DATA ANALYSIS AND INTERPRETATION OF LUNAR DUST EXOSPHERE

Final Report

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ABSTRACT

The lunar horizon glow observed by Apollo astronauts and recorded during the Surveyor missions is believed to result from the scattering of sunlight off lunar fines suspended in a dust layer above the lunar surface. For scale heights of tens of kilometers, theory and astronaut's observations suggest that the size of the dust particles will be smaller than 0.1 microns in radius and will act as Rayleigh scatters. This means that the dust scattered light will be 100% polarized at a 90 degree scattering angle and will depend on wavelength to the inverse fourth power ("bluing"). Believing these signatures to be observable from ground based telescopes, observational data in the form of CCD images has been collected from McDonald Observatory's 36" telescope and the reduction and analysis of this data is the focus of the present report.

INTRODUCTION

Evidence for electrically charged lunar fines above the moon's surface was recorded by the LEAM experiments conducted on the Moon [Berg et al., 1976]. In these experiments, charged particles were detected by three detectors with peak activity occurring with the passage of the daylight/dark terminator. In addition, Surveyor photographs taken at sunset [Rennilson and Criswell, 1974] and the Lunokhod-2 detection of "lunar twilight" brightness [Severny at el., 1974], as well as observations sketched and reported by astronauts just before sunrise, provide powerful evidence for the existence of light-scattering dust particles in the vicinity of the terminator.

If the scattering particles have a size that is smaller than about one sixth of the incident wavelength, the intensity of the scattered light depends on wavelength to the inverse fourth power and is classified as Rayleigh scattering. Hence, shorter wavelength (blue) light will be preferentially scattered. In addition, this light will be nearly 100% polarized when the moon is near first and third quarter with the degree of polarization decreasing with an increase or decrease of the moon's phase. This decrease in polarization is expected since an increase in phase corresponds to a decrease in the scattering angle between the incident and reflected rays.

In this report, we summarize the results and analysis of observations taken at various wavelengths of light at four different lunar sites using the 36 inch reflecting telescope at the McDonald observatory.

REDUCTION & ANALYSIS

The Signal

Light arriving at the telescope from the moon's surface is expected to consist of four components: 1) sunlight scattered directly off the surface, 2) "earthshine" back-scattered off the moon's surface, 3) luminescence from the lunar soil and 4) light scattered from dust above the lunar surface. While the magnitude of the luminescent light can be substantial [Kopal 1966], its occurrence is transient in nature and tends to be confined both in locality and to emission of photons possessing longer wavelengths; hence, in our hunt for dust, we can reasonably ignore this source.

From the before-mentioned probes and observations, the dust particles causing lunar horizon glow (LHG) would be expected to have a maximum contrast with background sources of light up to a few tens of kilometers from the terminator in the anti-sun (dark side) direction. Thus, within this region, scattered sunlight from the bright moon will be held to a minimum; however, there will be some light from the bright moon scattered from the earth's atmosphere into the telescope, but this light will be approximately the color of scattered moonlight and should reflect lunar polarization effects for each wavelength.

The percent polarization of the signal is defined as

$$P(\%) = 100 (I_{\perp} - I_{\parallel} / I_{\perp} + I_{\parallel})$$

where $I_{\perp}$ is the intensity of the light measured with the polarizer perpendicular to the scattering plane (defined as the plane containing the incident sun ray and the reflected moon ray) and $I_{\parallel}$ is the intensity of the light measured with the polarizer oriented parallel to the scattering plane. Dollfus [Dollfus 1970] has established that the polarization of red light reflected from the bright moon is on average one half that of blue light. Hence, in the vicinity of the terminator, any relative increase in the intensity and polarization of blue light compared to longer wavelengths *greater* than that which has been observed on the bright moon can be taken as indicative of the existence of submicron dust. It is interesting to note that in 1860 Secchi [Secchi 1859], observed a "small difference" in polarization between "the illuminated edge and the area which is adjacent to the edge of the shadow." In addition, Lyot [Lyot 1929] reported that "near the terminator, the polarization goes through a significant increase...." While both of these references refer to the bright side of the terminator, it is not at all improbable that high altitude dust may be the cause of these observed increases in polarization!

Estimates of the brightness of the "bluing" were produced by Herbert Zook on the bases the brightness of the LHG reported by the astronauts (Zook and McCoy, 1991, and private communication). In this report only polarization effects will be discussed since time does not permit the inclusion of estimates of the absolute brightness derivable from the data. The absolute brightness of the signal can be calculated from calibration frames taken of the star β Virgo 4550.

The data frames were corrected to remove spurious signals arising from the CCD bias and pixel to pixel variations. The CCD bias noise was removed to first order by subtracting the "overscan" section of the chip. Any residual noise was further removed by averaging several "zero" frames (images taken with zero exposure time) and subtracting this average from the data. The pixel to pixel variation was eliminated by "flatfielding" each frame with the appropriate flatfield image created by the "dome flat" method familiar to astronomers. Each wavelength and polarization angle has an associated flatfield image.

RESULTS

Figure 1 reveals an image of the moon indicating the location of the four sites that were analyzed. The locations and selenographic coordinates of the sites are as follows: site 1, 15° north latitude and 5° east longitude in Mare Vaporum; site 2, 35° north latitude and

Figure 1.- Location of four sites studied; 1) Mare Vaporum, 2) Mare Imbrium/Caucasus mountains, 3) Mare Imbrium and 4) Oceanus Procellarum.

8° east longitude at the edge of Mare Inbrium and the lower end of the Caucasus mountains; site 3, 23° north latitude and 30° west longitude in Mare Inbrium; site 4, 18° north latitude and 42° west longitude in Oceanus Procellarum.

Site 1.
Figure 2 shows an image of the Moon's surface located in Mare Vaporum. In this image, the terminator is clearly seen with a bright peak reflecting sun light in the upper left hand corner of the frame within the dark side of the terminator. Due to reflective optics in the telescope, this image is actually reversed top-to-bottom so that on the moon, the peak is located in the lower right hand corner. The distances spanned by the image is approximately equal to 279km normal to the terminator and 383km parallel to the terminator. The actual "raw" data spanned distances of 415km in both the parallel and perpendicular directions, but due to edge effects and numerical interpolation associated with the registering of the perpendicular frame with the parallel frame, the data was "trimmed". The letters "A" and "B" will be discussed below.

Examination of the bright side of the terminator revels topographical surface structure at the extreme upper and lower edges of the image. The highland mountains are thousands of meters high and scatter light so as to inhibit illumination of any dust among or behind them. The center portion of the image, however, represents a smooth mare region in Mare Vaporum. It is hypothesized that it is in these relatively smooth low lying areas that dust, existing tens of kilometers into the exosphere, will be detected.

Figures 3-a and 3-b represent horizontal, or east-west polarizations sections (slices) of the image of Mare Vaporum found in figure 2. These are plots of percentage of polarization as a function of distance. The units of distance are in number of pixels (1 pixel = 3.24km). Three different wavelengths are plotted on each graph with the wavelengths indicated on the plot. The multiplicative factors operating on the wavelengths seen in the key represent scale factors required to "normalize" the longer (redder) wavelengths to the shortest blue wavelength. The reason for these scale factors is to look for ***blue enhanced relative*** polarization in the area just past the terminator. Finally, each line represents an average of eleven lines taken east-west across the terminator with the approximate position of the terminator and the direction of the sun explicitly marked in each plot.

Figure 3-a depicts lines taken across the terminator at position "A" marked in figure 2. This position apparently represents the most mountain free east-west slice across the image. In figure 3-a, it is evident that the polarization of the 404nm light exhibits a marked enhancement just past the terminator as compared to the 486nm and 656nm light! While the 486nm light shows a slight enhancement over the 656nm, the enhancement is much

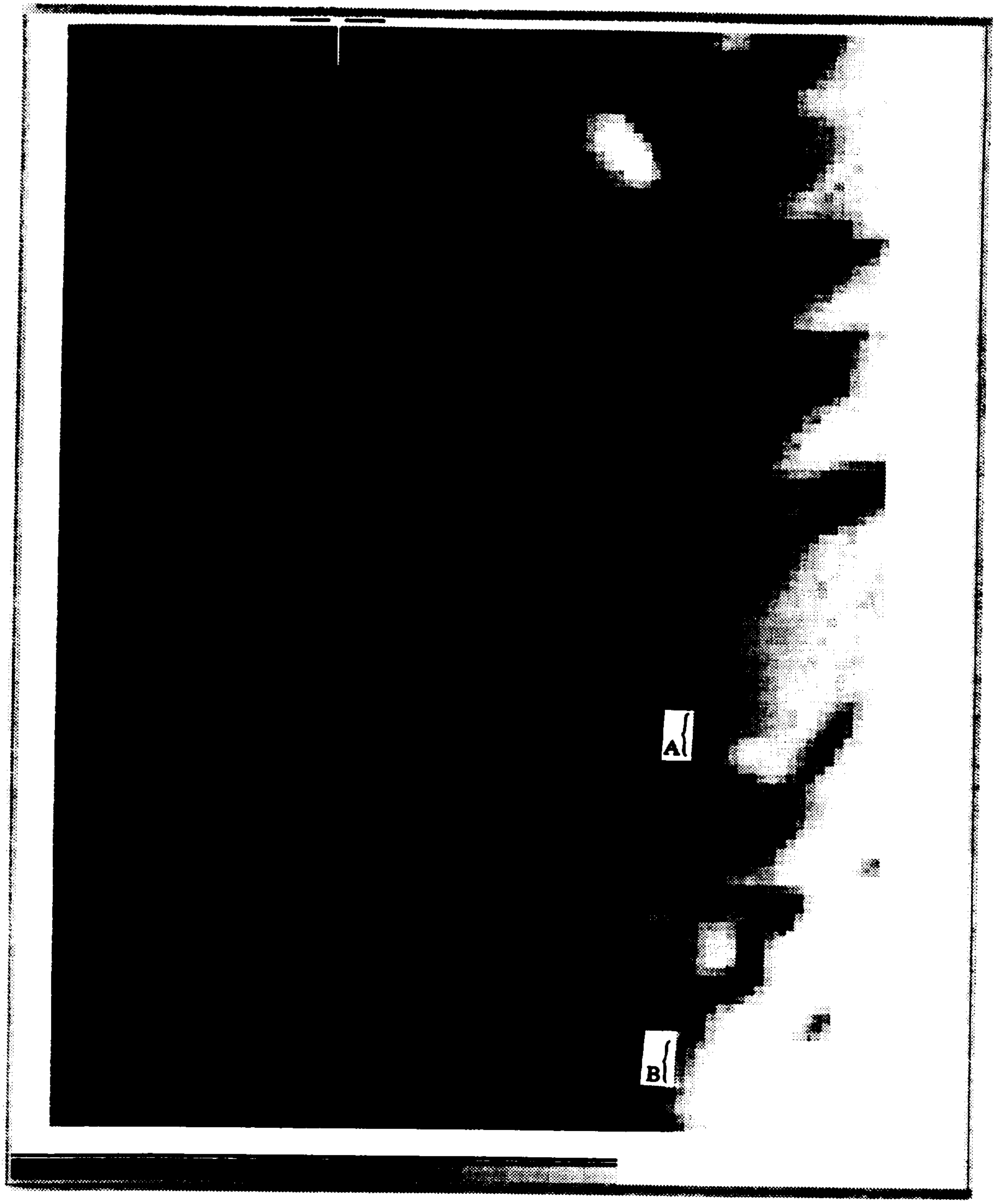
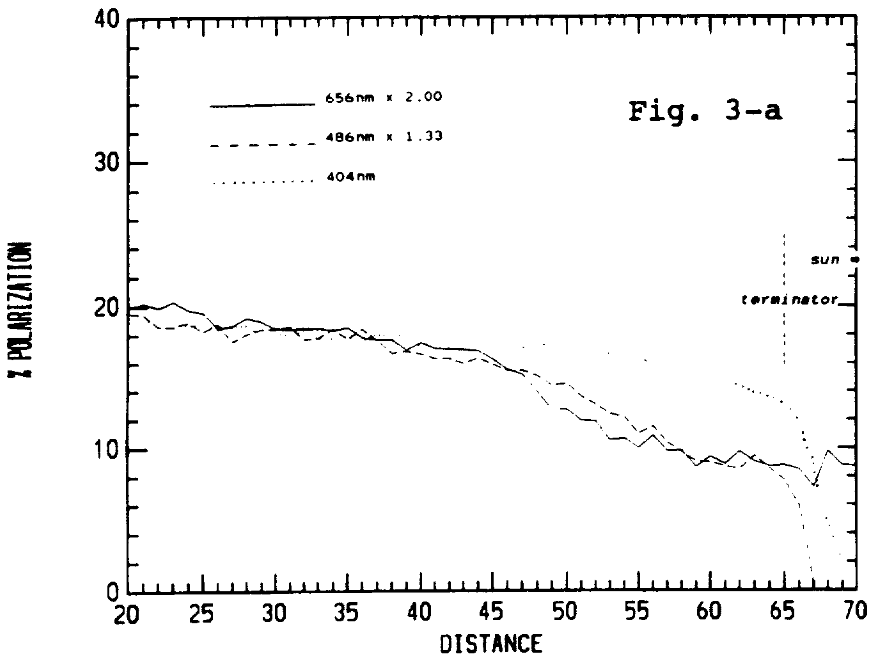


Figure 2.- Mare Vaporum; 15 degrees north latitude and 5 degrees east longitude.



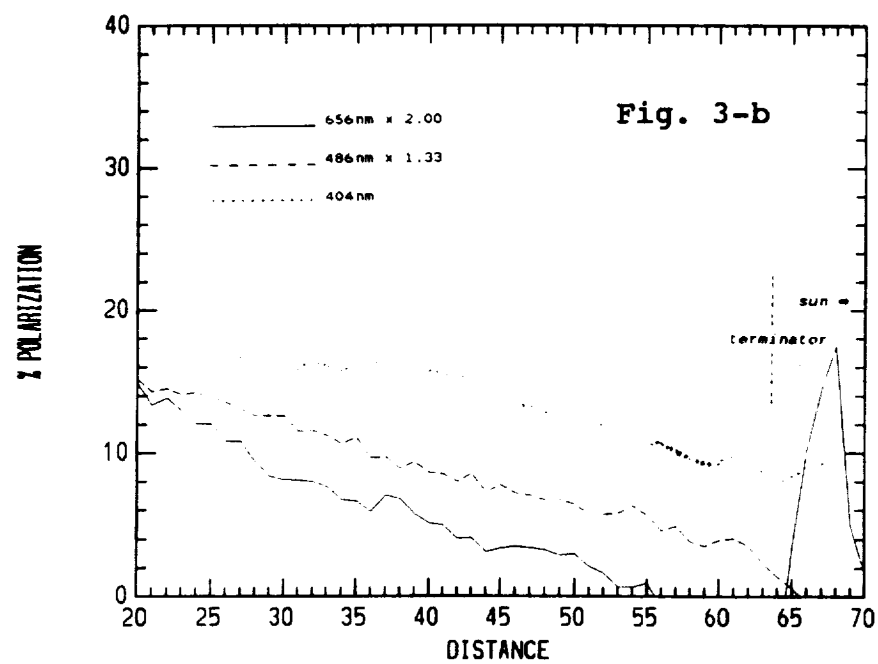


Figure 3.- a) Polarization curves for Mare Vaporum site; 3-a corresponds to the region marked with the letter "A" in figure 2 and 3-b corresponds to the region marked "B".

less than the 404nm light over the 486. Since submicron dust would favor the bluer light in a highly nonlinear way ("inverse lambda to the forth"), this "nonlinear" relationship between subsequent ratios of wavelengths can only be understood in terms of Rayleigh scattered light! It should be noted that further quantitative work on the functional relationship between the intensity and wavelength will be completed at a later date.

Figure 3-b depicts lines taken across the terminator at position "B" marked in figure 2 which is behind the highlands. In this figure, the polarization enhancement of the blue to the red is still seen but is not as strong and a "spreading" of the curves is also evident. This spreading and decrease in enhancement may be interpreted as being caused by decreased sun light due to the shadows of the highlands.

Site 2.

Figure 4 shows an image of the Moon's surface located on the eastern edge of Mare Imbrium with the tip of the Caucasus Mountains visible in the lower right hand corner. This image was taken during the same night as the Mare Vaporum site 1 above, so the light scattering angle is approximately the same.

Polarization plots are shown in figures 5-a and 5-b where figure 5-a represents the area marked "A" in figure 4 and figure 5-b depicts the area marked "B". The average polarization of the 404nm light shows an increase by about 10% compared to the average polarization of the Mare Vaporum plots. While this is probably due to differences in the geological and topographical make up of the lunar terrain [see Gehrels 1964], artifacts of the data processing can not yet be ruled out. Further work is needed to determine the cause and will be done at a future date. In figure 5-a, the enhanced polarization of the 404nm light over the longer wavelengths is evident whereas in figure 5-b it is not. Again, the pattern of increased polarization within topographically smooth areas as compared to mountainous regions is observed.

Site 3.

Site three involves an area of the Moon's surface located on the south-western edge of Mare Imbrium. This site was imaged three nights later so the phase of the moon (hence the scattering angle) has decreased. At this site most of the Mare is topographically smooth. It is thus expected that the enhanced blue polarization phenomenon should reveal itself all along the dark side of the terminator. This is indeed the case as figures 6-a and 6-b reveal, where these figures represent the average of eleven lines taken across the terminator at two different locations.

Site 4.

Our last image was taken of Oceanus Procellarum on the final night of observations when

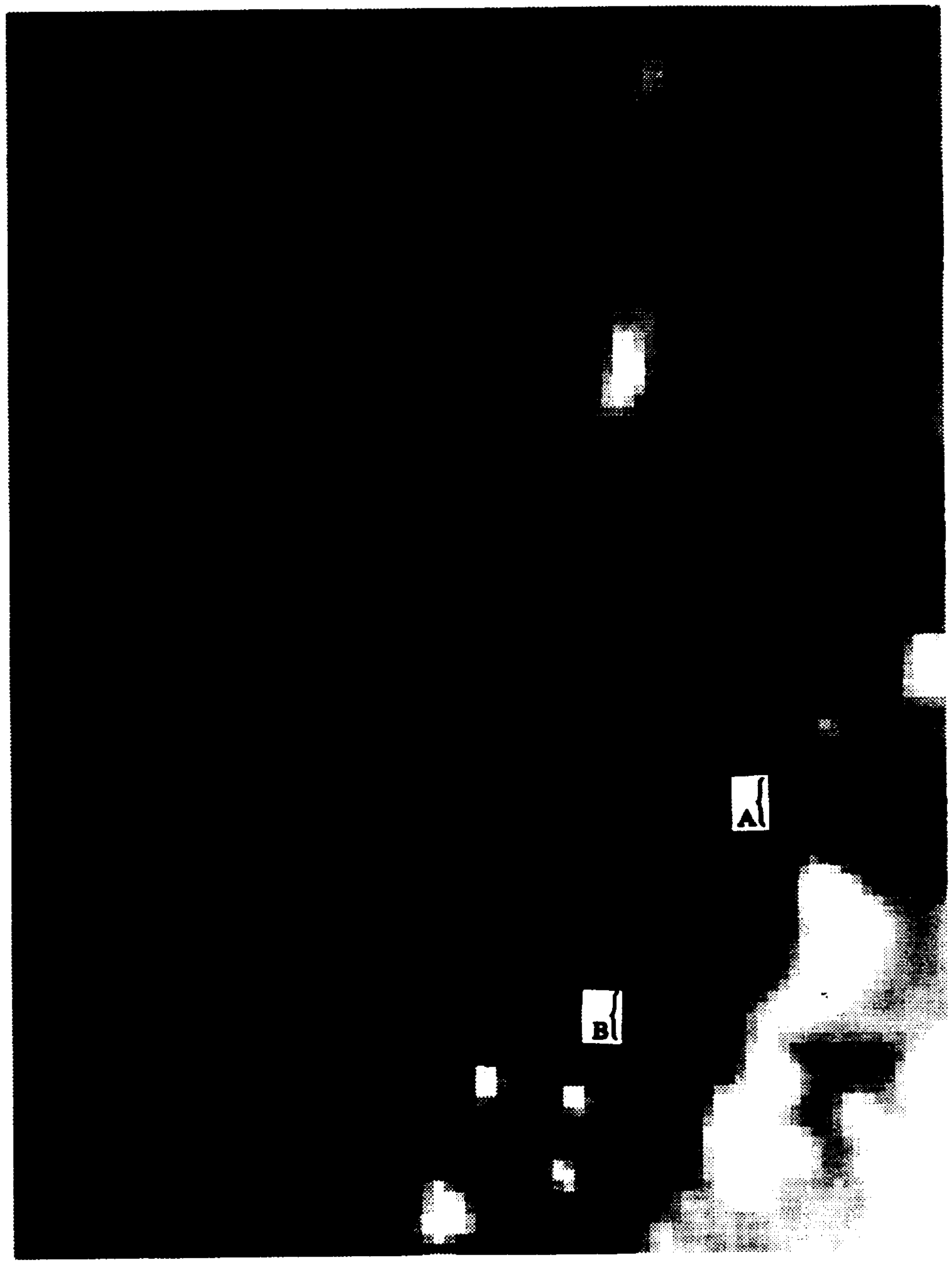
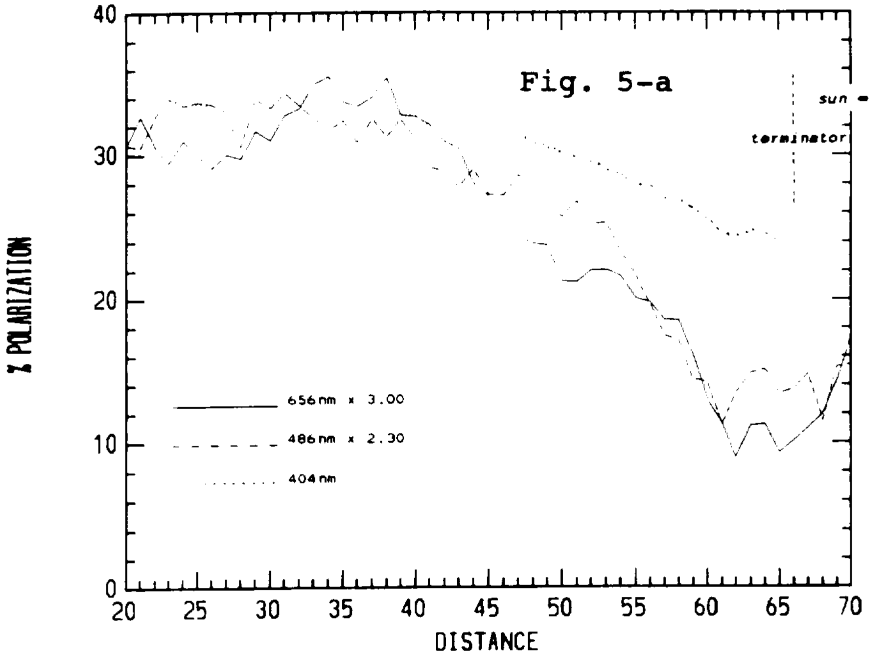


Figure 4.- Mare Imbrium and Caucasus Mountains; 35 degrees north latitude and 8 degrees east longitude.



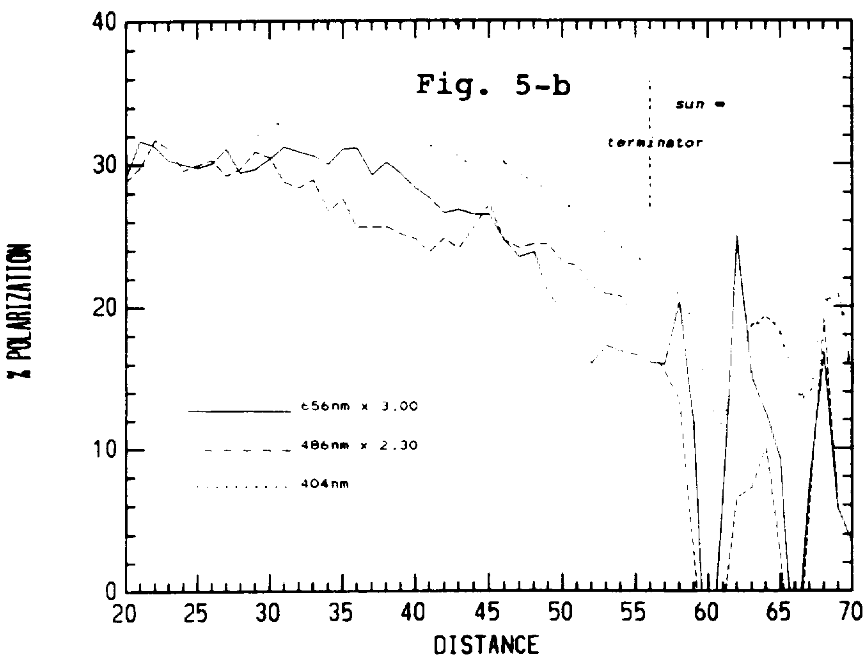
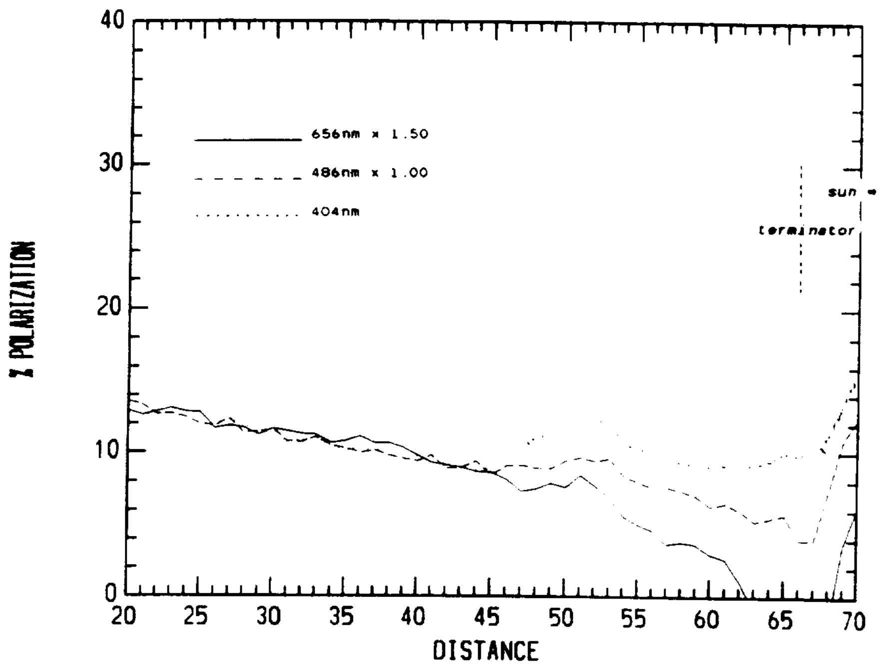


Figure 5.- a) Polarization curves for Mare Imbrium/Caucasus Mtns. site; 5-a corresponds to the region marked with the letter "A" in figure 4 and 5-b corresponds to the region marked "B".



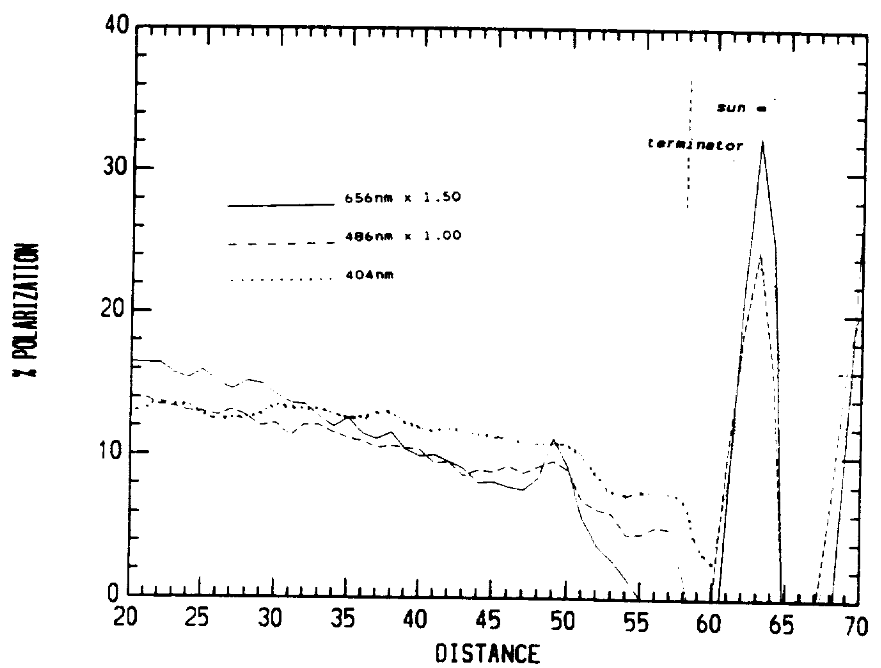


Figure 6.- Polarization curves for Mare Imbrium site.

the phase of the moon decreased further. At this phase angle, the scattering angle is such that polarization due to Rayleigh scattering should be decreased to 0.25. While no quantitative numbers are as yet available, the representative polarization plot found in figure 7 in fact reveals a slight polarization effect but definitely less than the earlier nights.

Conclusion and Summary

This report resents preliminary results of polarization-versus-wavelength analyses of CCD images of four lunar sites looking for evidence of a lunar horizon glow. The polarization trends that would occur due to Rayleigh-scattered light in the region of the dark side of the terminator are, indeed observed. It is our conclusion that very fine submicron dust is being ejected into the lunar exosphere causing sun light to scatter and thereby create the lunar horizon glow phenomenon.

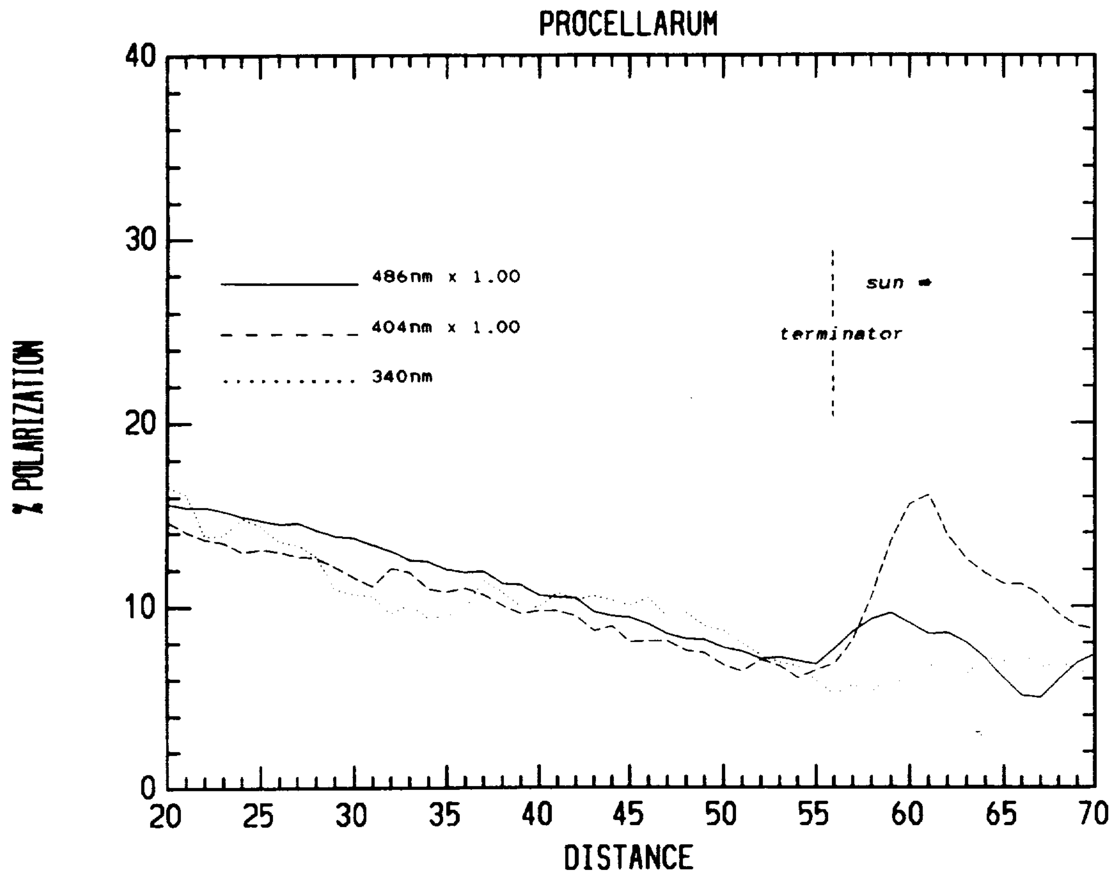


Figure 7.- Polarization curves for Oceanus Procellarum site.

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