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Basic optics, aerosol optics, and the role of scattering for sky radiance ☆

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ABSTRACT

The radiance of the night sky is determined by the available light and the scattering properties of the atmosphere (particles and gases). The scattering phase function of the aerosol has a strong dependence on the scattering angle, and depending on the viewing direction different parts of the atmosphere and the ground reflectivity give the most important contribution. The atmospheric radiance cannot be altered by optical instruments. On the other hand the light flux of a distant star increases with the size of the telescope, thus fainter stars become visible. Light extinction, scattering function, atmospheric radiance, ground reflectivity, color effects and others are discussed in detail and a simple theoretical treatment is given.

1. Introduction

In 1666, a remarkable letter written by Adrian Auzout, (French astronomer, 1622–1691) to Monsieur l'Abbé Charles was published as extract in *Le Iournal des Sçavans* [3]. The immediate reason was Abbé Charles' review of a book entitled *Ravagglio di nuove osservationi* by Giuseppe Campiani which reports new observations with new telescopes, published in the first issue of the journal. Auzout, being an expert, designer, and user of telescopes has some doubts and puts down some points, which will be investigated in the following.

(1) In relation to their size one cannot see further with bigger telescopes, since bigger telescopes increase the size of the images, but not the light. The aperture of bigger telescopes does not increase in relation to their increase in magnification.
(2) The bigger the telescopes, the more they magnify the vapors, the dust and other small things the air is always full of (les vapeurs, la poussiere & les autres petits corps dont l'air est toujour plein), therefore the object looks like seen through a veil.
(3) It will not be possible to see animals on the Moon.

Using today's nomenclature his theses (1) and (2) would read

(1) Bigger telescopes cannot increase the radiance; too small aperture even reduces the observed radiance.
(2) Light scattering by aerosol particles causes an additional radiance, which reduces contrast (the definition of the aerosol as "the vapors, the dust and other small things the air is always full of" is remarkable, and to the present author's opinion the first one).

We will discuss these findings in the following, especially with the aspect of light pollution.

2. Animals on the Moon

Auzout's argumentation about animals on the Moon was done with the knowledge of his time and the knowledge of

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Nomenclature

a	absorption number, $a=1-\varpi$, (Dimensionless), Ratio of absorption coefficient σ_a and extinction coefficient σ_e
A	albedo, (Total flux reflected/Total flux incident), (Dimensionless)
C	contrast, $C=(L_{object}-L_{background}/L_{background})$, (Dimensionless), Relative difference in radiance between object and background
D	d, R, Diameter/radius of aperture, (m)
I	radiant intensity, $I=(d\Phi/d\omega)$, (W sr^{-1}), Light flux emitted by a point source into a small solid angle divided by that angle
L	radiance, $L=(d^2\Phi/dA\ d\omega)$ $L=(d^2\Phi/dA\ \cos\psi\ d\omega)$, (W m^{-2} sr^{-1}), Describes best the perception "brightness" If the direction of flux is not perpendicular to the surface, the projection $dA \cos\psi$ is taken instead of dA
Mag	magnitude, $\Delta Mag=-2.5 \log(S_{star2}/S_{star1})$, (Dimensionless), S_{star1} and S_{star2} are the observed flux densities of two stars, the difference in magnitude of which is determined.
P(θ)	scattering phase function, $P(\theta)=4\pi(\gamma(\theta)/\sigma_s)$, ($sr^{-1}$), Relative volume scattering function, sometimes also used as $P(\theta)=(\gamma(\theta)/\sigma_s)$
S	flux density, irradiance, emittance, $S=(d\Phi/dA)$, (W m^{-2}), Light flux passing through or emitted by a surface divided by that surface. For near parallel radiation the surface usually is assumed to be perpendicular to the direction of radiation.
z	zenith distance, (deg or rad), angle between direction of observation and vertical to earth surface
α	Ångström exponent, $\sigma_{e,s,a}(\lambda) \propto (\lambda/\lambda_0)^{-\alpha}$, (Dimensionless), Simple characterization of wavelength-dependence of σ_e, σ_s, σ_a, the reference wavelength is usually $\lambda_0=1\ \mu m$
$\gamma(\theta)$	volume scattering function, $\gamma(\theta)=(d\Phi/S\ dV\ d\omega)$, ($m^{-1}$ sr^{-1}), $\gamma(\theta)=\varpi\sigma_e(1/4\pi)P(\theta)$
δ	(vertical) optical depth, $\delta=\int_0^H \sigma_e(x)\,dx$, (Dimensionless), In the atmosphere normally used in the vertical direction. The differential is $d\delta=\sigma_e\,dh$
ε	contrast threshold, (Dimensionless), Smallest contrast discernible
θ	scattering angle, (deg or rad), Angle between the direction of the transmitted light and the direction in which the scattered light is observed
λ	wavelength, (m, μm, nm)
μ	$\mu=\cos z$, (Dimensionless), Cosine of zenith distance
σ_a	absorption coefficient, $\sigma_a=\sigma_e-\sigma_s$, ($m^{-1}$), Part of extinction coefficient caused by absorption of light by particles/molecules
σ_e	extinction coefficient, $d\Phi=-\Phi\sigma_e\,dx$ $\sigma_e=\sigma_s+\sigma_a$, ($m^{-1}$), Relative flux reduction per unit length. Integration leads to the attenuation law $\Phi_{out}=\Phi_{in}\exp(-\sigma_e x)=\Phi_{in}\exp(-\delta)$
σ_s	scattering coefficient, $\sigma_s=\sigma_e-\sigma_a$ $\int_{4\pi}\gamma(\theta)\,d\omega=\sigma_s$, ($m^{-1}$), Part of extinction coefficient caused by scattering of light by particles/molecules
Φ	light flux, Radiant power, Power of radiation, (W), Light energy per time passing through or emitted by a (real or fictitious) surface
$d\omega$	solid angle, $d\omega=(dA/x^2)$, (sr), Solid angle under which a surface dA is seen at distance x, dA is perpendicular to direction x, otherwise the projected surface
ϖ	single scattering albedo, $\varpi=(\sigma_s/\sigma_e)=1-(\sigma_a/\sigma_e)$, (Dimensionless), Ratio of light scattering coefficient to extinction coefficient

an experienced astronomer. The idea was in the air, to produce telescopes with a length of 1000 or 10,000 ft, the longer the telescope the higher the magnification. Auzout, using his experience, concludes that the maximum length possible would be 400 ft, and then the Moon looks like seen from a distance of 60 miles, and this makes recognition of animals impossible. Since the Moon is at a distance of 38,400 km, the 400 ft. telescope would have magnification of 4000 × . Today's argument would be different, but in 1666 wave optics was unknown, Huyghens wave theory was published in 1678, Newton's Optiks appeared 1705. Refractive index variations in the atmosphere also were not discussed. Now we know, that wave optics requires a minimum diameter of the first aperture such that the angle of the diffraction limit $(1.22(\lambda/d))$ equals the minimum angular resolution desired. For recognizing the shape of an elephant on the Moon it would be needed to recognize 10 cm at a distance of 384,000 km, thus the minimal angular resolution would be 2.7×10^{-10} rad, requiring an aperture (lens/mirror) diameter of 2500 m. Even if a telescope of this size was used, the refractive index variations would make it impossible to see a detail of 10 cm on the Moon.

3. No radiance increase by telescopes

For a human observer, a film, or a CCD, the number of photons per unit time entering the photoreceptor of the eye, interacting with the AgCl crystal of a film, or hitting the charged capacitor of a CCD pixel, is the important magnitude for the signal. The light flux, being the energy of light per unit time (measured in W) is the analog to the number of photons per unit time.

Let us consider the human eye, having a lens of radius R, focusing the light entering the eye onto the retina which has a distance x from the lens. For simplicity and further considerations we assume the same medium on both sides