Limb Darkening on the Earth's Night Side at Wavelengths of 1–3 μ and 3–7.5 μ

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On 29 October 1965, an Aerobee rocket bearing an infrared-sensing, liquid-nitrogen-cooled astronomical telescope (Harwit *et al.*, 1966b) was launched from White Sands, N. M. The Aerobee attained a peak altitude of 200 km, and all the observations were taken at altitudes well above 65 km. As the rocket rolled and precessed, 24 scans of the sky and of the earth were completed. The astronomical significance of the flight has already been discussed elsewhere (Harwit *et al.*, 1966a). Here we will only discuss the observed limb darkening on the earth's night side.

A great deal of data already exists on the infrared appearance of the earth at relatively long wavelengths (Markov *et al.*, 1963, 1965; Walker *et al.*, 1966). In particular, Hanel and Wark (1961) published a theoretical limb-darkening curve at 6–6.5 μ, and discussed Tiros II observations in the atmospheric window at 8–12 μ. Our observations covered two spectral ranges. A gold doped germanium (Ge: Au) detector covered the range from 3–7.5 μ and an indium arsenide (InAs) detector operated in the 1–3.05 μ region. These latter observations are of prime interest because the earth's nighttime appearance at such short wavelengths has never been discussed.

The gold doped germanium detectors have peak response in the regions around 6 μ with a rapid drop in sensitivity beyond 7 μ. Our long wavelength observations roughly correspond to the Hanel and Wark 6–6.5 μ limb-darkening prediction. However, their curve covers only the strongly absorbing 6.3 μ water band while our observations extend beyond the absorption band. Hence, our observed limb-darkening curve is steeper than Hanel and Wark's theoretical curve, although the two curves agree within our observational

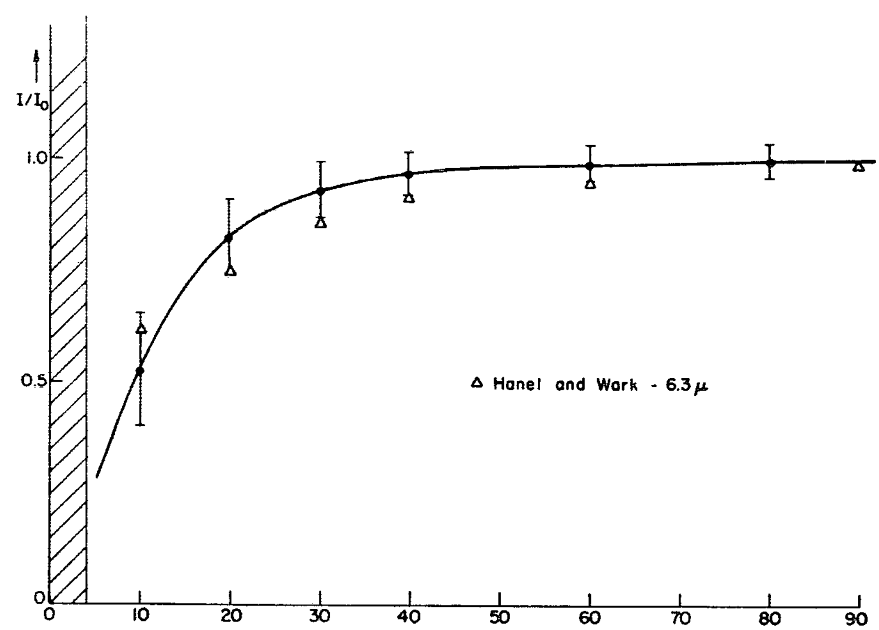

Fig. 1. Limb-darkening curve obtained with a gold doped germanium detector, preceded by a long wavelength pass filter that cuts on at 3 μ. The error bars represent uncertainties in the detector field of view as well as actual intensity differences from one scan to the next. The shaded region on the left side of the plot roughly corresponds to the telescope's field of view. Data gathered by Hanel and Wark on Tiros II are shown for comparison. I_0 represents $I(\alpha=90°)$.

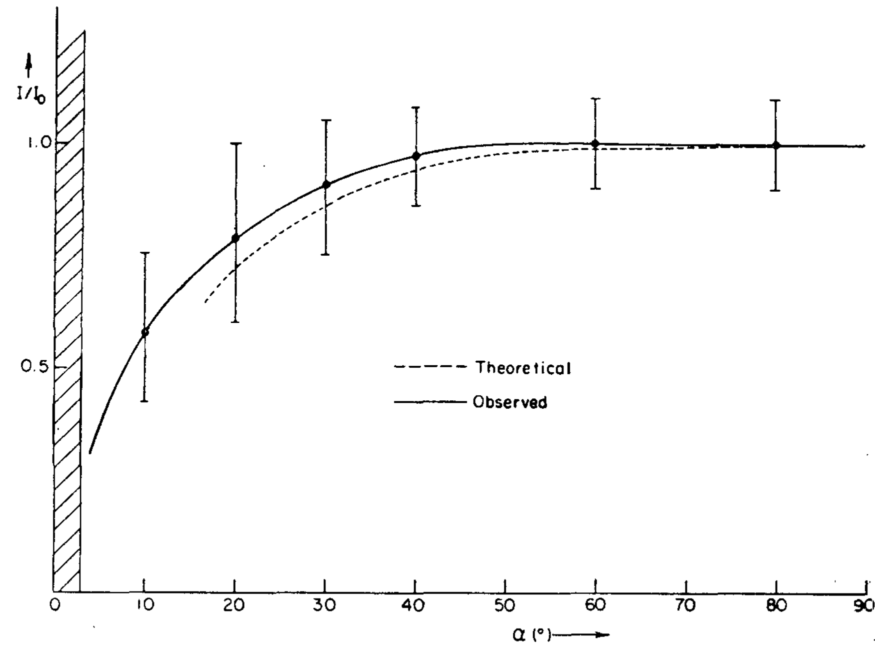

FIG. 2. Limb-darkening curve obtained with an indium arsenide detector, preceded by a long wavelength pass filter that cuts on at 1 μ. The significance of error bars and of the shaded region is the same as in Fig. 1. A theoretical limb-darkening curve based on meteorological data taken at the time of flight is shown for comparison

errors. Fig. 1 shows the data obtained with the Ge: Au detector and a comparison with the calculations of Hanel and Wark. The parameter α against which the relative intensity I/I_0 is plotted represents the elevation angle of the rocket at the point observed and is the complement of the zenith angle of the rocket from the point observed. We have chosen to display the observed intensity as a function of this angle because it should facilitate comparison with measurements that could be obtained in observations of other planets.

The InAs detector was constructed from material that exhibits peak sensitivity at $\sim 2.75\,\mu$. The sensitivity is down by a factor of 2 at wavelengths of 2.2 and 2.9 μ and there is virtually negligible response at 3.05 μ.

Fig. 2 shows the data obtained with the indium arsenide detector. Our plot shows definite limb darkening within 20° of the horizon. The peak signal obtained when the telescope points directly at the nadir corresponds to an effective blackbody temperature of $\sim$237K.

We explain the observed limb darkening on the basis of atmospheric opacity in the 2.7 μ water vapor and CO_2 bands. Virtually all the radiation to which the InAs detector responds is emitted in the 2.6–3.05 μ region. To see this, one need only consider that a 240K blackbody emits ten times more flux between 2.6 and 3.05 μ than in the range below 2.6 μ. To check the validity of the observations, the theoretical limb darkening in the wavelength range 2.6–3.05 μ was calculated numerically. The mean specific intensity $I_\lambda(\alpha)$ o radiation leaving the top of the atmosphere, in a spectral interval $\Delta\lambda$, is given by one form of the radiative transfer integral equation

$$I_\lambda(\alpha)=B_\lambda(T_2)+\int_{T_1}^{T_0}\tau_\lambda(\alpha,T)\frac{\partial B_\lambda(T)}{\partial T}dT,$$

where $B_\lambda(T)$ is the Planck radiance, T the temperature of an atmospheric 'level,' and $\tau_\lambda(\alpha,T)$ the mean transmission (over $\Delta\lambda$) from a level in the atmosphere to the top of the atmosphere. A 16-level atmosphere was adopted, and the top of the atmosphere was taken to be at an altitude of 65 km. At altitudes of 65 km and higher the transmission was $\sim$100% so that the telescope was always receiving radiation from lower layers in the atmosphere. T_2 is the temperature at the top of the atmosphere, and T_0 the temperature below which the transmission τ_λ is zero.

The tables and formulae given by Zachor (1961) were used to calculate the transmission $\tau_\lambda(\alpha,T_i)$ from an atmospheric level i to the top of the atmosphere. Pressure and temperature profiles, obtained by the meteorological support group at White Sands Missile Range (Hoidale, 1965), were extended to altitudes of 65 km by comparison with the standard profile for Albuquerque, N. M. (taken under similar atmospheric conditions), given by Wark *et al.* (1962).

Finally, a theoretical limb darkening curve is given by

$$\frac{I(\alpha)}{I_0(\alpha=90°)}=\frac{\int_{2.6\mu}^{3.05\mu} I_\lambda(\alpha)\phi(\lambda)d\lambda}{\int_{2.6\mu}^{3.05\mu} I_\lambda(\alpha=90°)\phi(\lambda)d\lambda},$$

where $\phi(\lambda)$ represents the wavelength response of the filter and detector combination. This relation is plotted on Fig. 2 for comparison with the observed limb darkening. The agreement is well within observational error. Different estimates of the atmospheric water vapor content will change the theoretical curve slightly. It should be noted that the finite field of view (3°) of the telescope will cause the observed curve to be somewhat less steep than an actual curve obtained at higher resolution. Clouds and geographical variations in surface temperature will affect the limb darkening, and the observational error reflects such variations from scan to scan. Zachor's "winter" approximation was used for the water vapor mixing ratio.

The relative contributions of different atmospheric layers to the total vertical ($\alpha=90°$) radiance may be calculated by

$$\frac{dI}{I}=\frac{\int_0^\infty \phi(\lambda)B(\lambda,T)d\tau_\lambda d\lambda}{\int_0^\infty\int_0^1 \phi(\lambda)B(\lambda,T)d\tau_\lambda d\lambda}.$$

Inspection of the data indicates that the major contribution to the total vertical radiance emanates from two layers close to the tropopause, one at a mean temperature of ~250K and the other at a mean temperature of ~230K. This is in good accord with our measured value of the absolute flux in the vertical direction, corresponding to a blackbody temperature of ~237K.

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