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Evidence for a high altitude distribution of lunar dust

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Abstract—The crew of Apollo 17 saw streamers accompanying spacecraft sunrise. The time variations (≃2 min and 5 sec) of the brightness of these streamers indicate that they were produced by light scattering in the lunar vicinity rather than brightness variations of material streamers emanating from the sun. The angular extent of the streamers (>30° fully developed) indicate that the light scattering particulates extended from the lunar surface to above the orbital altitude of the spacecraft. Although observed as typical sunrise phenomena by Apollos 10 and 17, and possibly by 8 and 15 as well, streamers were not observed during the flight of Apollo 16. The scattering particles seem to be present sporadically, most likely lunar dust of tenth micron scale, and not a result of spacecraft contamination.

STREAMERS

THIS PAPER will present evidence from Apollo lunar orbital observations, indicating the existence of solar light scattering from a significant population of lunar particulates extending to altitudes in excess of 100 km. This evidence comes from crew observations of the solar corona/zodiacal light (CZL) glow as it appeared above the lunar horizon while the Apollo vehicle approached orbital "sunrise." "Streamers" observed to be a part of this glow were seen to exhibit a time development in visual brightness inconsistent with an exclusively CZL source.

The relevant points of the observations are best exhibited by Fig. 1, which is a photograph (NASA-S-73-15138) of sketches made by E. A. Cernan (Commander, Apollo 17) recording his visual observations of sunrise as seen from lunar orbit. The five sketches are a time sequence, showing the appearance of the CZL glow region as it rose above the lunar horizon during the approach to orbital "sunrise." The only changes that should occur would be the progressive appearance above the horizon of new regions of the CZL closer to the sun, at the rate of 3° per minute, until the sun itself appears at "sunrise." Once a given region of the CZL has risen above the horizon, its appearance should not change as it continues to rise in the lunar sky. *In fact, at least two distinct changes do occur* as shown in the sketches made at T-2 min and T-5 sec. These show the appearance of "streamers," of linear extent perhaps twice that of the diffuse "corona" which has been visible at least 4 min (since T-6 min). These streamers were not visible when the smaller region of diffuse "corona" glow first came into view, but have now intensified with respect to that glow to become definitely visible. From T-2 min until sunrise, the streamers were observed to intensify at a progressively increasing

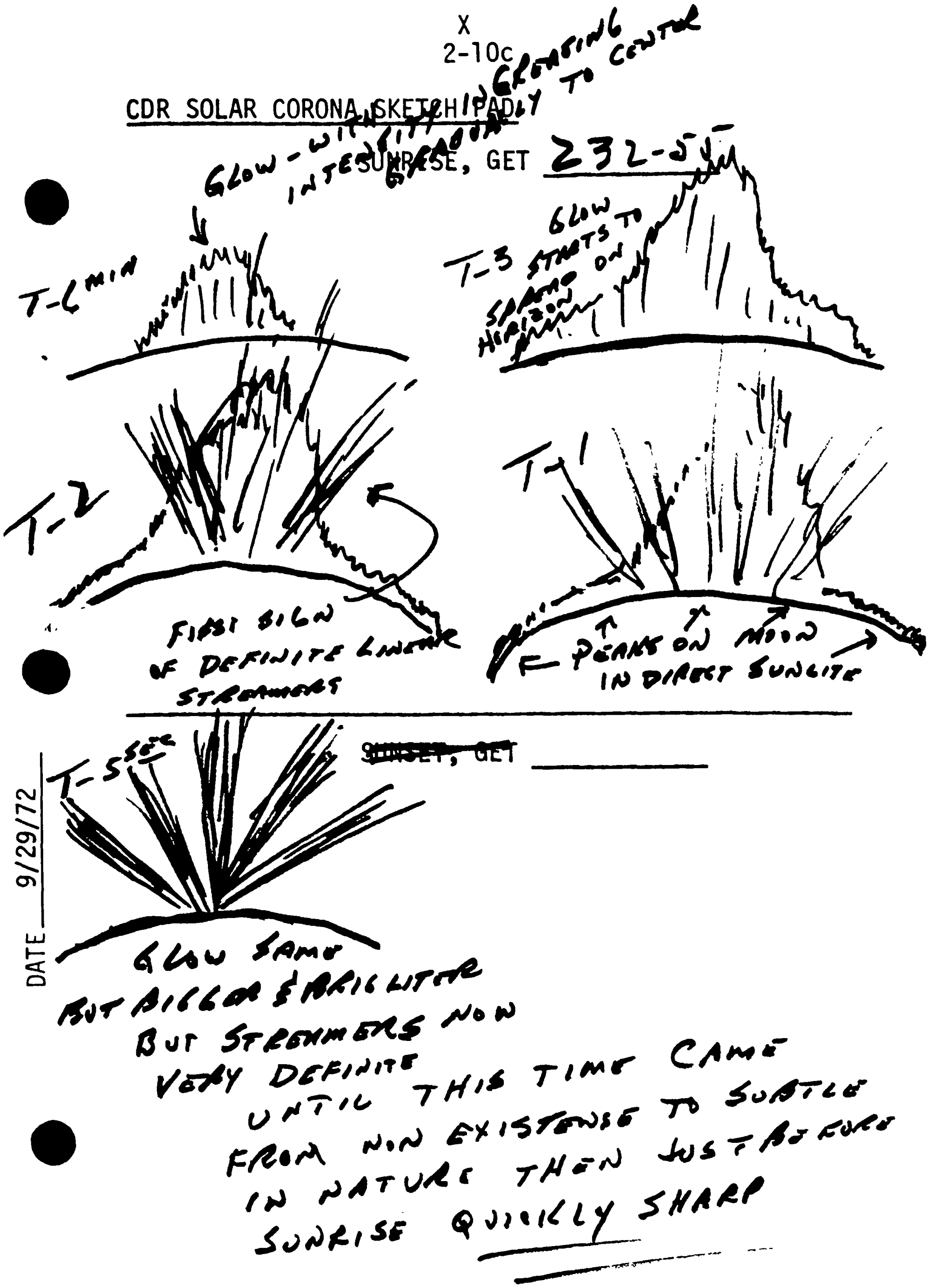


Fig. 1. Five sketches drawn by E. A. Cernan (Commander) of sunrise as viewed from lunar orbit during the Apollo 17 mission. The times in minutes (i.e. T-6, T-3, T-2, and T-1 min) and seconds (i.e. T-5 sec) refer to the time before first appearance of the sun. The observations were completed at an approximate ground elapsed time (GET) of 232 hour and 55 min. For all Apollo landing missions orbital sunrise occurred over the sunset terminator and on the side of the moon away from the earth.

rate such that their enhancement in the final 5 sec exceeded that during the previous 2 min.

LOCAL VERSUS SOLAR ORIGIN

Streamers observed from the vicinity of the moon have been tentatively interpreted as being of solar origin (Bohlin 1971) and representing extensions of the solar plasma streamers observed at 1.5–13 R_0 (MacQueen *et al.*, 1973, 1973a; Wilson and MacQueen, 1974). If this were the case, then a streamer originating on the visible disk of the sun and extending 30° as viewed from the moon, would be more than 75×10^6 km long. Sudden, virtually synchronous, brightening of a set of such streamers along their entire angular extent would require the propagation of a simultaneous disturbance along each streamer. Even at the speed of light, a disturbance would require 4 min to propagate along such a feature. The streamers must be produced by some process operating in the vicinity of the moon.

The only physically reasonable location for the observed streamers is between the edge of the lunar shadow and the vicinity of the lunar terminator. Concentrations of atmospheric gases observed by both lunar surface and orbital experiments are entirely too small to scatter visually detectable levels of light (Hodges *et al.*, 1973). Dust present in a lunar "atmosphere" at number densities many times the interplanetary density responsible for the zodiacal light can explain the observed scattering of the sun's rays from this region.

As a final point, it should be noted that an incredible coincidence would be required for any change in a coronal streamer to occur just as the command module approached the boundary of the lunar shadow.

A MODEL

Figure 2 depicts a physical situation which is consistent with the visual observations. During the final 5 sec of rapid change in streamer intensity, the Apollo spacecraft is approaching the lunar shadow boundary surface at an angle

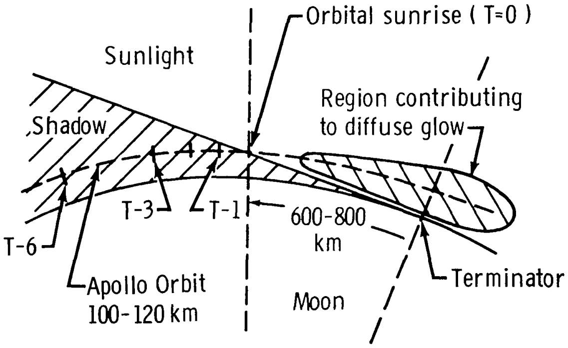


Fig. 2. This is a schematic cross section (approximately along a lunar longitude) of the moon in the plane of the spacecraft (s/c) orbit (dashed line). The s/c proceeds from left to right approaching the terminator at 3°/min or approximately 1.6 km/sec.

of approximately 20°. The boundary surface between lighted and unlighted space, therefore, passes less than 1 km above the observer at this time, and is closing rapidly. Since this surface will be irregular due to surface irregularities at the lunar terminator, a rayed effect qualitatively similar to that often observed from the ground during terrestrial sunsets would be expected to become increasingly evident upon close approach. The streamers would be superimposed upon an overall diffuse glow from scattering by more distant dust particles in the fully illuminated region above the terminator. This model is intended to provide a conceptual basis upon which to organize and evaluate the available observations. It is not necessarily definitive or complete.

Apollo 17 Observations

As a part of the Solar Corona/Zodiacal Light Experiments, the Apollo 17 crew made sketches of their visual observations of the appearance of the corona-zodiacal light (CZL) glow as it rose above the lunar horizon while they approached orbital sunrise. These sketches were intended to supplement the series of dim light photos made to obtain photometric intensities in red, blue, white, and polarized light. Examination of the sketches made by each of the three crew members shows that they were able to see structural details in the glow fainter and finer than the cameras could record. The photography was limited by film graininess, limited film latitude, and residual image motion. More important, the astronauts' ability to see the entire range of intensity from instant to instant enabled them to notice the clear presence of (unexpected) time variations which provide the primary basis for this analysis. While the photographic data may eventually provide some firm numbers on which to base improved optical scattering calculations, the detailed visual observations of the crew provide the crucial facts necessary to this basic analysis.

Cernan's sketches were shown in Fig. 1. Note that rather than a single sketch, he made a series of five sketches to show the time development of what he saw. This presentation seems to be due to having observed several previous sunrises, both on this mission and on Apollo 10, which lead him to realize that the time development was to be expected.

The first sketch, made 6 min before sunrise (T-6 min) appears to show the CZL as it would be expected to appear based on extrapolation of earth-based observations. It is shown as a symmetric glow, increasing in intensity from the threshold of visual sensitivity (outer perimeter sketched) toward the sun. At this time the sun is still 18° (70 $R_\odot$) below the horizon. It is hard to estimate the actual angular extent above the horizon of the visible outer perimeter. Lacking any stars for reference, let us assume about 6°. The zodiacal light is therefore visible from an elongation angle of 18° out to an elongation on the order of 24° from the sun.

The second sketch was made 3 min before sunrise, with the sun now 9° (35 $R_\odot$) below the horizon and an additional 9° of the CZL exposed. The spacecraft was moving toward sunrise at 3° per minute. The top of the glow area would now be about 15° above the horizon.

The third sketch is at T-2 min, the sun now 6° below the horizon. "Linear streamers" are now seen for the first time. They appear in a region previously visible for at least 3–4 min. The streamers are visible in both the CZL and beyond the outer perimeter of the CZL. The streamers extend into areas where *nothing* was previously visible. The CZL seems to retain its original shape and character, its upper perimeter now presumably providing an angular scale reference approximately 18° above the horizon. The appearance of the linear streamers represents an actual change in light visible from a fixed area with respect to the sun, between elongation angles of about 10° out to 20–30°, during 1 min.

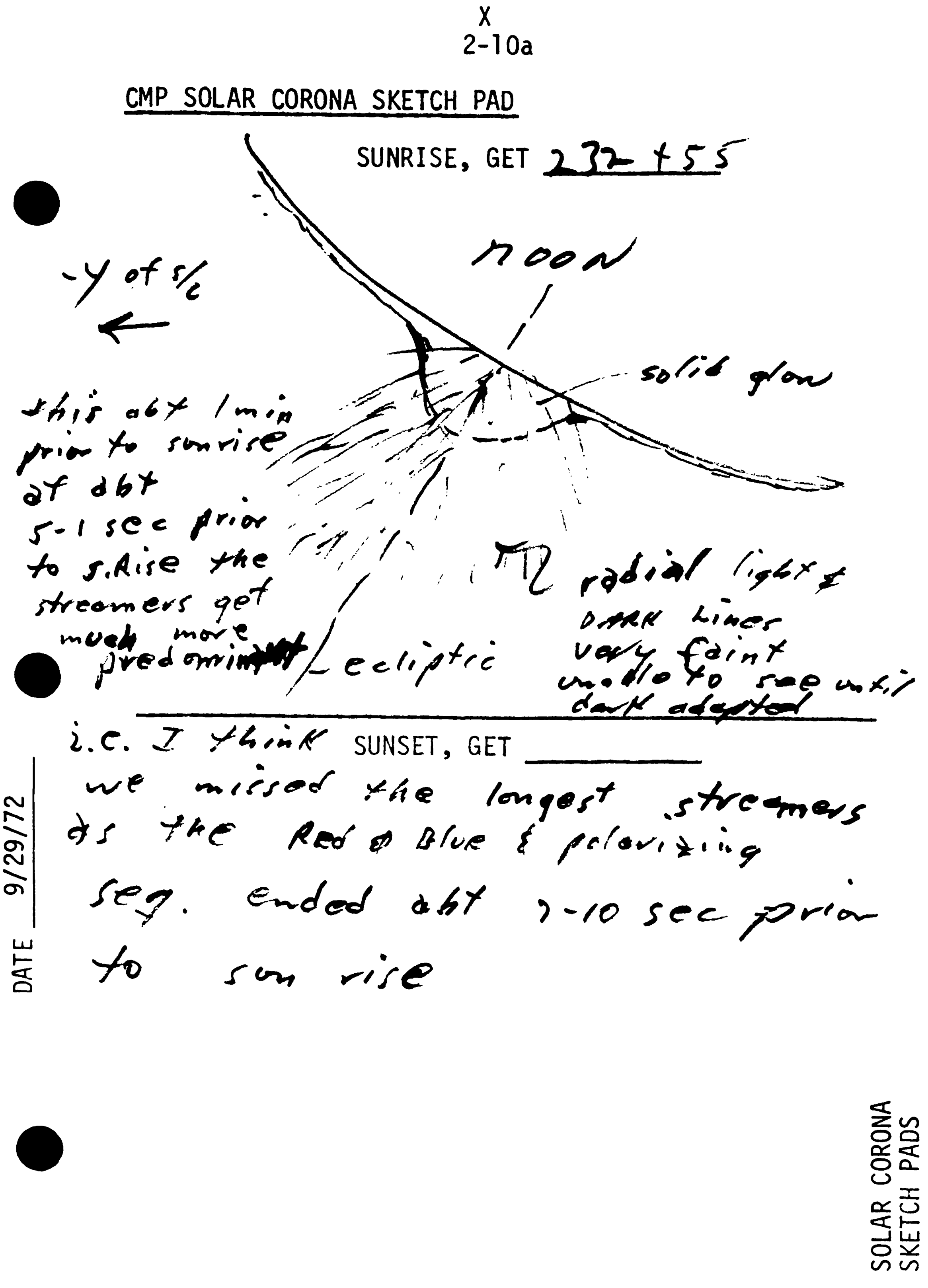
The fourth sketch is at T-1 min; the "linear streamers" display the same general appearance as 1 min earlier. The linear streamers now extend from 3° to beyond 20° from the sun.

The final sketch at T-5 sec shows a complete change in appearance of the entire region. A few (5?) distinct streamers now stand out sharply to dominate the CZL from the horizon out to some unspecified angle (presumably well beyond the original extent of more than 20°). He comments that the CZL has stayed the "same" or possibly has even gotten "bigger and brighter"; but the streamers seem to have completely preempted his attention.

Cernan (private communication 21 January 1974) verbally verified and elaborated on the above. He said this sequence of sketches is typical of numerous sunrises he has viewed from orbit, both during this mission and on Apollo 10. He felt he was fully dark adapted at all times. The streamers were definitely not present until about 2 min before sunrise when they first appeared as very subtle features and were initially best seen with averted vision. He could not count how many or identify any single specific streamer. He just had the impression of very many radial structures. The ends of the streamers definitely extended beyond the edge of the originally visible CZL. The CZL region gave the impression of a more sharply defined edge than did the ends of the streamers. At one point, he held up a hand (to try to estimate brightness), but could see no shadow cast nor visible illumination on his hand by the light present.

The streamers seemed to become progressively more distinct; but until the final 5 sec, he could not distinguish any particular streamer—only the subtle impression of many radial lineations. The final brightening occurred very fast compared to the first appearance 2 min earlier. Cernan noted that this sudden streamer brightening definitely preceded and was not coincident with sunrise. It occurred very slowly compared to the actual sunrise. The involuntary blinking and aversion on seeing the sun was a distinctly different, and subsequent, response to that of seeing the brightening of the streamers, approximately 1–5 sec prior to sunrise. He likened the first glimpse of any fraction of the solar disk to trying to look directly at a brilliant electronic strobe. Each streamer stayed very slender in shape as compared to the shape of a comet tail. He could not be certain exactly how many were present, whether five as in his own sketch or three as noted by Schmitt (Fig. 4). He also illustrated the final angular extent as more than twice that of the CZL.

Figure 3 is a photograph (NASA S-73-15137) of the sketch by R. E. Evans



X
2-10a

CMP SOLAR CORONA SKETCH PAD

SUNRISE, GET 232+55

noon

solid glow

-Y of S/C ←

this abt 1 min prior to sunrise at abt 5-1 sec prior to s.Rise the streamers get much more predominant

radial light & dark lines very faint unable to see until dark adapted

ecliptic

i.e. I think we missed the longest streamers as the Red & Blue & polarizing seq. ended abt 7-10 sec prior to sun rise

SUNSET, GET ____________

DATE 9/29/72

SOLAR CORONA SKETCH PADS

Fig. 3. This is the sketch by R. E. Evans (Command Module Pilot). It presents a composite of the sunrise features with comments on the time development. It is oriented approximately as the scene actually appeared to Evans through the viewing port.

(Command Module Pilot, Apollo 17) recording his visual observations of the sunrise as seen from lunar orbit. His single sketch seems to depict the general scene about 1 min before sunrise. He also depicts the "streamers" as radial dark and light lines extending far beyond the boundary of the solid glow region. Instead of a series of sketches, he notes in the margins that the streamers as shown were very faint and that he could not see them at first ("unable to see until dark adapted"). He also notes that 1–5 sec before sunrise the streamers get much more prominent; in particular, that the longest streamers occurred *after* the photographic sequences ended about 7–10 sec prior to sunrise.

Evans (private communication, 18 January 1974) confirmed that the streamers definitely extended outside the CZL. He estimates the fainter visible parts were dimmer than the milky way. He describes the brightening at $T \sim 1$–5 sec as tremendous and sudden, that it "just zaps out across the sky" very fast and very far (maybe 45°). His impression of time progression was "it starts at the horizon and goes" in an irregular rather than completely uniform front. He thinks the background corona also increased at the time of the flash, but not as much. He also mentioned a sharp increase in "background" illumination very close to the sun (less than $2\,R_{\odot}$). Apparently, he only observed the one sunrise, when the sketch was made.

Figure 4 is a photograph (NASA S-73-15414) of the solar corona sketch made by H. H. Schmitt (Lunar Module Pilot, Apollo 17) recording his observations of the lunar orbit sunrise. His sketch does not describe the CZL/streamer time development nor the time the observation was made. It is particularly valuable because it shows the relative location of Jupiter (labeled Venus) which establishes an angular scale for the rest of the sketch. The elongation angle of Jupiter ranged from 25° to 22° (American Ephemeris and Nautical Almanac, 1972) from the sun during the mission; this establishes the length of the three long "glow streamers" as being in excess of 30°. It also indicates the threshold of Schmitt's visual sensitivity limited his detection of the solid glow region to only 10–15° from the sun (half-way to Jupiter) as opposed to better than 20° for Cernan's original sketch; yet, he also saw the "radial lineations" in this region as reported by the others. He also shows (two) very strong, short (3°?) streamers extending up from the lunar horizon near the ecliptic.

Schmitt (private communication, 15 January 1974) indicated that he associated the glow streams with the short strong streams at the horizon, which he referred to as "spicules." He stated that just before sunrise, he could trace the glow streams back to their source at these "spicules" in the innermost corona. He seemed to consider the glow streamers to be a direct extension of inner coronal structure. He suggested that the flash effect at sunrise was not real, but a reaction to the rapid increase in brightness at the horizon as the inner $1\,R_{\odot}$ of the corona rose.

EVALUATION OF APOLLO 17 OBSERVATIONS

Our evaluation of the crew observations is that all are consistent with the basic time sequence defined by Cernan, subject to individual differences in which

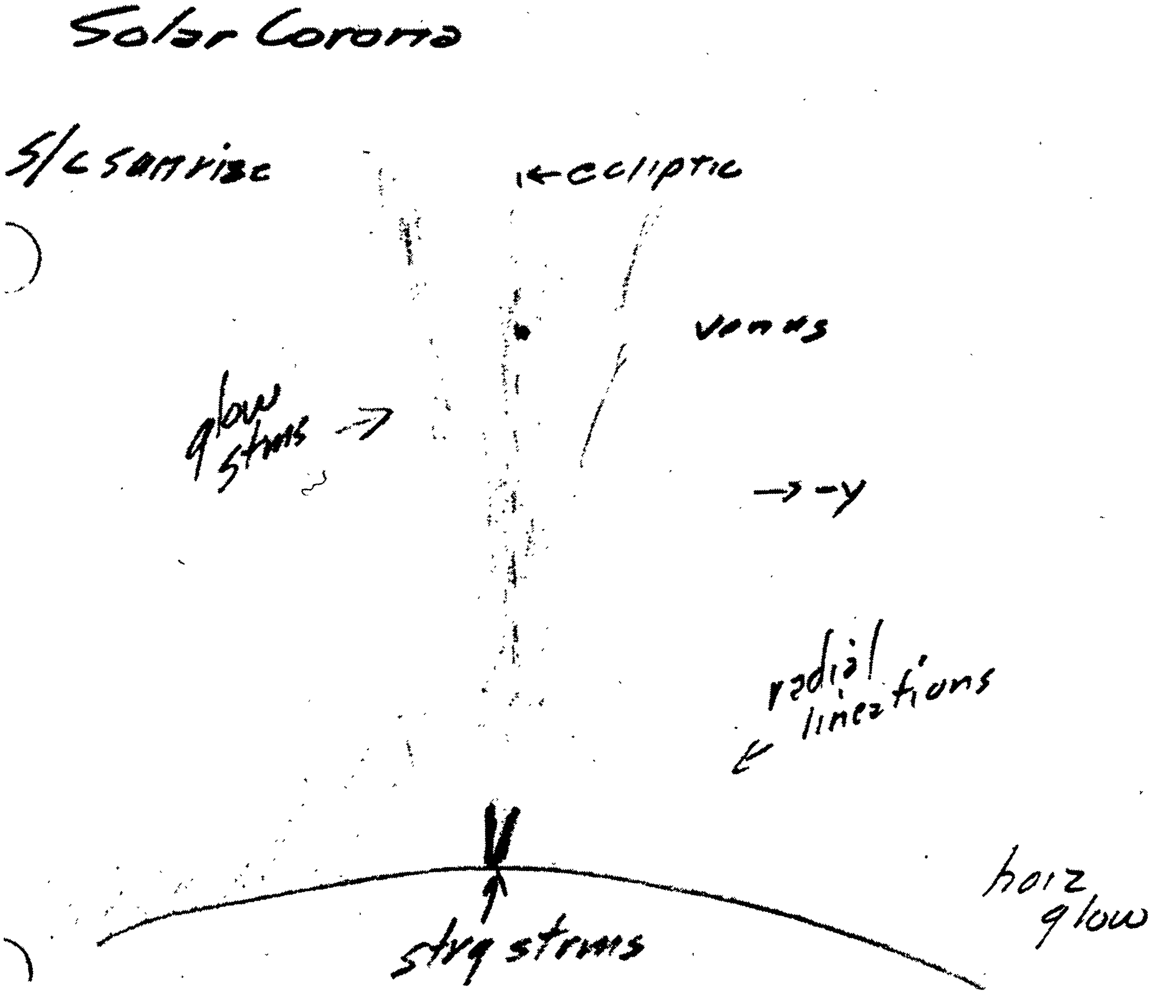


Fig. 4. This is the sketch by H. H. Schmitt (Lunar Module Pilot). It presents a composite of the sunrise features. The presence of the planet (labeled Venus) provides an internal scale by which the approximate angular extent of the streamers can be determined.

details happened to catch the attention of each observer. All agree on the existence of (1) a few long prominent streamers extending beyond 30° from the sun just before sunrise, (2) many radial lineations superimposed on the CZL, and (3) the horizon-glow. Cernan and Evans both agree that the few long prominent streamers developed suddenly in the last few seconds before sunrise, and were not visible along their full length before that time. Schmitt did not state definite agreement or disagreement with this observation. He suggested that any impression of change at this time would be due to confusion by the rapid increase in brightness of the inner corona and "spicules." If Schmitt's suggestion was correct, then the long glow streams which he clearly shows (Fig. 4) extending past Jupiter should have appeared even more prominent in the T-6 min (or T-3 min) sketches by Cernan (Fig. 1). At T-6 min (or T-3 min) Jupiter would be located approximately 5° (or $\simeq 14°$) above the horizon and the glow streamers depicted by Schmitt would be the only elements of his sketch that should be visible above the horizon at that time. They were not depicted by Cernan. Neither were they visible in the vicinity of Jupiter in any of the photo sequences including the polarized sequence exposed December 14 (AS-17-160 photos 23959–25964) which recorded the zodiacal light to and beyond the elongation of Jupiter. We, therefore, conclude that the temporal change did occur, but was not specifically noted by Schmitt. All three astronauts commented that the longest streamers could be traced along their full length from horizon to beyond 30°. All seem to agree that the longest streamers were narrow and well defined. The exact number present is not clear. Cernan shows five, but says it might have been more or less. Schmitt shows three out by Jupiter, but only two at the horizon. The rapid brightening seems to have allowed time to follow one or two streamers along their full length with the eye, but not enough time to count them.

Cernan and Evans agree that the many subtle radial lineations (streamers) observed superimposed on the CZL a minute or two before sunrise were not originally visible when the CZL first appeared. Cernan believes he was well dark adapted at all times. This judgment on his part reflected direct experience from having watched many orbital sunrises, and especially sunsets where dark adaption was a factor. Evans guessed that failure to detect lineations in the early CZL might have been due to a delay in dark adaption; however, this supposition does not adequately account for the observations.

Cernan was sufficiently well dark adapted at T-6 min to see the fainter portions of the CZL beyond 18°, probably to the vicinity of Jupiter nearly 25° from the sun, but could not see any radial structure until T-2. Schmitt's sketch indicates he could not see the CZL or radial lineations as a continuous background more than half-way out to Jupiter. Since he could see the radial lineations and long streamers, then they would have been visible to Cernan's relatively greater faint light sensitivity at T-6 had they been present at that time. We, therefore, conclude that the apparent slow change in intensity of the radial lineations (subtle linear streamers) was real and not an effect of delayed dark adaptation. Alternatively, this argument would conclude that the apparent CZL at T-6 did not rise with the star background. This alternative would reopen the question of dark adaptation but would directly establish our conclusion that there is a locally scattered component in the observed light.

This paper focuses on the streamers. The presence of horizon-glow (indicated by all three crew members) and the possible brightening of the CZL prior to sunrise are potentially significant in an investigation of light scattering processes near the moon. However, the horizon-glow and CZL observations cannot be subjected to the direct analysis possible with the streamers.

OTHER OBSERVATIONS

Review of the mission reports and conversations with some of the crew members from previous flights indicates that this phenomena may have been observed on several, but not all, of the previous missions. The crew of Apollo 8 reported, "The solar corona was observed once through the scanning telescope just before spacecraft sunrise. It appeared as a very bright glow just above the sunrise point at the horizon with dimmer streamers fanning out above and away from this point" (Anders *et al.*, 1968).

Stafford *et al.* (1971) also reported observations of both orbital sunrise and sunset several times during Apollo 10. They stated, "Eye adaptation restricted the viewing immediately following spacecraft sunset; otherwise, the observations were symmetrical. The corona had visible ray structures during the 4 to 6 minute period before sunrise or after sunset." Cernan (private communication) stated that his Apollo 17 observations were also typical of what he saw on Apollo 10. Note that a somewhat different time scale is implied by the Apollo 10 observations for appearance of the visible ray structures, as compared to those during Apollo 17; also note that dark adaptation was a factor only immediately following sunset.

Visual observations of the solar corona/zodiacal light were not recorded during Apollos 11, 12, and 14. Worden and Scott (private communication, 31 January 1974) indicated they saw a couple of streamers along the ecliptic, but could not recall any details concerning size or possible time development (Apollo 15).

T. K. Mattingly (Command Module Pilot, Apollo 16) was aware of the previous sightings of streamers and attempted several times to detect them while in lunar orbit. He definitely remembered looking for them because of his considerable personal disappointment in not seeing them (private communication, 24 January 1974). Mattingly did see and photograph the CZL (Mercer *et al.*, 1972; MacQueen *et al.*, 1973a).

ANALYSIS

It was shown in the section "Local versus Solar Origin" that both the 2 min and 5 sec time variations in streamers were inconsistent with brightening of a solar streamer. This was true if the brightening disturbance propagated along the streamer at the velocity of light (3×10^5 km/sec). The argument would be even stronger if propagation velocities observed by Skylab (MacQueen *et al.*, 1974) ($\simeq$200–500 km/sec) in the solar corona were utilized.

Propagation velocities of disturbances in the vicinity of the moon should be equal to or less than the solar wind flow velocity which is the order of 500 km/sec (Hundhausen 1970). A 5 sec brightening would imply a 1500 km source length about the moon, while a 2 min brightening would imply a 60,000 km length. In either case, these lengths are well within the earth–moon vicinity. In fact, combining the above limits on size and location of such disturbances with their precise correlation with the time of exiting from the lunar shadow (orbital sunrise), it is clear that these streamers must be produced by some process operating in the immediate lunar vicinity. Most likely, their changes are due to a relative viewing angle effect rather than the propagation of any actual physical change.

Figure 2 was presented to provide a model consistent with the visual observations. During the final 5 sec of rapid change in streamer intensity, the Apollo spacecraft is approaching the lunar shadow boundary surface at an angle

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of approximately 20°. Since this surface will be irregular due to surface irregularities at the lunar terminator, a rayed effect qualitatively similar to that often observed from the ground during terrestrial sunsets would be expected to become increasingly evident upon close approach. The streamers would be superimposed upon an overall diffuse glow from scattering by more distant dust particles in the fully illuminated region above the terminator. Present data are insufficient to determine whether the observed scattering occurs near the shadow interface, over the terminator, or both. Some actual physical variation in dust concentration, rather than irregularities in the horizon shadow, might be responsible for the streamer effect. However, any such source must necessarily extend to altitudes greater than the Apollo orbit (120 km) because of the greater than 30° extent of the streamers above the local horizon. Any point along a line of sight directed 20° or more above the horizon would be at an altitude higher than the observer.

Light scattering from a cloud of contaminants (Hoffman *et al.*, 1972) co-orbiting with the Apollo spacecraft would not account for the observations. Although such a cloud would indeed brighten suddenly as it entered the lighted region just ahead of the Apollo, it would first catch the sunlight at a point above rather than in front of the spacecraft. This can be easily visualized by referring to the T-1 min position in Fig. 2 and imaging a small spherical contamination cloud about that point. The observed brightening would, therefore, be mostly overhead, progressing toward the horizon rather than vice versa as observed.

A more thoroughly dispersed contamination of the entire orbital region would be impossible to distinguish from particles arriving in the area via natural means. As will be shown in the next section (Table 1), very minute total masses of submicron particulates are adequate to produce the observed effects. This total mass of particulates could be produced during rocket firings or water dumps. However, the absence of streamers on the Apollo 16 mission, which presumably produced the same order of magnitude of contaminants as the other flights, argues that the Apollo itself is not a sufficient source.

The negative result from Apollo 16 is also very significant in that it requires the population of these particles, whatever their source, to be variable in nature. Though apparently a common occurrence, there are times when the scattering as seen by Apollo 17 is not present. The circumlunar distribution of the light scattering particulates must vary significantly in concentration over periods of less than six months.

BRIGHTNESS AND COLUMN DENSITY ESTIMATES

Estimates of the column density [N_c (grains/cm^2)] of the light scattering particulates can be made along a line of sight at angle θ with respect to the sun, if the scattered brightness $B(\theta)$ is known. This is rather tricky for visual observations of brightness. The best calibration available is via comparison with some similar reference object which is observed simultaneously. Assuming the solid glow region observed was the true "mean" CZL as observed from earth, it can be used to provide the necessary reference for estimating the brightness of the superimposed subtle streamers at T-1 min. The streamers were described as subtle in contrast to the background CZL from $\theta = 3°$ to $20°$. Therefore, we estimate their intensity to be a small and nearly constant fraction of the background CZL. An estimate of $0.1\, B_{\mathrm{CZL}}$ should be good within a factor of 3 or 4. The most probable error would be an underestimate, if the solid glow in fact included a substantial contribution from the diffuse glow region (Fig. 2) over the terminator in addition to the CZL.

Using the values adopted by Bohlin (1971) from Blackwell *et al.* (1967) for B_{CZL}, we estimate the values of $B(\theta)$ listed in Table 1. We also list the zenith brightness ($\theta = 90°$) observed from the lunar surface by Lunokhod 2 for comparison (Severny *et al.*, 1973). This observation was made along a vertical column illuminated above an altitude of approximately $\frac{1}{2}$ km. Lunokhod 2 was located just behind the lunar dusk terminator. These observations were made approximately two months after Apollo 17 and on the other side of the moon (note: Apollo orbital "sunrise" was always located over the sunset terminator).

For simplicity, we assume that the particles are all of one size, with radius a, scattering incident light of wavelength $\lambda \approx 5000$ Å. Following Van de Hulst (1957) we have

$$N_c = \langle Nd \rangle = \frac{B(\theta)}{F(a, \theta)\pi a^2 E} \tag{1}$$

where E = solar illumination (13.7 lm/cm^2), $F(a, \theta)$ is the scattering efficiency of an individual particle, and θ is the solar elongation angle.

For particles with $a \geqslant .5\ \mu$, we assume nonconducting spheres and use Fraunhofer diffraction

$$f(a, \theta) = \frac{x^2}{\pi} \left| \frac{J_1(x \sin \theta)}{x \sin \theta} \right|^2 \qquad \text{where } x = \frac{2\pi a}{\lambda} \tag{2}$$

and

$$f(a, \theta) \approx \frac{1}{\pi^2 x \sin^3 \theta} \qquad \text{for } x \sin \theta \geqslant 1 \tag{3}$$

Table 1.

		$\langle Nd \rangle = B(\theta)/E\pi a^2 f(\theta)$ particles/cm^2					
θ	$B(\theta)$ cd/cm^2	$a = 0.01\ \mu$	$a = 0.1\ \mu$	$a = 0.5\ \mu$	$a = 1\ \mu$	$a = 5\ \mu$	$a = 10\ \mu$
3°	3×10^{-6}	2×10^{10}	2×10^4	9.0	.7	.02*	.01*
10°	2×10^{-7}	2×10^9	2×10^3	0.6	.1	.06*	.03*
20°	4×10^{-8}	4×10^8	400	0.4	.5*	.09*	.04*
from lunar surface							
90°	8×10^{-7}	10^{10} (column mass = 10^{-7} g/cm^2)	2×10^4 (column mass = 2×10^{-10} g/cm^2)	400* (column mass = 6×10^{-10} g/cm^2)	200* (mass = 2×10^{-9} g/cm^2)	36* (mass = 6×10^{-9} g/cm^2)	19* (mass = 2×10^{-8} g/cm^2)

*uses (Eq. 3).

For particles with $a < 0.5\ \mu$, we assume Rayleigh–Gans scattering

$$f(a, \theta) = 0.006x^4(1 + \cos^2\theta)|G(u)|^2 \tag{4}$$

where $G(u)$ is a function ($u = 2x\sin\frac{1}{2}\theta$) qualitatively similar to $J_1(u)/u$. Tabulated values may be found in van de Hulst (1957).

Light scattering by small particles is particularly sensitive to optical properties, particle shape and orientation. Exact solutions require elaborate calculations using exact values for particle optical properties and shape. Lacking such detailed knowledge, and realizing the theoretical problems of predicting the properties, extensive computer simulations are not utilized here. The formulae we have used are commonly made approximations most applicable to nonconducting (dielectrical) grains. They give a reasonably good estimate of the behavior and number densities to be expected of very simple distributions of the idealized type of particles normally assumed for such calculations. If the actual particulates are conducting, have strong optical resonances, or unusual shapes (such as needles or snowflakes), their scattering properties may be very different.

Calculated values of $\langle Nd\rangle$ are shown in Table 1 for particles ranging in size from 0.01 to 10 μ. We conclude that particles larger than 5–10 μ can be ruled out on the basis of the Apollo window micrometeoroid results, which place an upper limit on the number densities which is lower than in Table 1 (Cour-Palais, 1974).

Examination of the values calculated from column density shows that the vertical column mass required to be suspended is a minimum for 0.1 μ particles. For larger particles, the large angular dependence of scattering efficiency limits the increase of large angle scattering efficiency to a net a^{-1} dependence; therefore, column mass required to account for Lunokhod (and higher angle Apollo) observations increases as a^2. For particles smaller than .1 μ, angular dependence becomes small ($G(u) \approx$ constant), scattering efficiency falls off as the sixth power of a, and total mass of scatterers in any column increases as a^{-3}. This effect would seem to rule out any significant contribution by particles much smaller than 0.1 μ.

Furthermore, upon examination of the relative number of scatterers (a) looking from orbit at $\theta = 20°$ (therefore viewing only particles at altitudes above the Apollo orbit), (b) looking from orbit at $\theta = 3°$ (therefore viewing particles at altitudes down to 10 km), (c) looking vertically from the surface (therefore viewing particles at altitudes down to $\frac{1}{2}$ km), we could expect an increasing number density of particles with decreasing altitude viewed. This consideration favors a model composed mostly of 0.1–0.5 μ particles.

A model could be constructed to account for the estimated brightness observed by using 0.1 μ particles with number densities versus altitude of 10^{-1} cm^{-3} at 1 km, 10^{-2} cm^{-3} at 10 km, and 10^{-5} to 10^{-6} cm^{-3} at 100–200 km. The model seems to work best if an enhanced number density of particulates the order of 10^{-3} cm^{-3} is present along the shadow/sunlight interface. These appear to be in excess of the concentrations predicted by available analyses for meteoritic secondaries above the lunar surface (Gault *et al.*, 1963) in view of recent downward revisions of the estimated primary micrometeorite flux (Hartung *et al.*, 1972).

The model results do not depend upon whether the particles are assumed to be on suborbital ballistic trajectories, in closed lunar orbits (or otherwise suspended indefinitely above the surface), or on escape trajectories (either ballistic or even possibly swept by solar wind interactions or radiation pressure), or for that matter whether or not they are actually of lunar origin. However, if the particles are of lunar origin, the resulting mass transport and lunar removal rates do depend on the type of trajectory the particles follow. Using an estimated vertical column mass of 2×10^{-10} g/cm^2, we calculate a maximum mass churning rate for the case where all particles are on suborbital ballistic trajectories (70 sec time of flight) of about 3×10^{-12} g/cm^2-sec. To the extent that the particles are suspended or in closed orbits and escape trajectories, the mass churning rate would be reduced. Particles in closed orbits would contribute to neither churning nor removal. However, 0.1 μ particles could experience rapid removal due to radiation pressure. Particles which are in escape trajectories will not contribute to mass churning but instead will produce a net removal of material from the moon at the rate $N_c(90°)m/T$ (g/cm^2-sec), where T is the mean dwell time during escape $N_c(90°)m$ the vertical column mass, and m is the particle mass. As an example, if the 0.1 μ particles in the sample model previously calculated are removed with 1% efficiency (from the column otherwise undergoing simple ballistic churning) by some mechanism such as photoelectric charging and resulting sweeping by the solar wind, the results would be the net removal of 2×10^{-13} g/cm^2-sec (assuming $T = 1000$ sec). These estimates for churning and net removal are upper limits and could actually be anything from zero up to these limits. Computation of possible long term (month, year, etc.) cumulative churning and/or transport is inappropriate at this time. Information on the spacial extent of possible lunar source regions is not available and the temporal behavior is unknown.

Conclusion

A plausible case has been made that there must be a concentration of particulates near the moon which scatter sufficient sunlight to be visible to astronauts in lunar orbit. Preliminary calculations indicate the scattering is from particles which should reasonably be expected to be in the submicron ($\simeq 0.1\ \mu$) rather than tens of micron size range. Scattering by free electrons or the tenuous lunar atmosphere should not produce a visually observable flux of light. The particulate distribution is apparently variable over a scale of less than six months and is apparently not related to spacecraft contamination about the orbit. While it does seem reasonable that the particulates are of lunar origin due to their proximity to the moon, the streamer observations do not, in themselves, provide conclusive evidence of lunar origin. Neither do the observations indicate the source mechanism for the particles. However, simple calculations of probable number densities and resulting potential mass transport and removal rates do provide *compelling* motivations for quantitatively studying light scattering phenomena in circumlunar space.

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