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Langrenus: Transient Illuminations on the Moon

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The program for lunar surface texture analysis with imaging polarimetry conducted at Observatoire de Paris included the large crater Langrenus near the lunar limb. When making the relevant observations, bright features were discovered near the Langrenus central peak. They appeared in both the photographic images and the polarigraphic images, on which they evolved simultaneously.

Very few cases of so-called lunar transient phenomena have been reported in the past; they were diverse and controversial. Most of the visual apparitions were described as short-duration flashes. None of them were suggestive of the slowly evolving effect presently observaed.

The brightness enhancements produced a simultaneous increase of polarized light. Such a dependance is not compatible with reflectivity variations at the solid surface of the Moon, which should associate brightness increases with polarization decreases. It does not agree with incandescence and with flashing discharges, which do not produce polarized light. Specular reflection on properly oriented relief slopes may increase the brightness and the polarization simultaneously, but the process can hardly explain the amplitude of the enhancments observed.

Particles erupted by volcanic processes such as fire fountaining should leave after the active phases, a deposition of dark material at the lunar surface, which is not observed. It is clusters of hills made of a bright material that are present at the event emplacements.

The simultaneous increase of brightness and of polarization is consistant with light scattering on clouds made of separated grains. Small bright highland soil grains may be levitated above the lunar surface by outgassing from the lunar interior.

The events occurred at the border of a mare basin, near the central peak of a large crater, in a terrain presumed to be particularly fractured and fissured. The intense radon emanation that was measured around the site with the Apollo orbital instruments indicates gas release from the lunar interior, and supports the interpretation of the brightening events as soil grains levitated by the degassing.

Key Words: **Moon surface; polarimetry; photometry; geological processes.**

1. LANGRENUS AREA IMAGING POLARIMETRY

After the instrument video-polarimeter was designed at Observatoiore de Paris (Dollfus *et al.* 1989, Dollfus 1990), planetary surfaces and several lunar regions have been analyzed with imaging polarimetry. The video-polarimeter produces images of the telescopic field with the different components of the polarizrd light. The instrument isolates the four Stokes parameters I, Q, U, and V which describe the state of polarization and produce separate image for each component.

For the case of the Moon, there is no circular polarization and $V = 0$. The linear polarization is oriented perpendicular to the optical plane and, with conventional azimuth definition, $U = 0$. Thus, the polarimeter describes the lunar optical properties with a photographic *image I* formed with the nonpolarized light flux and a polarigraphic *image Q* with the linearly polarized flux. The flux Q normalized to the intensity I expresses Q/I, the degree of polarization, and an *image Q/I* is also constructed. The flux Q corrected for its residual sensitivity to albedo produces a polarigraphic *image* Q_o, which does not depend on the lunar surface albedo.

The technique for lunar surface analysis with polarigraphic images is summarized in a paper in this same issue (Dollfus 2000, hereafter designated Paper III). More details are given in two previous publications by Dollfus (1998, Paper I) and Dollfus (1999a, Paper II).

On images I, Q_o, and Q/I, contrasts are related to albedo, A, to surface roughness mean slope angle, θ (integrated for all size roughness elements smaller than the resolution of the image), and to grain size, Md (median value of the regolith grain size distribution). The contrasts are expressed in terms of A, θ, and Md by equations.

For *image* I (Eq. (1) of Paper III),

$$\Gamma\{I\} = \Gamma\{A\} + \Gamma\{M(w, a)\} + R(L, l, a)\,\Gamma\{\theta, \theta_{\text{ref}}\}, \quad (1)$$

where $\Gamma\{I\}$ means $(I - I_{\text{ref}})/(I + I_{\text{ref}})$. The same is true for $\Gamma\{A\}$ and $\Gamma\{M(w, a)\}$.

$M(w, a)$ is a small multiple scattering computed correction, $\Gamma\{\theta, \theta_{\text{ref}}\}$ means $[(\theta - 25)/(\theta + 25)]/[(\theta_{\text{ref}} - 25)/(\theta_{\text{ref}} + 25)]$, $R(L, l, a)$ is a coefficient for roughness detailed in Paper I, L and l are the selenocentric optical coordinates, and a is the phase angle.

For *image* Q/I (Eq. (2) of Paper III),

$$\Gamma\{Q/I\} = -1.36(p(a)/p_{\max})\Gamma\{A\} + (F(a)/F_{\max})\Gamma\{C_1(d)\}, \quad (2)$$

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where $p(a)/p_{\max}$ are $F(a)/F_{\max}$ are coefficients tabulated in Paper I, and $C_1(d)$ is linearely related to the median grain size Md by

$$C_1(d) = 0.021\,\mathrm{Md} + 1.76. \tag{3}$$

For *image* Q_o (from Eq. (5) of Paper III),

$$\Gamma\{Q_o\} = (F(a)/F_{\max})\Gamma\{C_1(d)\} + (p(a)/p_{\max})C_2[\Gamma\{M(w,a)\} + R(L,l,a)\Gamma\{\theta,\theta_{\mathrm{ref}}\}]. \tag{4}$$

With proper combinatons of *images* I, Q/I, and Q_o, new documents can be constructed to display on images the roughness θ and the grain size Md at the surface of the Moon (Papers II and III). These *image* θ and *image* Md are calibrated quantitatively.

In Papers I and II, lunar regions Tranquilitatis/Serenitatis border, straight wall, and Messier area have been polarimetrically analyzed in terms of albedo, A, roughness, θ, and grain size, Md. Crater Langernus was analyzed in Paper III.

During the Langrenus observations, in December 1992 and January 1993, unexpected illuminations were recorded on the floor of the crater (Dollfus 1999b). It is these brightenings that are analyzed here.

2. THE PHOTOGRAPHIC AND POLARIGRAPHIC IMAGES

Images of the Langrenus area were obtained with the videopolarimeter attached to the 100-cm telescope at Meudon Observatory (France). The three dates of observation were December 29, 1992, December 30, 1992, and January 2, 1993.

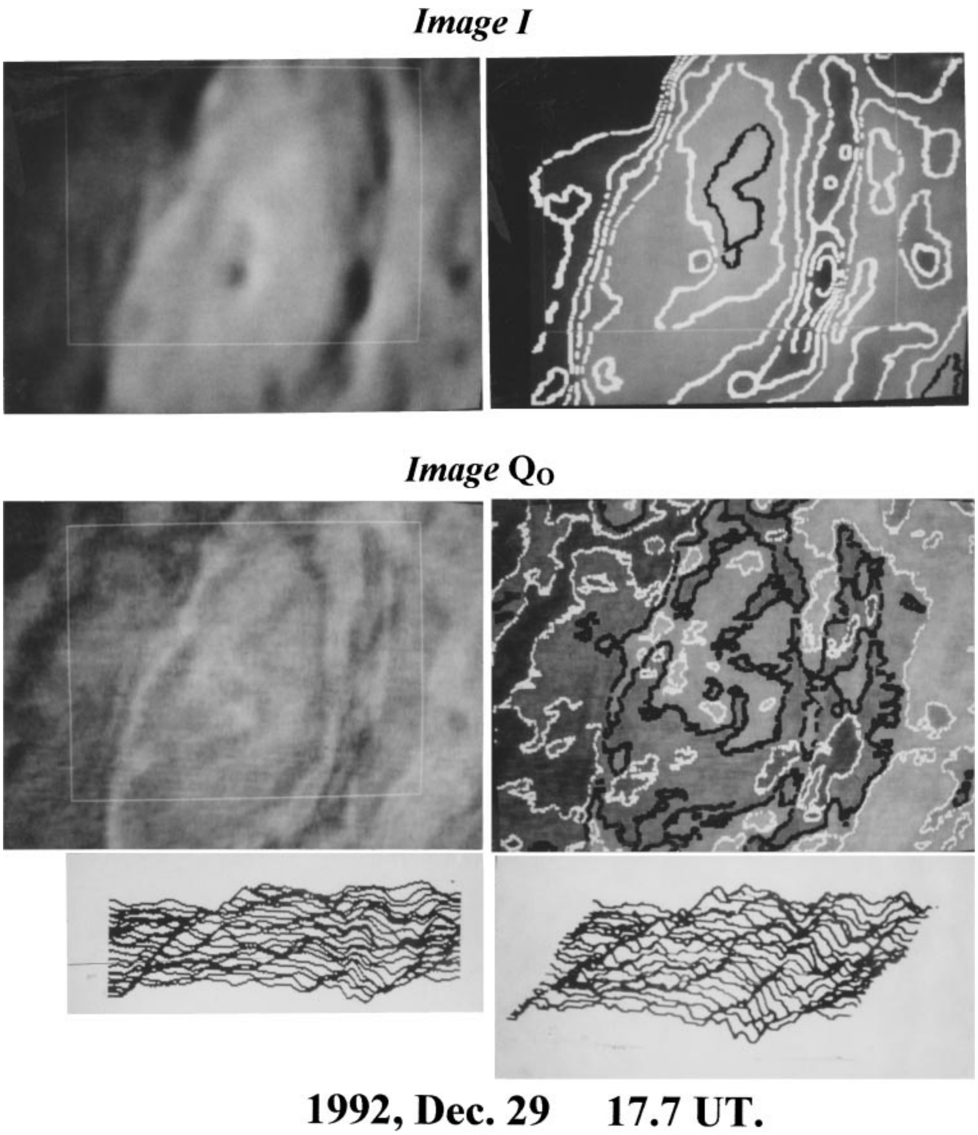

Image I

Image Qo

1992, Dec. 29 17.7 UT.

FIG. 1. Floor of crater Langrenus on December 29, 1992, at 17.9 UT, before apparition of the bright event. Video polarimeter images recorded in orange light. The field covers 85 × 69 arcsec; phase angle -116°; north is up. (Top) Photographic *image* I of the nonpolarized light. Isophote values normalized to the crater floor: 1.025 (black)–1.00 (white)–0.95–0.90–0.85. (Bottom) Polarigraphic *image* Q_o of the polarized light. Isophote values: 1.15 (white)–1.05 (black)–0.95 (white).

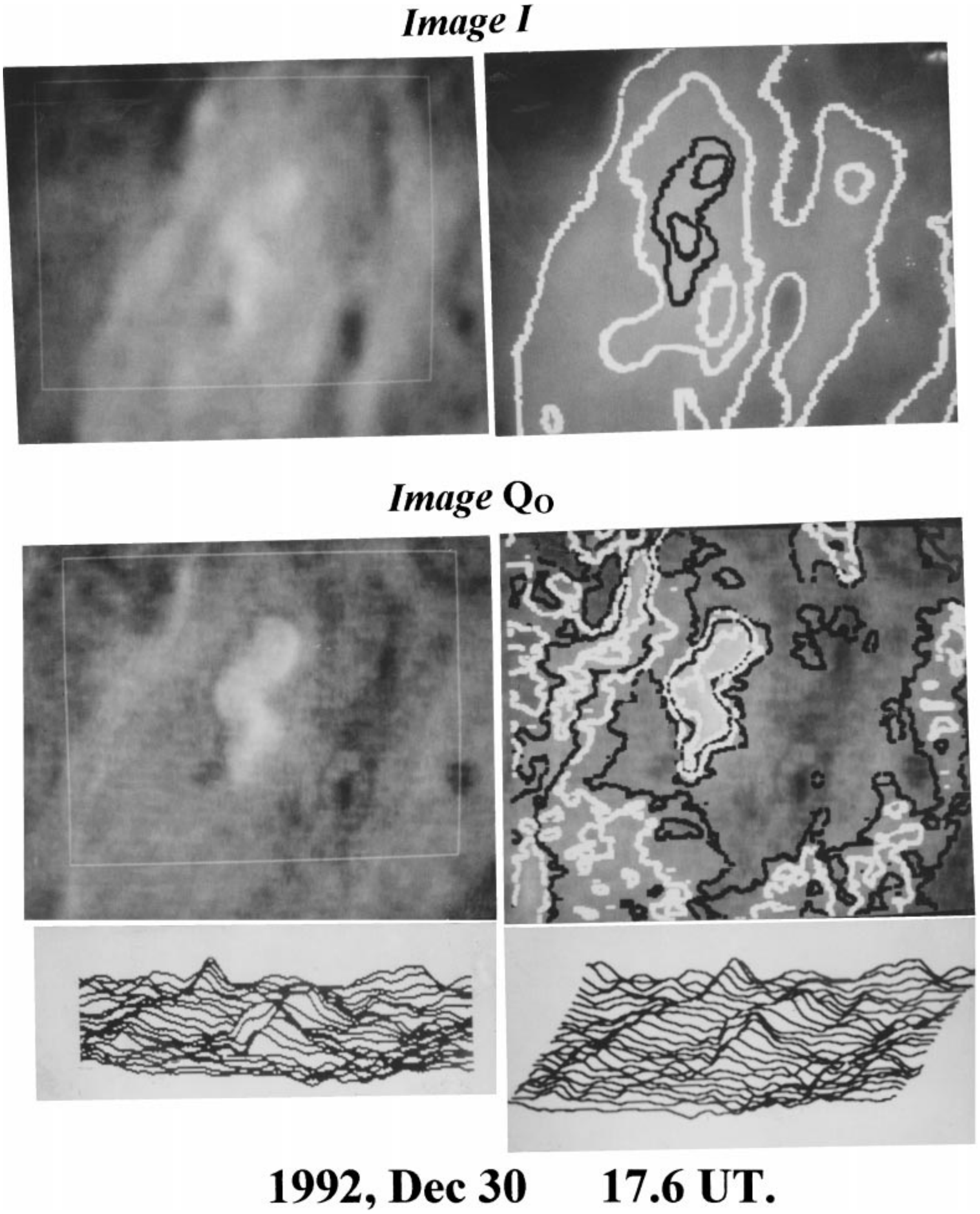

FIG. 2. Crater Langrenus, same as for Fig. 1 but for December 30, 1992, at 17.6 UT, during the development of the bright event. Phase angle −104°. (Top) *Image I*. Isophotes: 1.10 (black)–1.05 (black)–1.00 (white)–0.95–0.90. (Bottom) *Image Q_o* Isophotes: 1.25 (white)–1.15 (black)–1.10 (white)–1.00 (black).

The full images are reproduced in Paper III (Dollfus 2000), respectively the nonpolarized *image I*, the degree of polarization image Q/I, and the flux of polarized light *image Q_o*, for the three dates. The roughness image θ and the grain size image Md are also given. The geometric, photometric, and polarimetric data are tabulated.

The brightenings occurred at the floor of crater Langrenus interior. This portion of the field is enlarged (×2) in Figs. 1, 2, and 3, respectively for *image I* (top) and *image Q_o* (bottom). The field is 85 × 68 arcsec. An isophotic map is attached to each image. Associated with the Q_o images, 3D reconstructions of the Q_o intensities are presented, over the field outlined by the gray line rectangle. This rectangle covers an area of 100 km in the N–S direction and 250 km for E–W, when projected at the surface of the Moon. The 3D models are presented as seen from the south and also from the southeast. The *images Q/I* are presented separately in Fig. 4 for the three dates of observation.

3. THE DECEMBER 29, 1992, OBSERVATION

For the observation of the first night, the phase angle was $a = -116°$, the angle of illumination was $i = -54°$ and the viewing

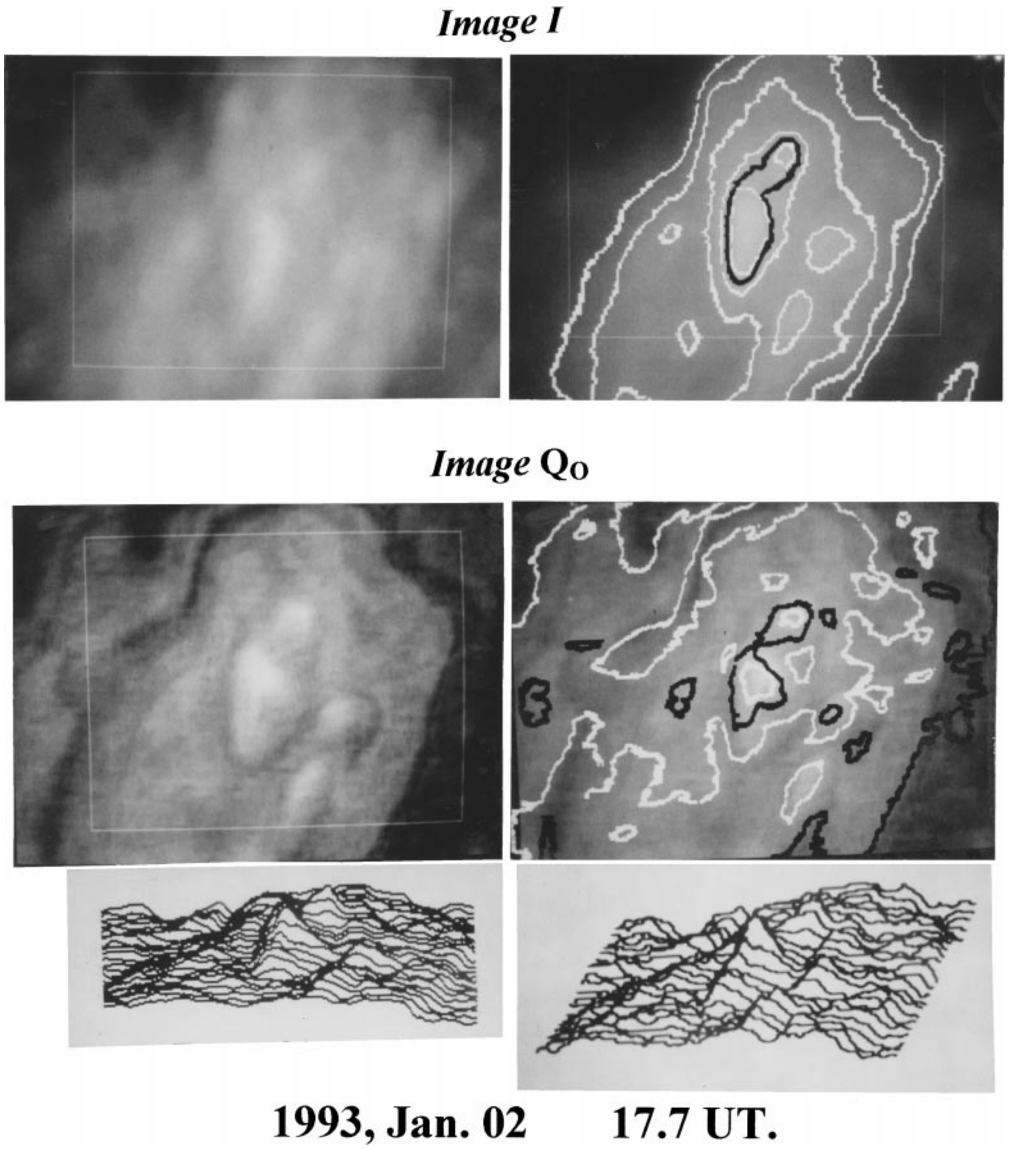

FIG. 3. Crater Langrenus, same as for Fig. 1 but for January 2, 1993, at 17.7 UT, after evolution of the bright event. Phase angle -72°. (Top) *Image I*. Isophotes: 1.08 (white)–1.06 (black)–1.03 (white)–0.97–0.90–0.85. (Bottom) *Image* Q_o. Isophotes: 1.13 (white)–1.07 (black)–1.00 (white)–0.93 (black).

angle $e = +62^\circ$. The incident and emergent planes were almost coplanar. For this date, all the images recorded with the instrument appeared normal, showing the lunar surface as expected, with no reason to suspect any anomaly.

The photographic *image I* (Fig. 1, top) shows the Langrenus bottom floor with a faint bright patch north of the central peak, somewhat S shaped; the contrast with the floor surface is

$$(I_{\text{bright}} - I_{\text{floor}})/(I_{\text{bright}} + I_{\text{floor}}) = +0.030 \pm 0.005.$$

There is also a faint bright patch southwest of from central peak.

These light hued areas are related with surface topographic features. Figure 5 is an image of Langrenus taken by the astronauts of Apollo 8 from an altitude of 240 km. The viewing direction is from SSE and the phase angle is nearly the same as for the December 29, 1992, observation. There is, over the crater floor, several assemblages of bright points corresponding to relief features. These hill fields agree with the light hued features of our December 29, 1992, photographic *image I*. When stretching Fig. 5 to correct for the perspective and reproduce the viewing conditions of our December 29 observation (Fig. 6), the hill field features are seen to be similar on both images.

On the polarigraphic *image* Q_o (Fig. 1, bottom), there is faint Q_o brightness features on the crater floor. The contrasts are small, not exceeding 0.02, as expected for natural and limited grain size and smoothness variations. The shapes and places of these faint contrast features are not clearly related with the light hued hummocky areas seen in *image I*. For the hilly

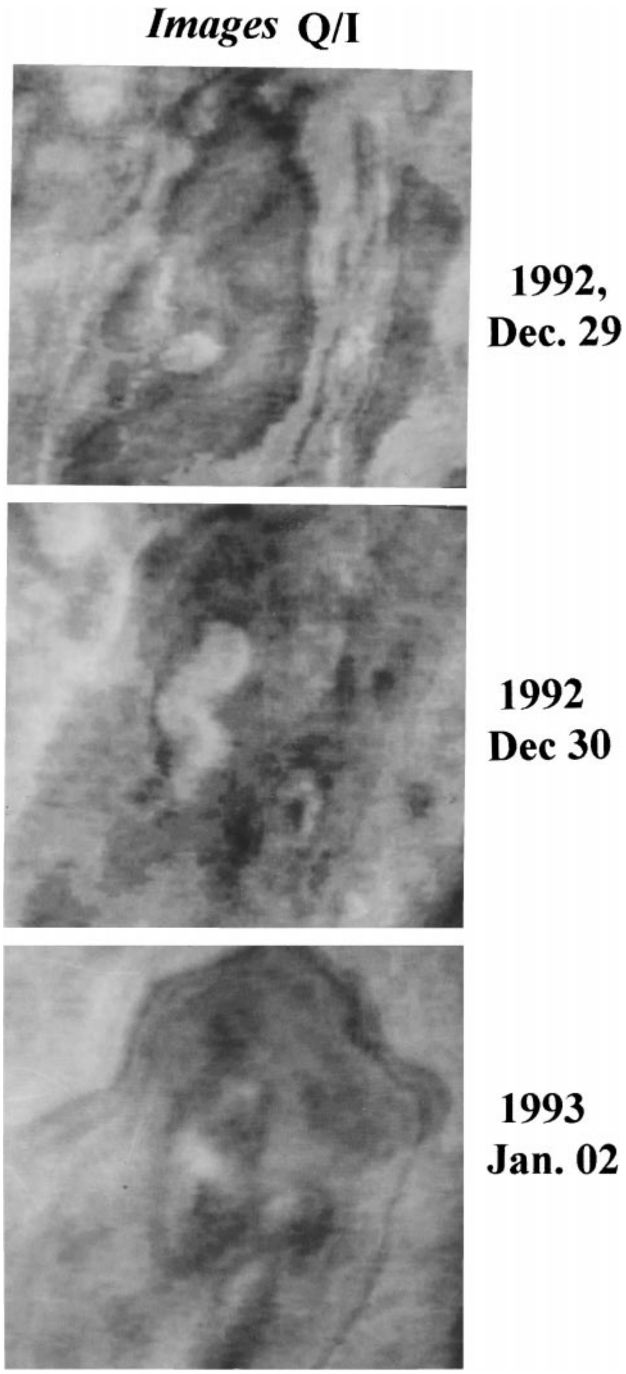

FIG. 4. Floor of crater Langrenus. Video-polarimeter images recorded in orange light. Polarigraphic *images* Q/I for the degree of polarization. (Top) December 29, 1992, before apparition of the bright event. (Center) December 30, 1992, during development of the bright event. (Bottom) January 2, 1993, after further evolution of the bright event.

region, where the events will occur, the contrast in Q_{o} light is $+0.00 \pm 0.01$.

On *image* Q/I (Fig. 4, top), the region of interest appears in Q/I light complex, with some parts slightly darker than the crater floor (less polarized), with a small contrast -0.01 ± 0.01. The negative value is a natural consequence of the reciprocity between intensity and degree of polarization, characterizing lunar type surfaces.

To conclude for the Langrenus floor observation of December 29, 1992, around 17.9 UT, on inspection of the photographic and polarigraphic images, nothing is suspected to be unusual. A feature north of the central peak, of interest for what follows, expresses optically the presence of assemblages of hills, few kilometers in size, seen individually in spacecraft images, and offering a light hued surface. The polarization behavior corresponds to a usual response for the lunar surface.

4. THE DECEMBER 30, 1992, OBSERVATION

The situation was totally different during the observations of the following night. Although, with $a = -104^\circ$, $i = -43^\circ$, and $e = +62^\circ$ the viewing geometry was not very modified, the aspect at the emplacement of the hill field was drastically changed. A very bright patch, totally unusual, appeared in the polarigraphic images.

On *image* Q_{o} (Fig. 2, bottom), the very bright feature is clearly delineated, and the contrast produced was as high as $+0.09 \pm 0.01$.

The bright patch appeared in each of the individual frames composing the final image Q_{o}. During the observing run at the telescope, pairs of images were taken for the two directions of polarized light, at a rate of a pair each minute, for 6 min. The photometric scans across each of the 6 individual images are reproduced in Fig. 7. The polarized flux increase is recognized permanently on each image. The six pairs of images are added to produce the final and less noisy *image* Q_{o}, with the scan at the bottom in the figure.

For the photographic image I (Fig. 2 at top), the bright feature produced with the nearby crater floor a contrast of $+0.036 \pm 0.05$, which is larger than the value found during the preceding night. The photometrtic scans across the brightened area are presented in Fig. 8, for each of the six images composing the final document. The white lines correspond to December 29, 1992, and the dark lines to December 30, 1992. The brightness incrase of December 30 (gray surface) appears permanently on each image, showing no variation during 6 min and no occasional defect in the individual CCD images. (The departures between the curves at left are due to changes in the relief illuminations and shadow variations when the phase angle decreased from 116° to 104°).

For *image* Q/I (Fig. 4 at center), the anomaly is also striking. A bright feature of contrast $+0.11 \pm 0.01$ replaces the dark hued patch of the preceding night.

The brightening event of December 30 was not flashing. It remained visible in all the direct *images* I and in all the polarigraphic *images* Q_{o} and Q/I, all during the 6-min observations. The contrast was unusual, reaching very high values on the polarization images.

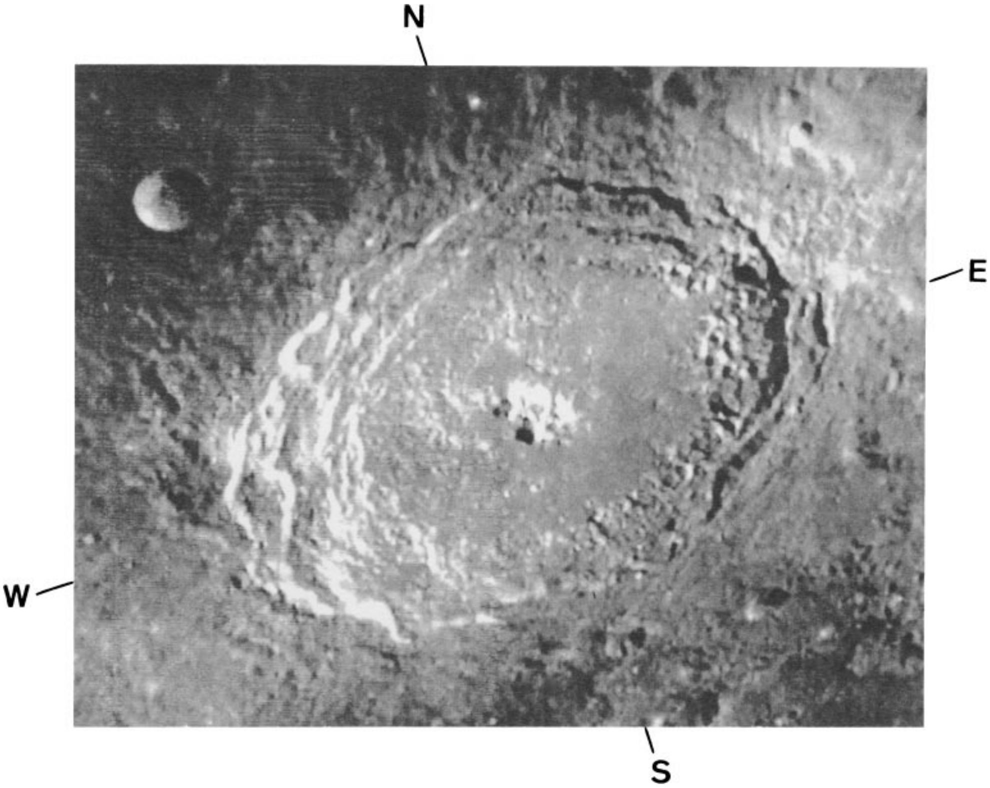

FIG. 5. Apollo 8 orbital image of crater Langrenus taken on December 24, 1969, from an altitude of 240 km. Same phase angle as for December 29, 1992, observation of Fig. 1. The viewing direction is from SSW. The area over which the bright event occurred is the hill-field North of central peak.

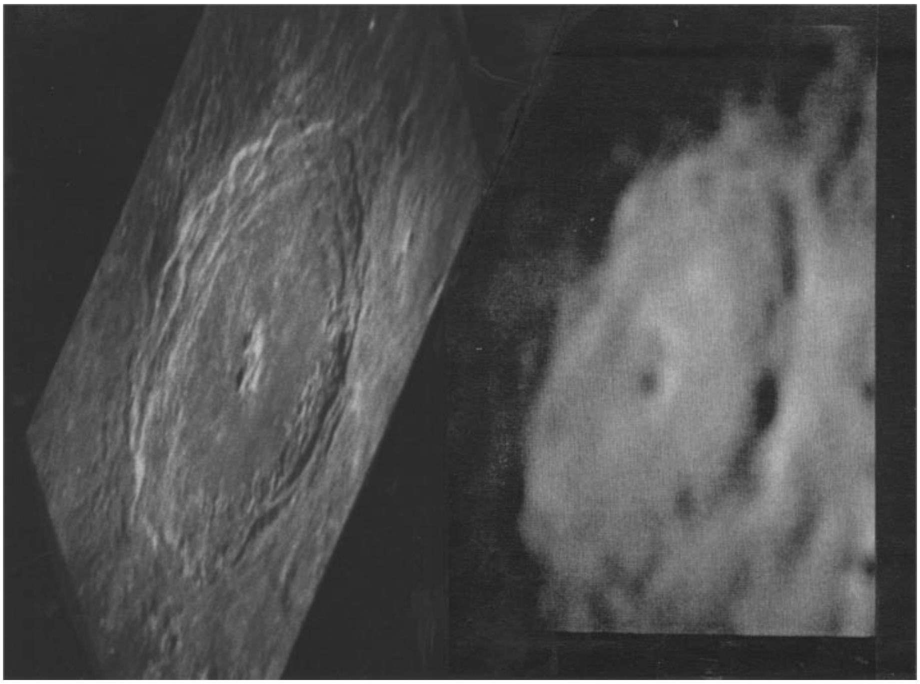

FIG. 6. Crater Langrenus. North is up. (Left) Apollo 8 image of Fig. 5, rectified to reproduce the viewing angle of the December 29, 1992, telescopic observation. (Right) December 29, 1992, telescopic observation (video-polarimeter *image I*). The hill fields identified in the Apollo 8 image are recognized as light hued features in the telescopic image.

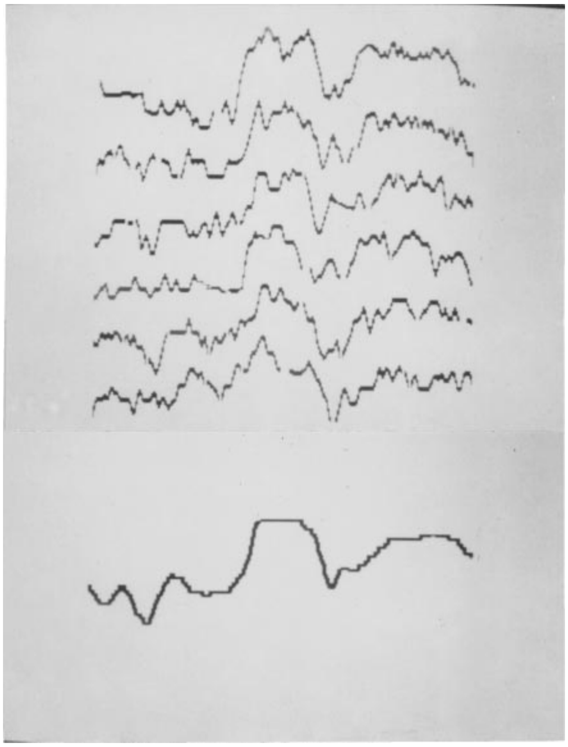

FIG. 7. *images* Q_o for December 30, 1992; scans across the Langrenus floor, intersecting the brightened area. Six scans correspond to successive images taken each minute (from 17h29m UT (top) to 17h34m UT (bottom)) and forming by their addition the final image Q_o. The brightening appears on each of the six images. The scan at bottom is for the final *images* Q_o.

5. THE JANUARY 2, 1993, OBSERVATION

Three days later, on January 2, 1993, the geometrc conditions of illumination evolved, with $a = -72°$, $i = -12°$, and $e = +62°$. The angle between incidence and emergence planes was 119°. Compared to the observation of December 30, the sensitivity to polarization was reduced by a factor of 1.3 and the sensitivity to roughness by a factor of 4. The photometric effect produced by the hill slopes was greatly reduced also, by a factor of 4.3.

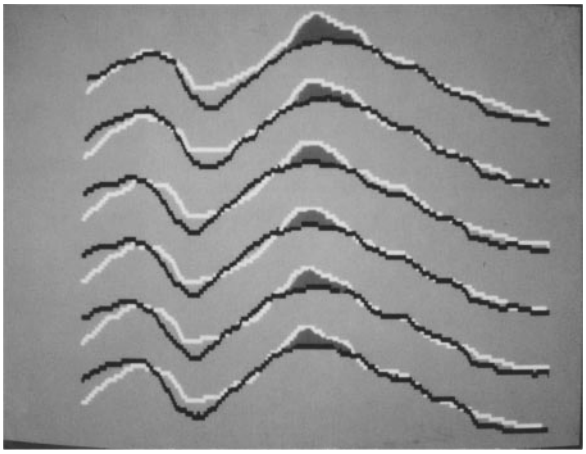

FIG. 8. *images I* for December 29 and 30, 1992; scans across the Langrenus floor, intersecting the brightened area. Individual scans over six images taken every minute and forming by their addition the final *images I*. Dark lines, December 29, 1992; white line, December 30, 1992; gray surfaces, brightness increase between the two dates. The departures at left are due to changes in the rempart illumination under slightly different phase angles.

However, what was observed at the site of the December 30 brightening is again a spectacularly bright feature, of similar but not identical aspect. On image I, the contrast with the adjacent terrain was around $+0.035 \pm 0.005$. This contrast reached 0.045 ± 0.007 in the brightest regions.

In image Q_o, the contrast was still more enhanced with the value $+0.115 \pm 0.015$. On this polarigram, some features are seen bordered with a faint dark line. This artifact results from a technical problem at the telescope, requiring that the six images I_1 with polarization normal to the optical plane were taken first, and then the six images I_2 with the polarization orthogonal. Meanwhile, the telescopic seeing conditions changed and the images I_2 are less sharp.

Brightenings were observed not only at the emplacement of the hill field area north of the central peak, but also on several aligned and arcuated patches along the southeastern and southern borders of the crater floor (Fig. 9).

For image Q/I (Fig. 4, bottom), these patches appear bright also, producing a contrast $+0.03 \pm 0.01$, where the normal surface effect should induce a decrease of polarization and a dark feature (Eq. (2)).

6. CHARACTERIZATION OF THE SITE WITH EVENT OCCURRENCE

The hill field regions of interest for what will follow produce contrasts in photographic *image I* for at least three reasons: the albedo of the material forming the hills. The photometric response to topopgraphic slopes and the surface roughness of the hill surfaces.

The albedo effect appears in the mosaic of Apollo 14 images of Fig. 10, with illumination near retrodiffusion. Slope and roughness effects disappear when approaching retrodiffusion with $a = 0°$. Accordingly, Fig. 10 is almost an albedo image. The hummocky area north of the central peak is framed end enlarged. The hills are seen individually and appear bright. The Langrenus floor itself is a high-albedo terrain, with $A = 0.147$ and the material forming the sloping faces of the hills must be still brighter, with an albedo approaching the largest values found at the lunar surface.

The slope effect can be computed, assuming the hills to be axisymetric cones of slope angle s. The telescopic image of Fig. 11, taken near grazing incidence with $i = +78°$ shows the hills casting shadows, from which a slope angle around $s = 20°$ is derived. The photometric response is $\cos i/(\cos i + \cos e)$. The hills are not resolved and the effect is integrated over the apparent surface. For December 29, 1992, with $a = -116°$, computation for an isolated cone with $s = 20°$ produces with the nearby flat

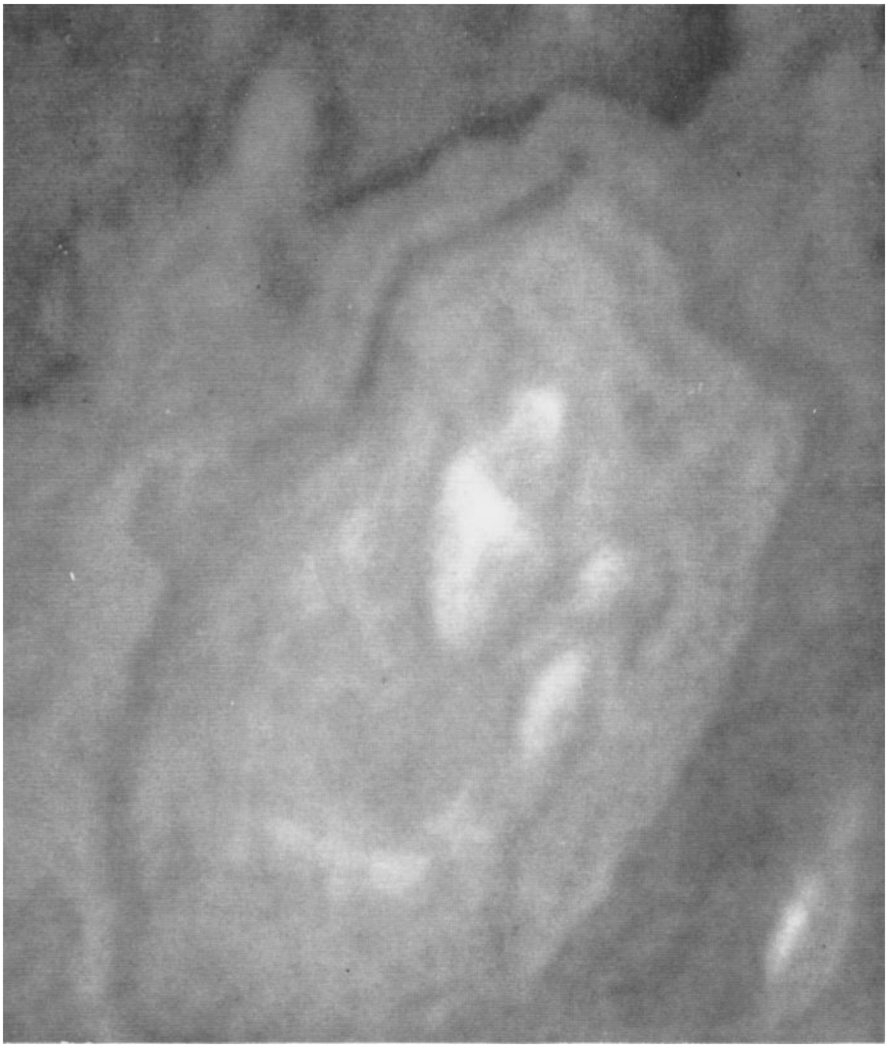

FIG. 9. Langrenus floor. Polarigraphic *image* Q_o for January 2, 1993. The areas with enhanced polarized light appear as bright features.

floor a mean contrast of −0.053. The negative value means a dark hued patch.

The roughness effect is characterized by the coefficient $R(L, l, a)$ in Eq. (1) and its value for $a = -1186^\circ$ is −0.26 (Paper I, Figs. 11 and 12).

For the hill field regions, Eq. (1) expressing contrasts in *image* I is complemented by a term $\Gamma\{s(L, l, a)\}$ for the relief effects:

$$\Gamma\{I\} = \Gamma\{s(L, l, a)\} + \Gamma\{M(w, a)\} + \Gamma\{A\} + R(L, l, a)\Gamma\{\theta, \theta_{\mathrm{ref}}\}. \tag{5}$$

With the small contrasts, the multiple scattering term $M(w, a)$ is neglected. The area of interest is compared with the crater floor for which $A_{\mathrm{ref}} = 0.147 \pm 0.004$ and $\theta_{\mathrm{ref}} = 23 \pm 3^\circ$ (Paper III). The value of $\Gamma\{s(L, l, a)\}$ is −0.053. If the hills are assumed to cover 1/3 of the area on which they form clusters the effect is diluted by a factor 3 and the contrast observed of $+0.030 \pm 0.005$ corresponds to $+0.090 \pm 0.015$ for individual hills. For these hills, Eq. (5) writes

$$0.090(\pm 0.015) = -0.053 + (A - 0.147)/(A + 0.147) - 0.26[(\theta - 25)/(\theta + 25) + 0.042]. \tag{6}$$

With *image* Q_o, it is Eq. (4) which applies. At phase angle $a = -116^\circ$, we have $f(a)/f_{\max} = 0.98$ and $F(a)/F_{\max} = 0.94$, the referece area gives $\mathrm{Md} = 110\ \mu\mathrm{m}$ (Paper III). For the hilly surface, Eq. (4) writes, when combined with Eq. (3),

$$0.00(\pm 0.03) = 0.94[(\mathrm{Md} - 110)/(\mathrm{Md} + 110 + 168)] - 0.34[(\theta - 25)/(\theta - 25) + 0.042]. \tag{7}$$

With relationships (6) and (7), a characterization of the hill slope surface properties is constrained. Values such as $A = 0.165$, $\theta = 12^\circ$ and $\mathrm{Md} = 80\ \mu\mathrm{m}$ are compatible with the measurements and errors. They correspond, for the hill slopes, to

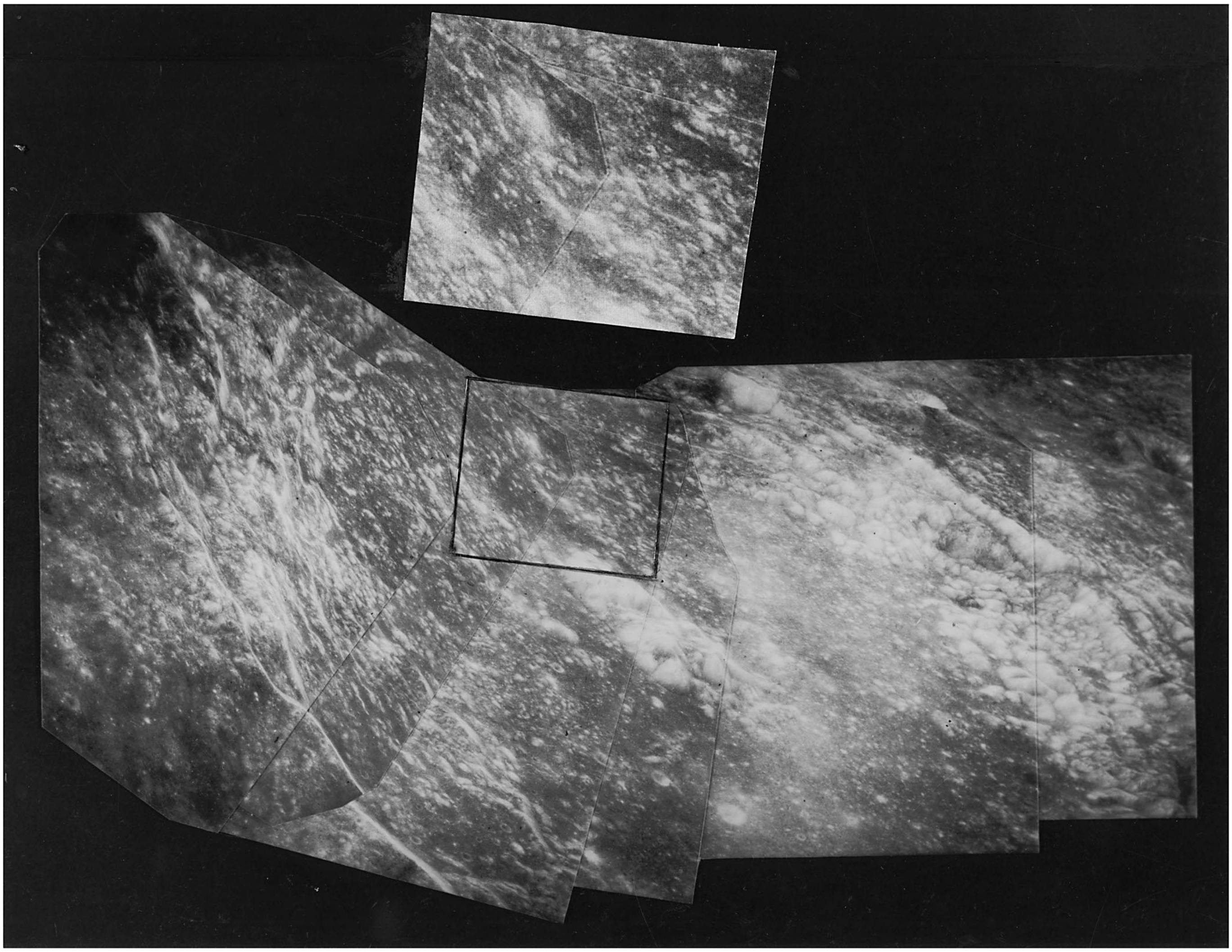

FIG. 10. Crater Langrenus floor around the central peak (detail). Mosaic of six Apollo 14 images (NASA documents 147310147–147310152). The viewing azimuth is from south-west. The area in which the brightenings occurred is enlarged in the cartouche. The illumination geometry corresponds to almost retrodiffusion.

terrains brighter, smoother, and made of smaller grains than for the nearby area. This adjacent crater floor is itself particularely rough with $\theta = 23^\circ$ and large grained with $\mathrm{Md} = 110\ \mu\mathrm{m}$.

This hill field area characterization, however, faces a small problem. For the *image* Q/I of December 29, Eq. (2) writes, when combined with Eq. (3):

$$\begin{aligned}-0.03(\pm 0.03) = {} & -1.33[(A-0.147)/(A+0.147)] \\ & + 0.94[(\mathrm{Md}-110)/(\mathrm{Md}+110+168)]. \quad (8)\end{aligned}$$

With the values of A and Md derived above, computation predicts a dark feature, but the contrast observed is slightly less negative than computed. There is an indication that, on Dec. 29, the degree of polarization was already slightly enhanced, as if the event which appeared fully deployed the following night showed already a hint of beginning.

To conclude, for the site north of the central peak where optical displays occurred, analysis and measurements on the photographic and polarigraphic images of December 29, 1992, characterize a hummocky assemblage of kilometer-size hills, exposing slopes of a rather bright material, with a surface texture smoother than the very rough adjacent terrain and made of finer grains. The nature of the terrain, on these hills, has nothing exceptionnal, being comparable to other regions at the surface of the Moon. A faint anomaly is suspected in image Q/I, which indicates a small local enhancement of the degree of linear polarization.

7. A TEMPTATIVE OPTICAL EXPLANATION

The brightenings observed on December 30, 1992, and January 2, 1993, are not compatible with the optical response produced by the ordinary lunar surface. They desserve a specific explanation.

FIG. 11. Telescopic view of crater Langrenus by Gérard Therin with an oblique illumination enhancing the releifs. North is up. The area in which the brightenings occurred is north of the central peak.

Equations (1) to (4), which relate the contrasts in *image* I, Q_o, and Q/I with albedo, grain size and roughness, assume that reflectance at the lunar surface is the scattering process commonly occurring all over the lunar terrains. However, there is an optical effect which is not considered in these equations because it does not usually play any role, which is specular reflection. The effect was analyzed in Paper II and in facts was detected in specific conditions on the Moon. It requires that the incidence and emergence planes be coplanar, and that the normal to the surface bisects the two beams ($i = -r$). It requires also the presence at the lunar surface of large grains, several millimeters in diameter at least, clean of dust, or of shining facets very specifically oriented.

These conditions cannot be a priori excluded for the case of the hills of the Langrenus floor. Incicence and emergence planes are near coplanar. On December 30, with $i = -40^\circ$ and $e = +64^\circ$, the normal to the surface bisects the incident and emergent beams if the terrain is tilted by 12° toward the observer, producing $i = -e = 52^\circ$. The hills have mean slopes of around $s = 20^\circ$ and probably parts of the surface include slopes of 12°. The same is true for January 2 with $i = -10^\circ$ and $e = +68^\circ$, requiring slope angles of 29°. On December 29, a tilt of 5° is required.

On the hill slopes, the median grain size Md was estimated above, on the basis of the December 29 analysis, to be around 80 μm, a large value for which the size distribution may include large grains. On the properly oriented facets of the hill constructs, specular reflection on these large grains could add light to the ordinary reflectance process and produce brightenings in the photographic images I and still more in the polarigraphic *image* Q_o and Q/I.

However, there is a problem of intensity. To produce a specular reflection in the direction of the observer, the shining elements must have the proper slope of 12° and its normal contained in the optical plane. The hills have mean slope angle, around 20°. The fraction of their surfaces having the required slope value of 12° probably does not exceed 0.3 of their total surfaces. The facets of these regions which are properly oriented within ±5° represents $10/360 = 0.028$ of the surface. The hills, on the average, cover one-third of the hill field area. All including, the shining areas cover only 0.0028 of the total surface.

On January 14, 1989, the flat area Mare Fecunditatis around the double crater Messier was observed with the video-polarimeter under specular conditions (Paper II). The light due to specular effect produced a contrast of +0.06. In the present case, with the limited total surface of shining elements, the effect should be $0.06 \times 0.0028 = 1.7 \times 10^{-4}$. In fact, the contrast increase observed on December 30 was around +0.01. It exceeded the Mare Fecunditatis case by a factor of near 50.

Specular reflection introduces a polarization. Our phase angle of 104° is near the Brewster angle and corresponds to the maximum effect. For the case of Mare Fecunditatis, a Q_o polarization contrast of +0.10 was observed. With the hills exposing only 0.0028 of shining areas, the contrast should be, under the same conditions, around 3×10^{-4}. The value really observed reaches 0.09 and is out of scale.

The flat shining area Mare Fecunditatis was characterized by polarigraphy with grains of median diameter Md = 60 μm (Paper II), implying the presence, in the size distribution, of a significant number of grains larger than 1 mm, able to produde specular effects. In the present case, the hill slopes have apparently still larger median grain sizes and their ability to produce specular reflection could be larger.

Specular effects may indeed play a role in the optical effects observed at the Langrenus floor. However, they can hardly explain the intense brightenings which are observed, except for advocating very unusual and atypic properties for the hill slope terrains.

New observations in the relevant range of phase angles, with a high photometric accuracy and a sharp angular resolution, may be of help in assessing the real contribution of specular reflection in the optical effects which were observed.

8. TRANSIENT ILLUMINATION INTERPRETATION

The Langrenus floor event produced a brightness enhancment associated with an increase of polarization. This peculiar behavior is a stringent condition for helping in the interpretation.

Pure gas scattering is a highly polarizing process. However, the luminance produced is several order of magnitude smaller than the brightness observed.

Monochromatic emissions by gas, like those suggested to explain the Alphonsus spectrum event observed in 1958 by

Kosyrev (1959, 1961, 1963) produce a nonpolarized light and cannot explain the Langrenus case.

Luminescence and incandescence at the lunar surface are unable to produce the brightness enhancements required (Geake and Mills 1977) and the light produced is not polarized.

Lightning-type discharges above volcanic eruptions suggested by Mills (1970) and advocated to explain a lunar flash observed by Kovolos *et al.* (1988) may be energetic enough, but the light again is not polarized and the process cannot apply for the Langrenus event.

The same is true for the electrodynamic effects advocated by Zito (1989) when rock fracturing may result from seismic activity. There is no polarized light produced.

The simultaneous increase of brightness and of degree of polarization which characterizes the present observation is not compatible with a real albedo change occurring at the surface of the terrain. An albedo increase should procduce a decrease of the degree of polarization Q/I. This is because the polarization Q is essentially formed at the surface of the grains, whereas the intensity I results essentially from the light emerging from the interior of the layer after multiple scattering. Because of the randomness of the multiple scattering process, this light is almost nonpolarized and dilutes the polarization Q produced at the surface, resulting with a decrease of the degree of polarization Q/I. The effect is expressed by Eq. (2).

However, the effect is reversed if the particles are not deposited at the surface but detached above the ground. Multiple scattering between grains is seriously decreased and the polarization is much larger.

For isolated grains of few micrometers diameter, Mie scattering theory applies. Grains made of an absorbing material, when $n_i > 0.01$, are computed to produce a strong polarization under the phase angles considered. Such is the case for the grains forming the lunar soil.

A small amount of flying dust may suffice to show up as a bright polarized feature. The lunar terrain is rough and, under the conditions of observation close to the lunar terminator, its luminance is decreased by the oblique illumination. According to photometric models (Minnaert 1961, Hapke 1981), the luminance of Langrenus' floor, for December 30, 1992, is reduced to almost 1/10th of its value at full Moon. The dust cloud is seen over a low luminance background and a thin haze suffices to produce a significant brightness increase.

The intensities and the polarizations which are associated in the event are consistant with a thin and transparent cloud, made of small, dark particles, isolated and separated from the ground.

9. NATURE OF THE LANGRENUS EVENT

Eruptions of volcanic style are able to expell upward plumes of small particles, condensed from the material coming from the lunar interior. A mist of smoke-sized particles produced by the condensation would be an efficient agent in producing scattering and polarization.

However, the ejected material differs in nature from the solid grains forming the lunar surface and the particles are usually darker. At the end of each active episode, the material ejected should be deposited at the lunar surface. Dark mantlings should be formed, which are not observed. Conversely, it is hills made of a bright material which are seen in the high-resolution Apollo images (Figs. 5 and 10).

Venting or degassing from the lunar interior could raise upward grains of the lunar soil. Gas pressure could separate grains from the surface and uplift them above the ground. The process was proposed and analyzed by Geake and Mills (1977). A sequence of sepaerate puffs may be an essantial mechanism for luminous effects to be visible.

Garlick *et al.* (1972a,b) conducted laboratory experiments about grain levitation, with a gas flowing from below a dust layer. Lunar samples were used. As for our Langrenus results, simultaneous increases of brightness and of polarization were observed.

The effect was observed when Mars was analyzed with polarimetry (Ebisawa and Dollfus 1993). Under the action of strong winds, small particles from the martian surface are detached by the saltation mechanism, they are uplifted into the atmosphere and produce tiny mists of suspended small opaque grains. The brightness is slightly increased and the polarization is strongly enhanced.

At the end of the laboratory experiments, when the grains are deposited again, the aggregated fluffy structure which characterizes the lunar surface is not totally recovered, but the surface remains slightly smoother and brighter than initially, and the polarization properties are not completely recovered. The effect was discussed by Geake and Mills (1977), who suggested that, in vacuum, the strong cohesion of grains may reconstruct the fluffy texture characteristic of the lunar surface more easily. The peculiar nature of the hills discussed in Section 6 may be related to this effect.

10. OTHER REPORTED TRANSIENT OPTICAL EFFECTS

Local and ephemeral brightenings, obscurations, or color changes have long been sought on the Moon. Many such events have been suspected, and they remain controversial (Sheehan and Dobbins 1999). Five cases, however, are better demonstrated.

(a) Dinsmore Alter, when observing at Mt. Wilson on October 26, 1956, took two photographic images of crater Alphonsus at 12h54m UT, in blue and near-IR. He noted an obscuration of part of the Alphonsus floor on the blue image, compared to IR (Alter 1963). The claim was not fully documented, but it inspired Nikolai Kozyrev to make the observation that follows.

(b) On November 3, 1958, at 03h30m UT, Nikolaï Kozyrev observed Alphonsus with the 50-inch Crimean telescope and noted on the central peak a reddish spot. A spectrogram was immediately taken with the slit crossing the peak. The spectrum showed bright features at the emplacement of the peak, on which Swan bands of gaseous CO_2 emission could be recognized (Kozyrev 1959, 1961, 1963, Alter 1963). Kozirev explained his observation by degassing from the lunar interior, due to active volcanic processes. Audouin Dollfus, and later Gerard Kuiper, had the opportunity to scrutinize positively the original plate with Nikolai Kozirev at Poulkovo Observatory. Gas emission does not produce polarized light.

(c) In October 1963, Greenacre and Barr (1963) noted visually a red spot sparkling in Aristarchus, using the 24-inch Flagstaff Observatory telescope. They gave alert and a confirmation went, also visually, from observers at the 69-inch Perkins Observatory telescope. Later, Hartmann and Harris (1968) analyzed the site with the Lunar Orbiter images and found that four of the five glowing spots were located around structures considered volcanic: cones, flows, or fissures. However, the authors were not able to detect on the Lunar Orbiter images traces of grain deposition which, at the terminating phases of fire fountaining episodes, should have settled on the ground.

(d) Observers at Abastumani Observatory, Georgia, when carrying out routine polarimetric measurements on the Moon with a photoelectric polarimeter (Dzhapiashvili and Ksanfomaliti 1966), noted on July 3, 1952, unusual wanderings of the polarimetric response when pointing at Crater Posidonius. The fluctuations did not occur on the other lunar areas and never occurred on other observing nights (reported by Middlehurst 1972).

(e) On May 23, 1985, at about 17h41m UT, Kolovos *et al.* (1988) took from Greece a sequence of photographic images at time intervals 8 s over a site near Proclus C and detected on one of these images a short-duration speck of light, in the nonilluminated part of the lunar surface, close to the terminator. The authors explained this short flash as outgassing and subsequent lightning-type electrical discharges, like those observed above terrestrial volcanoes (Mills 1970, Geake and Mills 1977). The optical energy released was estimated to be 4.5×10^{17} erg s^{-1}, compatible with that required. A debate followed about alternative explanations such as dead Earth satellites producing short duration reflections from facets or solar panels (Rast 1991, Maley 1991, Kovolos *et al.* 1992).

These few cases are the only ones presently documented by photographic images or by a visual claim followed by a confirmation. There was, in addition, many visual inspection reports, using usually small telescopes, about isolated flashing events with no confirmation. They were generally considered questionable (see Appendix). Visual inspection is not adapted to slowly varying events. None of these large number of reports implied crater Langrenus.

11. OUTGASSING, GRAIN DRAG, AND LEVITATION

The Langrenus illuminations occurred near the center of a very large crater, where the soil has been intensely broken and faulted by the impact which created the feature. Furthermore, this impact occurred exactly at the border of the large basin now filled by the Mare Fecunditatis material. This basin was also the result of an impact, far larger and older, which already fractured the crust. Such a place is particularly suited for gas extrusions from the interior.

Using the Apollo 15 and 16 Alpha-Particle Spectrometer in orbit around the Moon, Gorenstein *et al.* (1974) observed enhanced concentration of radon emission at the edge of Mare Fecunditatis and particularly around the Langrenus area. Gas venting is needed, from the interior of the Moon. The authors already suggested that optical effects may be associated.

Gas released from cracks may drag and eject grains from fissures. These grains have the light hue and high albedo of their crustal composition. Gas pressure may also levitate grains from the lunar soil. These grains are maintained detached from the surface as long as the gas contihues to flow, or even longer if electrostatic forces are produced. On these grains, scattering of solar light is able to produce intensity and polarization increases, as observed. The grains ejected from fissures may be responsible for the light-hued hill constructs which are observed on the site with the Apollo images.

12. CONCLUSIONS

Transient illuminations were observed on the Moon. They occurred on the floor of crater Langrenus. Totally absent the day before discovery, they appeared fully developed on December 30, 1992, around 17.6h UT. These brightenings were still present 3 days later, having evolved in shape and intensity. The events occurred in a part of the crater floor where clusters of hills are observed, few kilometers in size each, made of a high-albedo material.

The observations were made with the video-polarimeter of Observatoire de Paris at Meudon. The instrument produces conventional photographic images of the intensity, and polarigraphic images of the linearly polarized light. The bright events appeared on both types of images, with more contrast on the polarigraphic images.

Specular reflection on the hill slopes may play a role in producing brightness and polarization effects, but can hardly explain the intensities which are observed.

The luminance increases are associated with polarization enhancements and this response excludes incandescence, luminescence, albedo variations, gas emission, and electric discharges. However, the effect is consistent with clouds of small opaque particles, detached above the lunar surface.

Volcanic eruptions may produce such clouds but site inspection with the Apollo documents do not identify traces of dark deposits at the surface, like those usually associated with volcanic eruptive processes. Rather, it is a field of hills which is observed, and the hummocks are still brighter than the adjacent high-albedo terrain.

Gas release by fissures of fractures is a plausible mechanism for levitating grains from the soil, and producing the intensities, polarizations, and evolutions that are observed. The site configuration suggests a terrain particularly fissured and fractured. Radon release has been observed during the Apollo orbital operations, particularly intense on the site, indicative of gas venting from the lunar interior.

APPENDIX: ATTEMPTS TO RECORD VISUALLY LUNAR TRANSIENT PHENOMENA

Searching for transient events at the surface of the Moon was an exciting purpose for visual observers using private telescopes and having free time for observations.

Green (1962) published a table of about 20 reported visually observed events between 1840 and 1960. Many other observations were added since. The events observed were diverse: reddening, lightening, flashing, shadowings, and moving clouds. A list compiled by Middlehurst *et al.* (1968) and extended by P. Moore refers to 713 events. Cameron (1972, 1978) published a catalog with 1468 events, essentially by members of the Association of Lunar and Planetary Observers (ALPO) and by the specific groups Astro-Net and Moon-Blink (Cameron and Gilheany 1967), with European contributions (Hilbrecht and Küveler 1984).

Many of these so-called lunar transient phenomena (LTP) may not be real, in view of effects like atmospheric turbulence and eye fatigue. The case is reminiscent of the net of "canals" which had been noticed across the disk of planet Mars.

Frequency diagrams plotted as a function of the lunar orbital longitude shows a maximum around perigee and a smaller one near apogee (Middlehurst 1972). Apollo 12 passive seismic experiment showed also a strong seismic events peak at perigee, which corresponds to the highest tidal stress on the lunar crust. The Langrenus display occurred, however, when the Moon was at apogee.

Also, the distribution of LTP sites suggests an association with the borders of the regular maria and also with craters containing crack systems or central peaks (Middlehurst 1972). This distribution was considered consistent with an origin from the interior of the Moon (Runcorn 1976). The Langrenus event occurred indeed at the boundary of Mare Fecunditatis around the central peak of a large crater. During long telescopic visual watches, however, the observers are tempted to focus their attention on interesting features in the field of view.

At the occasion of the Apollo lunar manned missions, a Lunar International Observers Network (LION) was organized with the participation of 176 amateurs from 31 countries, reported by Citron (1973). Apollo 11 astronauts, when looking visually at the Moon from orbit, suspected flashing points on the walls of Aristarchus, seen on the dark portion of the lunar surface because illuminated by the ashen-light. Alert was immediately given and several flashing point events were reported by visual observers using small telescopes. An attempt by A. Dollfus at Pic du Midi, under excellent seeing conditions, was reported at the 1976 IAU meeting by J. E. Geake (1976) as follows:

> The 1 m diameter telescope was used in coronograph mode, to supress the light scattered by the illuminated crescent, giving unprecedented observational conditions. A. Dollfus observed the site of the reported LTP's (the wall of Aristarchus), and at first saw nothing unusual; then, after some time, he saw some flashes. He was doubtful as wether they were real, and took a rest, after which he again saw no flash at first, but did see some after few minutes. The experience was renewed several times. He concluded that the flashes he saw were all due to eye fatigue. He saw no events that he regarded as real during the one and half hours of observation."

During the period of Apollo missions, and along the 7 following years, a program for searching LTP with less subjective methods than simple visual inspection was supported by NASA at Corralitos Observatory, using a 24-inch telescope with an image orthicon detector and color blink (Hynek *et al.* 1976). The observation was visual but on a screen, with images contrast enhanced, seeing effects integrated, and a technique for flickering between images of different colors. Despite the extensive survey, no color or feature changes were observed with certainty. The Corralitos staff could not confirm the visual observations claimed in real-time by the Astro-Net observers, nor the events announced by the Moon-Blink and LION coordinated watches. They did not confirm the events listed in the tables by either Middlehurst (1968) or Cameron (1972) that corresponded to their watching periods.

Very recently, Calkin *et al.* (1999) presented a poster communication at the 31th meeting of the Division of Planetary Science of American Astronomical Society. An obscuration over the "cobra head" (Vallis Schröter near Aristarchus) having been reported by a group of amateurs observing visually on April 23, 1994, the authors analyzed the site later in the images obtained by spacecraft Clementine in orbit around the Moon at that date. A difference in color wes noted, compared with the images acquired before the event. However, a further reanalysis of the Clementine images did not support the claim, clarifying conversely that the visual description did not record on plates.

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