Pulkovo by Miss Polozhentseva, proved that this report was not correct. It can be concluded from the above data that the duration of the gas-escape process was longer than 30 min and shorter than 2 hr 30 min. During the next night, 3–4 November, I managed to obtain two further spectrograms of Alphonsus. These spectrograms showed that the state of the crater remained normal.

Figure 1 illustrates the position of the spectrograph slit during the exposure of the spectrogram with gaseous emission. The height of the Sun above the horizon of the crater was equal to 18°. The next picture (Fig. 2) reproduces two spectrograms of Alphonsus, obtained one after another from 3 hr 00 min to 3 hr. 40 min (UT) with the indicated slit position. These spectrograms show clearly the spectra of eastern and western walls of the crater and the spectrum of the central peak with its shadow.

An additional emission, superimposed on the normal spectrum of the central peak, constitutes a striking feature of the first spectrogram. The most characteristic peculiarity of this additional emission consists of a band with a comparatively sharp red edge of about 4740 Å. The brightness of this band attains 40% of the normal brightness of the peak at the same wavelengths. This band is characteristic of the spectra of cometary heads. It is beyond any doubt a band of Swan resonance series of carbon molecule C_2. A system of weak bands with maximum of about 4400 Å is noticeable towards the violet. The blurring of the Fraunhofer line at 4384 Å confirms the existence of emission there. Two bands with maxima of 5470 Å are seen on the long-wave side. It is possible that the last band also constitutes a Swan band.



* FIG. 1. Photograph of a group of craters, Ptolemy, Alphonsus and Arzachel, showing the position of the slit during the author's spectrographic observations on 3 November 1958.

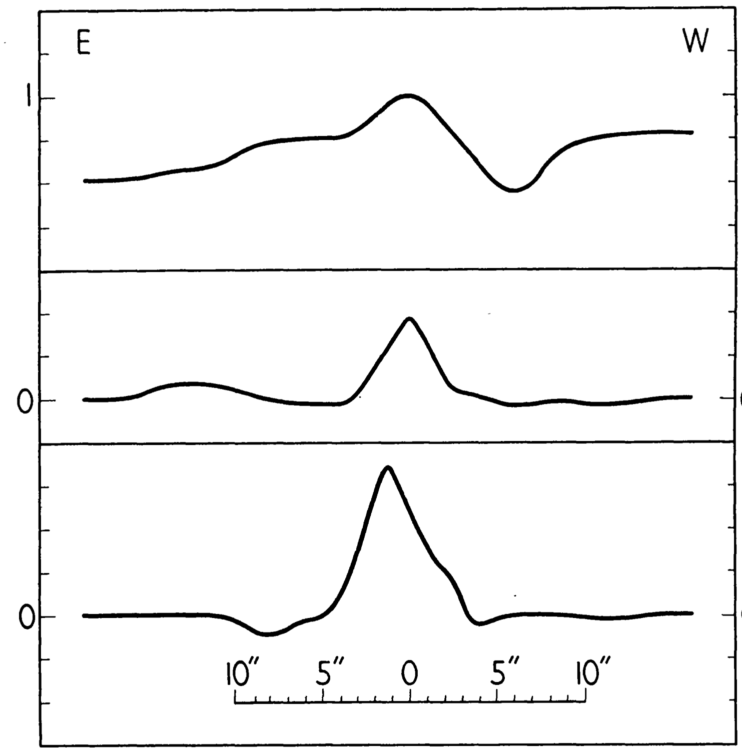


FIG. 2. Profiles of the intensity of the central peak of Alphonsus and the additional emission along the slit of the spectrograph. The top curve gives the profile of the peak in its normal state. The curve at the centre shows a section of weak additional emission (λ 4620, 4580 Å); and the bottom curve, a section of the additional emission in the bright part of the λ 4740 Å band (the average of sections in the light of $\lambda\lambda$ 4740, 4730, and 4660 Å bands). The unit of intensity is the maximum intensity of the central peak.

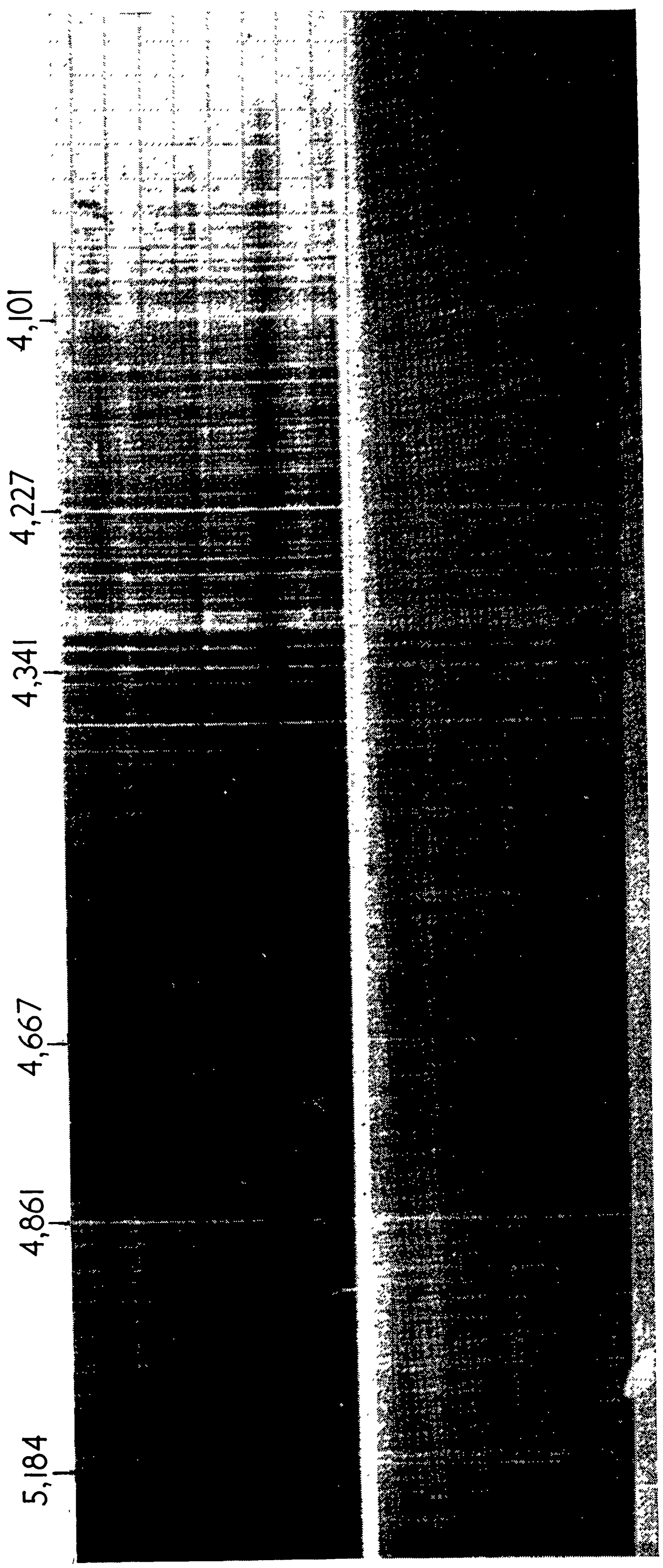


Fig. 3. Spectrograms of the crater Alphonsus, taken on 3 November 1958. The upper spectrum, exposed between 3 hr 00 min and 3 hr 30 min UT, shows an additional emission in the spectrum of the central peak. The one below, exposed between 3 hr 30 min and 3 hr 40 min, shows the crater in its normal state.

The emission spectrum of the central peak was studied thoroughly by A. A. Kalinyak at the Pulkovo Observatory with the aid of a microphotometer. He will publish a special report on this research. I would like to discuss only certain essential peculiarities of the spectrum. The measurements demonstrate that the band at 4740 Å had a distinct structure, which confirms the gaseous nature of this emission. A number of maxima of the band structure coincide with vibration transitions of C_2 molecule. However, the entire band is much more complex, its extension along the spectrum is almost twice as great as the normal extension of this band, and its maxima are strongly washed out. It is very important, for clarification of these circumstances, that the entire bright portion of the band from 4640 Å is shifted toward the Sun away from the central peak and the position of weak bands. This shift is conspicuous on the spectrogram, and is confirmed by measurements perpendicular to the dispersion. The results of measurements are presented in Fig. 2. The upper curve on this diagram gives the normal profile of the central peak, obtained from measurements in the region $\lambda\lambda 4740 - H_\beta$, where the emission is clearly absent. The middle curve, obtained by subtracting brightnesses of the normal profile from brightnesses of the peak in region $\lambda\lambda$4575–4610 Å, gives the profile of a weak emission. The emission band of 4740 Å, based on three cross-sections on borders of the band and in its centre, is shown on the lower curve of the diagram. This curve gives the same shift of brightness maximum toward the Sun by $1''\!.2$, i.e. by 2 km.

The following conclusions can be drawn from these data. The gases consisting of complex molecules, producing a weak emission, escaped from the central peak of Alphonsus. This circumstance must not be regarded as accidental. Assuredly, the peak of this formation has a funnel, i.e. constitutes a genuine volcano. Hence we can conjecture that the central peaks of lunar craters may be of a similar origin to the cones of terrestrial volcanoes and are, consequently, gradually accumulated formations. The outer craters themselves may be similar to calderas of terrestrial volcanoes, formed by subsidence due to the depletion of magmatic seat. A large diameter of lunar craters, exceeding by nearly one order of magnitude the size of terrestrial calderas, can be explained by the fact that the gravity on the Moon amounts to one-sixth of the gravity on the Earth surface; and, as a result, an arch may have an appreciably greater diameter without collapsing.

The complex molecules, escaping from the funnel of the central peak, had to disintegrate under the action of the short-wave radiation of the Sun. The radical C_2 could be produced only in this way. In the presence of a sufficiently great number of primary molecules the short-wave radiation of the Sun, which caused the photodissociation, could not penetrate far into the gaseous cloud. Therefore, the molecules of C_2 could be produced only on the border of the cloud facing the Sun. The shift of brightness maximum of 4740 Å band may be due to this fact. This should make it possible to draw a very simple estimate of the amount of gas escaping from the central peak. The non-transparency of the cloud shows that no less than 10^{15} molecules should have been present in a column with the base of 1 cm^2 in the path of solar rays. In order to obtain the actual amount, this number should be probably increased by one order. It is obvious from the photometric cross-sections, introduced earlier, that the observed part of the gaseous cloud had a diameter of about 3–5 km. Therefore, assuming the cross-section area of the cloud as 10^{11} cm^2, we find for the total number of molecules the value of the order of 10^{27}. The gas density is of the order of 10^{11} particles per cm^3. At such a density the mean free path should be about 1 km, which ensures the dispersion of particles without collisions. The rates of gas discharge should not differ appreciably from thermal velocity, i.e. several hundreds of m/sec. Therefore, on termination of gas discharge, the cloud should scatter in several minutes; and this was noted during the observations. It is evident that 10^{27} molecules should be released during this time at a steady state of the cloud. In 1 hr, 10^{30} molecules yielding C_2 should have been released. We will probably obtain a correct estimate of the total amount of all molecules if we increase this figure by one more order. Thus, during the process under observation, the Moon's interior released about 1 million m^3 of gas, at terrestrial pressure. We must note that this quantity is small by comparison with cubic kilometres of gases escaping during violent eruptions of terrestrial volcanoes. This comparison shows a low intensity of the process, at which appreciable changes in the relief could hardly occur.

The entire band of 4740 Å showed the same shift in the direction toward the Sun. Therefore, in spite of an unusually great extension along the spectrum, the entire band must be of the same chemical nature, i.e. constitute the band of C_2 molecule. Another peculiarity of our carbon spectrum consists in the fact that, according to measurements of Kalinyak, the band of 5165 Å is missing in the spectrum altogether. These peculiarities prove that conditions of excitation of C_2 molecule occurred under quite unusual circumstances. To understand these conditions, it is important to bear in mind that the amount of photons, capable of exciting the luminescence of 4740 band, is very small (or the order of 10^{15} photons per 1 cm^2). On the other hand, the absorption coefficient in this band per one molecule equals 10^{-16}, or even less. Thus, the probability of molecule excitation per second equals 1/10. The velocities of C_2 molecules, obtained on photo-dissociation, should be the same as in cometary heads, i.e. on the order of 1 km/sec. Therefore, the overwhelming majority of C_2 molecules should escape without giving rise to luminescence beyond the limits of the gaseous cloud under observation. Consequently, only one act of excitation could have been observed for each molecule. This excitation occurred most probably at the moment of photo-dissociation of a complex primary molecule. At such an excitation, the population of levels in C_2 molecule could have been quite unusual. Apart from that, the energy levels of C_2 molecules in the state of nascence could have been shifted by the field of molecular residue. By virtue of these considerations, the emission spectrum thus obtained should be similar to the spectrum of a cometary nucleus, rather than to that of a head.

In 1959, I obtained twelve spectrograms of Alphonsus. All these spectrograms show the usual solar spectrum. However, on 23 October 1959, one more spectrum of a particular state of Alphonsus was obtained under very good conditions from 2 hr 10 min to 2 hr 25 min (UT). Unfortunately, no peculiarities in the appearance of the crater were noted in guiding, and the exposure was not repeated. The next night was cloudy; and on 25 October the crater was no longer accessible for observations.

At the time of the exposure, the Sun was setting for Alphonsus at a height of 19°. The orientation of the slit differed only by 4° from that in the 1958 observations, being more closely perpendicular to the axial crest of the crater. In order not to disturb the current programme of stellar observations in 1959, we had to take photographs with an additional prism installed at the collimator immediately behind the slit. This prism halved the working part of the slit and turned the image with respect to the direction of dispersion. Owing to the reduced height of the slit, we obtained on spectrograms only the wall of the crater illuminated by the Sun, and the floor almost exactly up to the shadow of the eastern wall. In the centre appeared the spectrum of the region near the central peak with its shadow. A special characteristic of the spectrum of this region is that the red part of the spectrum, behind the triplet of magnesium of 5184 Å, is conspicuous. Particularly noticeable is a bright feature of small cross-section (1″.2), which is invisible in the blue of spectrum. This feature is located as a distance of 6″ (i.e. 11 km from the shadow toward the Sun) toward the east. The shadow in this part of the spectrum is very short; it is preceded from the side of the Sun only by a small increment in brightness of the central peak. It is interesting to compare directly the violet and red regions of this spectrum with that of 1958. The narrow feature of the red region of the 1959 spectrum is evidence of very good images during which this spectrum has been obtained. At the same time, the region of the central peak with its shadow is wider in the violet part of spectrum than in the 1958 spectrum. Thus, the spectrum of 1959 is anomalous also in the short-wave region.

The interpretation of this complex spectrum must begin naturally with measurements of the brightness of the narrow red feature in relation to the brightness of the crater floor on the side of the Sun, where no appreciable anomalies are present. The results of measurements are presented in the diagram (Fig. 4), where the ratios of red-feature brightness to crater-floor brightness are plotted on Y-axis. Irregularities of contrast, obviously due to emission bands, appear towards the blue. These bands continue farther toward shorter wavelengths and occupy the whole area of the lunar surface from the red feature to the shadow. On the other hand, beginning with

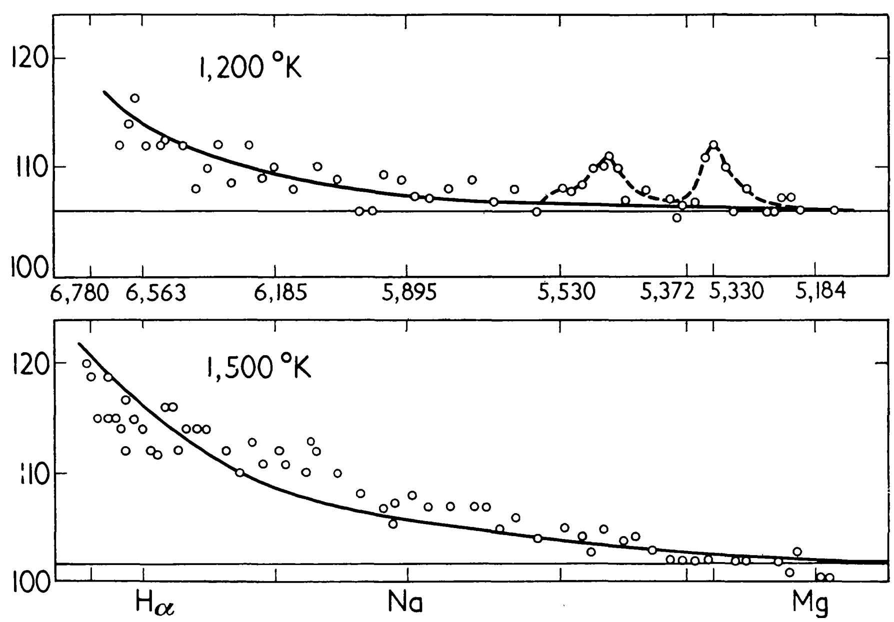


FIG. 4. Intensity distribution in the spectrum of the red glow observed in Alphonsus on 23 October 1959. The upper curve gives the intensity distribution with respect to that at the floor of the crater; and the bottom curve gives the same distribution in comparison with that prevailing in the shadow.

wave lengths of 5300–5400 Å, a monotonic increase in contrast becomes apparent, which may be traced on our photograph up to 6600 Å. It is possible that a weak monotonic increase in contrast is due to thermal radiation. In this section, the brightness of solar spectrum decreases toward the red by 20%, and is, in all probability, compensated fully by the increase in albedo of the lunar surface. Therefore, we may assume that the brightness of the comparison spectrum is identical for the entire region under consideration. Then, as indicated by the curve plotted on diagram, the monotonic trend of contrast corresponds fully to the radiation of black body at the temperature of 1200° K.

The explanation of the red feature by thermal radiation can be verified by calculation of temperature according to the absolute value of the radiant energy. Introducing $x = 1{\cdot}44/\lambda T$, we have

$$e^{-x_{☾}} = 2{\cdot}1 \times 10^{-5} A_{h_{\odot}} . K[(e^{x_{\odot}} - 1)^{-1}].$$

The numerical coefficient in this equation constitutes the factor of dilution of solar radiation at the distance of the Moon; $A_{h_{\odot}}$ is the albedo of the floor of the crater at the elevation $h_{\odot}$ of the Sun, and K is the contrast of the detail in the selected wave length. We shall carry out the calculation for $\lambda = 6500$ Å and $T_{\odot} = 6700°$. According to the diagram of contrast, $K = 0{\cdot}08$. Finally, at $h_{\odot} = 19°$, the albedo of the crater floor in the red should be taken as $A_{h_{\odot}} = 0{\cdot}015$. As a result of the calculations, we find that $x_{☾} = 20{\cdot}7$ and, consequently, $T_{☾} = 1080°$ K. This value of temperature is in good agreement with the colour temperature of 1200° determined above.

In fact, the unsteadiness of images and the guiding errors should reduce the contrast of the details, which would cause a decrease in the energy temperature. Since the factor reducing the contrast range does not depend on the wavelength, the colour temperature is obtained correctly. To obtain the energy temperature of 1200°, the contrast range should be reduced to 1/8. Consequently, the true extension of the red feature was not equal to 2 km, but was on the order of 300 m. In all probability, the slit of the spectrograph may have crossed a lava flow of this width. The lava of terrestrial volcanoes retains its plasticity up to 1000° K. On the other hand, at the outlet from volcano, the lava has a temperature of about 1400° K. The value of 1200° K inferred above for the red feature on the Moon agrees so well with these data that the correctness of identification of this feature with a lava stream is strongly indicated.

The calculations show that 1 km² of the Moon's surface, heated up to 1200° K, should radiate in infrared light (8000 Å) as a fourth or fifth magnitude G spectral type star. On 26 October, we took direct photographs of the Moon, showing crater Alphonsus, on infrared plates. The conditions were such that a record of an object of the above-indicated brightness should have been easily secured. The result of observations was negative. We must assume that the processes of the lava flow had ended already on 26 October.

The short shadow in the red part of spectrum, and the small contrast range of the elevation producing this shadow, indicate that the slit did not pass through the central peak. The brightest object of the crater center was set on the middle part of the slit for guiding. Such an object in our case was a gaseous cloud emitting at wavelengths shorter than 5500 Å. The probable position of the slit can be seen on the beautiful photograph by Alter. The slit passed most probably near the foot of the central peak from the south, where elevations of the axial crest of Alphonsus produced a noticeable (though short) shadow. Some 11 km from the edge of the shadow in the direction of the slit we located the position of the red feature near a small conical hill on the eastern ridge of a branch of the axial crest. It appears that the axial crest of Alphonsus is now in the formative stage, and that this hill is a volcano producing lava flows. The liberation of emission-producing gases occurred above the lava stream and above the entire valley formed by the fork of the axial crest. The emission bands are packed so closely that they give an impression of a continuous spectrum. Unfortunately, the spectrum does not show such distinct signs of emission as the C_2 band. This is connected, in all probability, with a different chemical composition of gases. In fact, the liberation of gases in this case may have been of a fumaroli type. On the Earth, however, fumaroles have a different chemical composition from that of gases escaping from the craters of active volcanoes.

The spectrum of 1958 appears to be more significant only because of the presence of the 4740 Å band. In reality, however, an appreciably more active volcanic process took place on 23 October 1959 in the crater Alphonsus; this process was tantamount in its magnitude to great eruptions of terrestrial volcanoes.

All these observations reveal that, even in our time, the Moon has an internal energy sufficient for mountain-forming processes. This result shows directly that the history of formation of the Moon's relief is a history of internal processes of the cosmic life of the Moon. The external actions constituted circumstances of secondary importance, and the role of meteorites was hardly greater than the role which they had played in creating the face of the Earth.