TERRESTRIAL ATMOSPHERIC COMPOSITION FROM STELLAR OCCULTATIONS

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ABSTRACT

Stellar ultraviolet light transmitted through the upper mesosphere and lower thermosphere of the earth's atmosphere is primarily affected by the photoabsorption processes of ozone and molecular oxygen. The stellar ultraviolet photometers aboard the OAO-2 satellite have measured the intensity changes of several stars during occultation of the star by the earth. The measurements of the relative intensity change in certain atmospheric absorption bands are used to recover the vertical number density profiles of the absorbing species. Using the OAO-2 occultation data, we have obtained the vertical number density profiles of molecular oxygen in the 100-200 km altitude region and ozone in the 60-100 km altitude region.

I. INTRODUCTION

In the earth's upper atmosphere, stellar ultraviolet light is strongly absorbed in the Schumann-Runge continuum of molecular oxygen and the Hartley continuum of ozone. By monitoring

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the intensity of ultraviolet starlight in these continuum regions, as the star is occulted by the earth (Fig. 1), we are able to obtain information on the number density distribution of molecular oxygen in the lower thermosphere and ozone in the upper mesosphere (Hays and Roble 1968a,b). In this paper, we describe the technique used to obtain the number density distributions from stellar occultation measurements. The data were obtained by the Wisconsin Stellar photometers aboard the Orbiting Astronomical Observatory (OAO-2) satellite.

We discuss the inversion process and also show the molecular oxygen and ozone distributions determined from a typical occultation scan.

II. OCCULTATION TECHNIQUE

The occultation technique utilizes the principles of classical absorption spectroscopy to determine the number density distribution of the absorbing species in the upper atmosphere. This is illustrated in Figure 1, where the star is a source of ultraviolet light and the OAO stellar photometers are the detectors with the atmosphere between acting as the absorption cell.

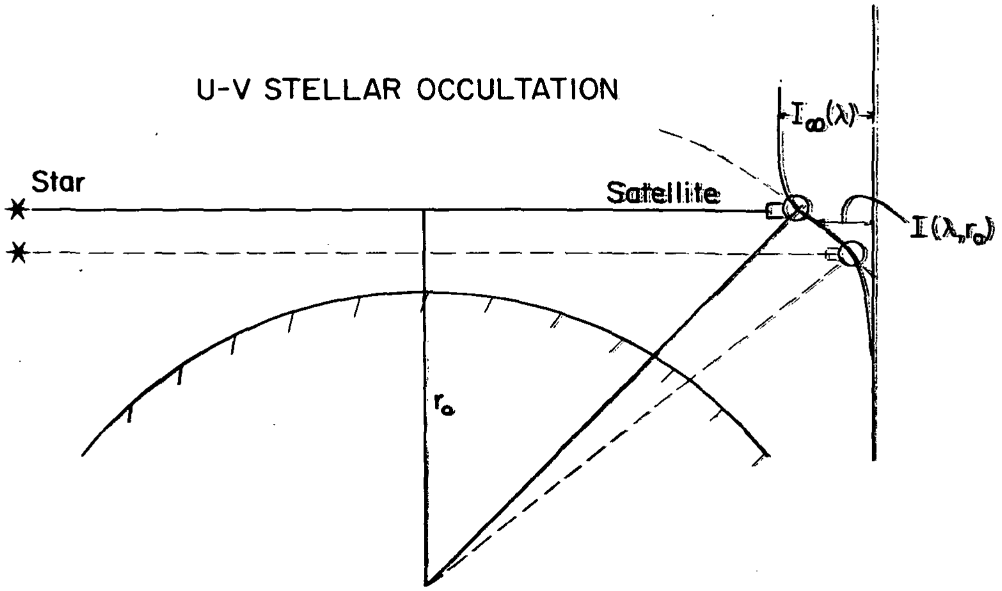

Figure 1.—Geometry of ultraviolet stellar occultation.

The occultation occurs when the air mass between the detector and the star increases such that ultraviolet light is relatively absorbed in spectral regions where molecular oxygen and ozone have large absorption cross-sections. The intensity of the transmitted ultraviolet light is related to the tangential column number density of the absorbing species by Beer's law,

$$I(\lambda, r_0) = I_\infty(\lambda) \exp[- \sum_i \sigma_i(\lambda) \cdot N_i(r_0)] \tag{1}$$

where $I_\infty(\lambda)$ is the unattenuated intensity of the star, at wavelength λ, above the atmosphere, $\sigma_i(\lambda)$ is the absorption cross-section of the i^{th} absorbing species, $N_i(r_0)$ is the tangential column number density of the i^{th} absorbing species at a tangent ray height, r_0. The intensity of the star is measured using the OAO ultraviolet spectrometer. By also knowing the absorption cross-section, one can relate the tangential column number density to the intensity of the transmitted ultraviolet light. Ideally, the best results are obtained if the ultraviolet wavelength is chosen such that a single species dominates the absorption process.

Once the tangential column number density of the absorbing species is known, then it is a simple problem to invert the data and obtain the vertical number density distribution of the absorbing species. A simple geometrical argument shows that the tangential column number density for a spherically stratified atmosphere can be written as

$$N_i(r_0) = 2 \int_{r_0}^{\infty} \frac{n_i(r)\ r\ dr}{\sqrt{r^2 - r_0^2}} \tag{2}$$

where $n_i(r)$ is the number density of the i^{th} absorbing species at radius r. Equation (2) is an Abel integral equation (Hays and Roble 1968a,b) easily inverted to give the number density of the absorbing species at tangent ray height r,

$$n_i(r) = \frac{d}{dr}\left\{-\frac{1}{\pi}\int_r^{\infty} \frac{r}{r_0} \frac{N_i(r_0)\ dr_0}{\sqrt{r_0^2 - r^2}}\right\} . \tag{3}$$

Thus, the stellar occultation technique can be used to obtain the vertical density distribution of any absorbing atmospheric species which can be spectrally isolated.

Hays and Roble (1968b) calculated the tangential ultraviolet transmission of the earth's upper atmosphere. Their results show that the strong absorption of O_2 in the Schumann-Runge continuum near 1500 Å and of O_3 in the Hartley continuum near 2500 Å are both spectrally isolated regions where the stellar ultraviolet absorption is primarily due to a single species. The absorption cross-section of both molecular oxygen and ozone at these wavelengths has a peak of around 10^{-17} cm^2. Therefore, we are able to determine the distribution of these species near altitudes where the tangential column number density is approximately $N_i \sim 10^{17}cm^{-2}$. If a spectral region away from the peak cross-section is utilized, one is able to observe higher tangential column number densities or equivalently measure the number density at lower altitudes within the atmosphere. In order to illustrate the altitude regions applicable, the tangential transmission of stellar ultraviolet light is shown in Figure 2 for the earth's atmosphere at various tangent ray heights (Hays and Roble 1968b). Here a black body energy distribution was assumed and the unattenuated energy spectrum is shown as the upper curve in Fig. 2. The CIRA 1965 model atmosphere was assumed to represent the vertical number density distributions of the various atmospheric species and the ozone density is assumed to be that calculated by Hunt (1966). The ultraviolet light in the wavelength interval 1400-1600 Å is absorbed primarily by molecular oxygen in the 130-230 km altitude range. In the wavelength interval 2400-2600 Å, the ultraviolet light is absorbed primarily by ozone in the 60-100 km altitude range.

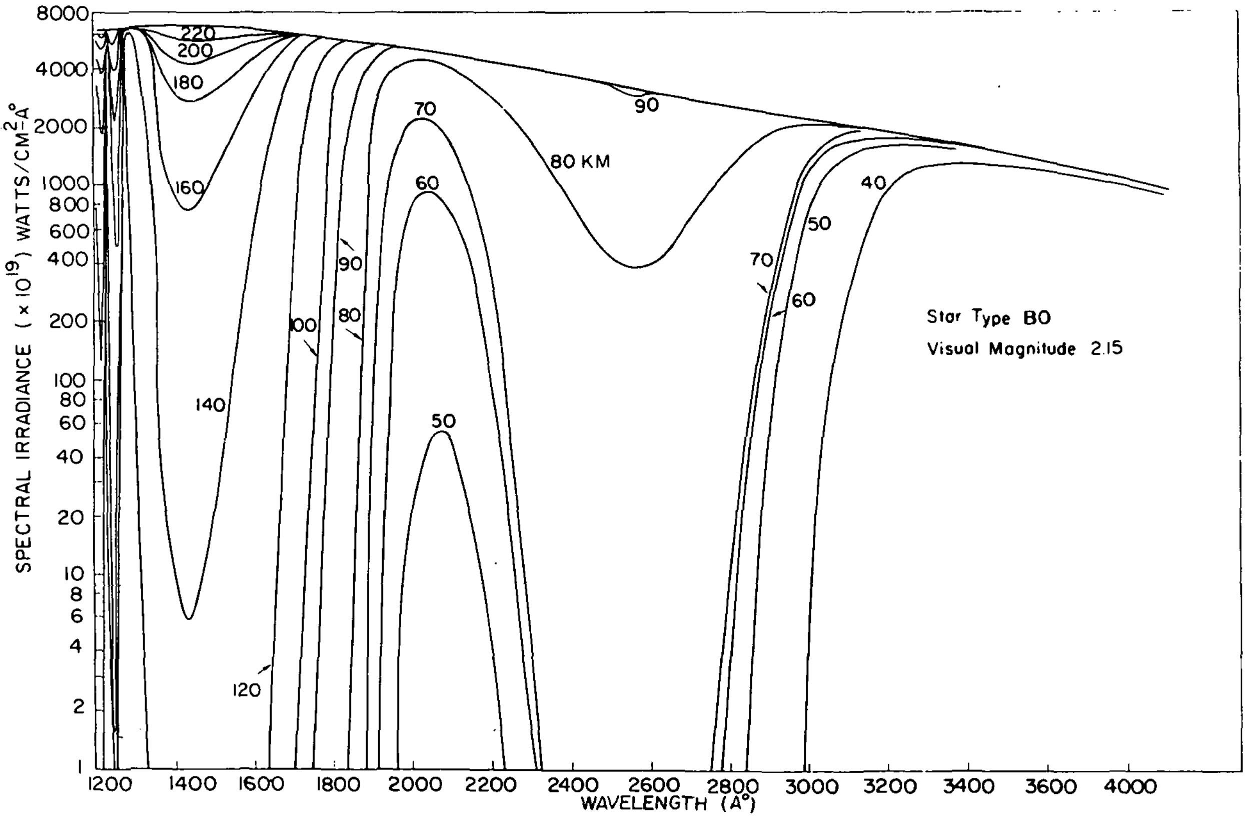

Figure 2.—Ultraviolet stellar spectra for a class B0 star at various tangent ray heights during occultation. Attenuation due to molecular oxygen absorption, ozone absorption, and molecular scattering (Hays and Roble 1968b).

III. OBSERVATIONS

The OAO-2 satellite has tracked several occulting stars, monitoring the intensity change of the star with the Wisconsin stellar photometers. The filters of interest in the Wisconsin package are those located in the Schumann-Runge continuum of molecular oxygen near 1500 Å and the Hartley continuum of ozone near 2500 Å. Figure 3 shows the normalized intensity data obtained during a single occultation from three stellar photometers having filters centered at 1500, 1920 and 2380 Å. The normalized intensity in this figure is plotted as a function of time; however, by knowing the star's position and the satellite orbital elements, we are able to relate time to the tangent ray height of the occulting star. The normalized intensity in the molecular oxygen channel is seen to decay first due to absorption at a high altitude. Next, the intensity in the 1920 Å channel decreases; however, it is difficult to utilize the data

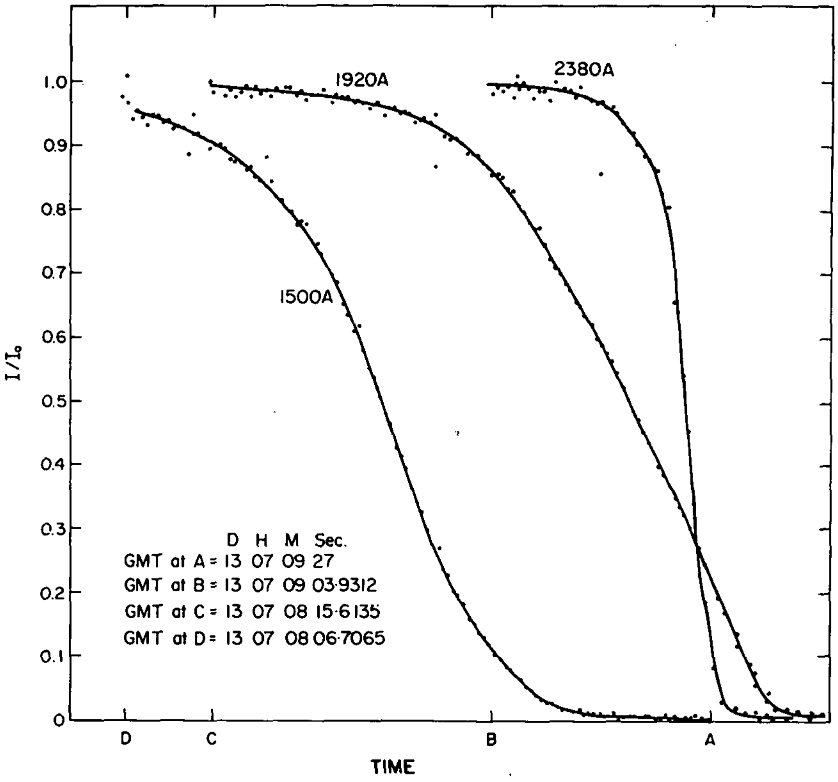

Figure 3.—Normalized intensity of a star during occultation as a function of time. The curves correspond to the intensity measured in the 1500, 1920 and 2380 Å channels of the Wisconsin stellar photometers aboard the OAO-2 satellite.

in this channel to obtain information on the atmospheric composition because of the complex absorption in the Schumann-Runge band system. Lastly, the intensity in the 2380 Å channel decays rapidly in the altitude region where ozone absorption becomes important. The quality of the data obtained by the OAO-2 stellar photometers is excellent allowing detailed structure to be obtained. The data in the 1500 Å channel were inverted and the results are shown in Figure 4 where the molecular oxygen number density profile is shown as a function of height. In addition, the molecular oxygen distributions for the average and low exospheric temperature models of Colegrove et al. (1966) are shown for comparison. The data obtained on 13 January 1970 agree

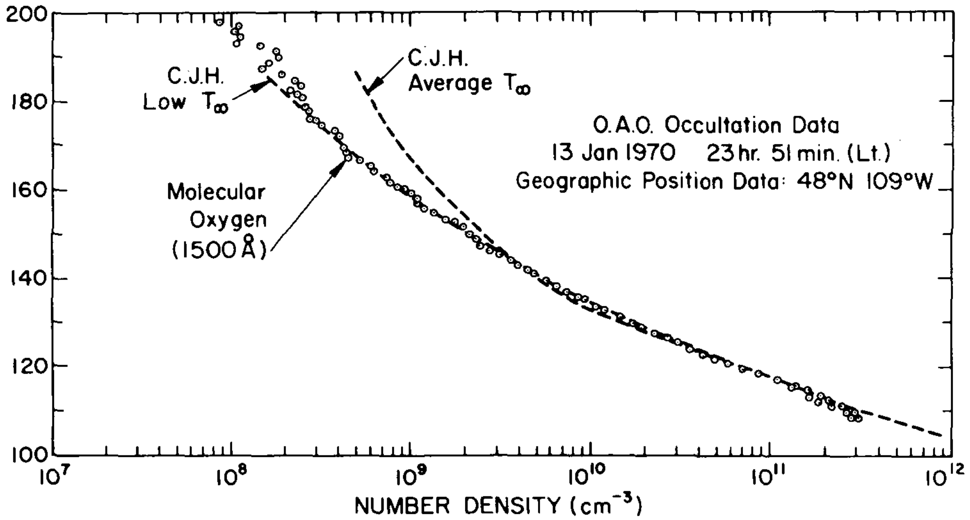

Figure 4.—The number density distribution of molecular oxygen determined from stellar occultation measurements. The models used for comparison are discussed in the text.

with the low exospheric temperature model. The temperature distribution in the lower thermosphere computed from the molecular oxygen number densities, assuming diffusive equilibrium, is shown in Figure 5. The data are compared to the high and low exospheric temperature models as determined by Colegrove et al. (1966). These data are only a sample of the approximately 20 stellar occultation scans which have been reduced thus far and they illustrate the quality of the data which is obtained from the occultation measurements.

Most of the ozone scans obtained with the 2380 and 2460 Å filters aboard the OAO-2 satellite have a normalized intensity scan which is similar to the one shown in Figure 6. In this figure, the intensity of the star in the 2380 Å channel is

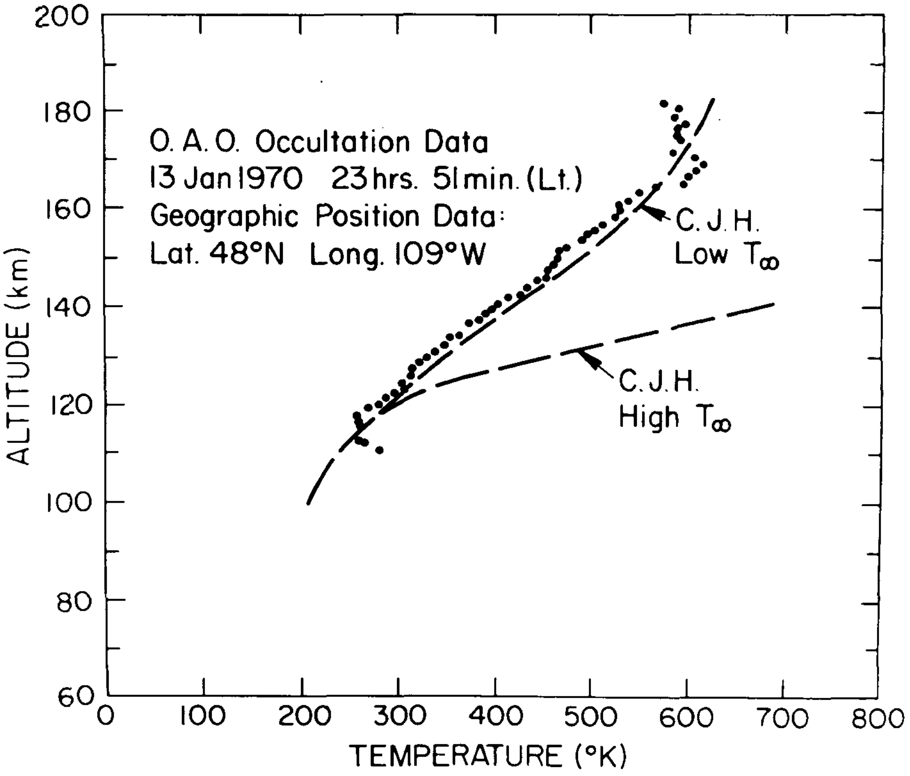

Figure 5.—The temperature distribution in the lower thermosphere determined from the molecular oxygen number density distribution assuming diffusive equilibrium.

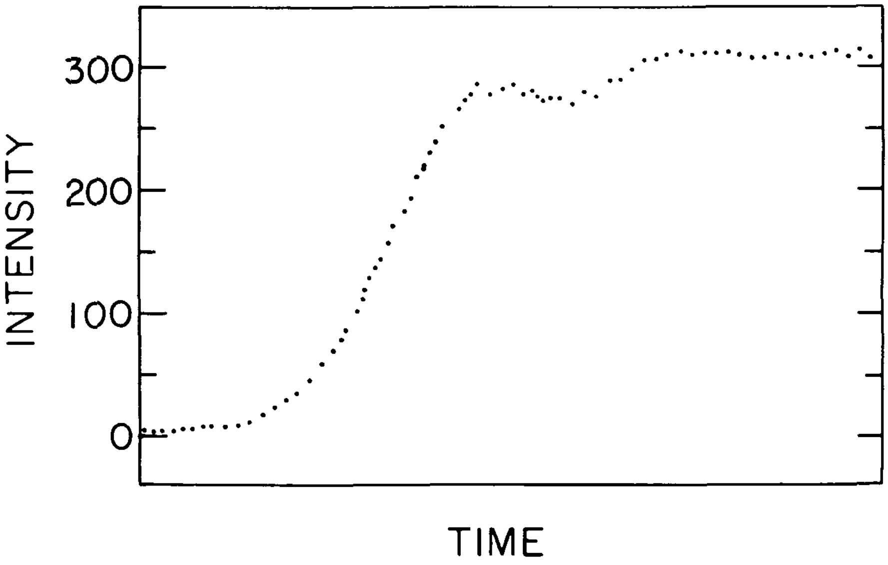

Figure 6.—The measured intensity in the 2380 Å channel of the Wisconsin stellar photometer as a function of time for a star rising from occultation.

plotted as a function of time, or equivalently tangent ray height, for a star rising from occultation. The signal increases as the star rises above the atmosphere until a dip in the intensity curve occurs at a tangent ray height near 90 km. These data, when inverted, give the number density distribution of ozone which is shown in Figure 7. The dip in the measured intensity curve is caused by a bulge in the nighttime ozone number density distribution with the peak occurring near 90 km and a minimum of near 80 km for this particular scan. The stellar occultation measurements clearly define the structure of the nighttime ozone distribution at high altitudes where no previous measurements existed. These data are important in the study of the ozone photochemistry in the upper mesophere.

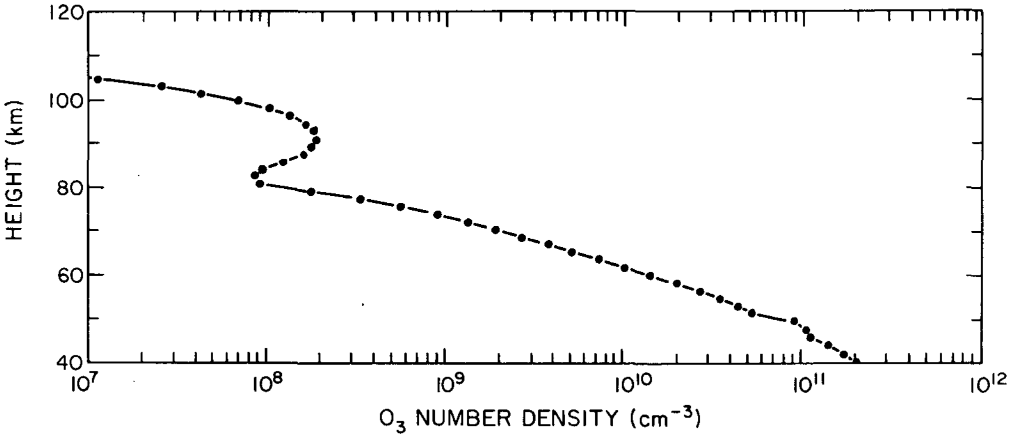

Figure 7.—The ozone number density distribution determined from the intensity scan shown in Figure 6.

IV. DISCUSSION

The OAO-2 occultation data obtained with the Wisconsin stellar photometers have been used to obtain high quality data on the nighttime distribution of molecular oxygen and ozone in the earth's lower thermosphere and upper mesosphere. So far, the feasibility of the stellar occultation technique in obtaining information on atmospheric composition has been demonstrated. However, with the growing number of occultation scans, we are beginning to analyze the scans for information on seasonal variations, geomagnetic storm effects and latitudinal and longitudinal variations. With the stellar occultation data, a considerable amount of information will be obtained about the earth's own upper atmosphere in addition to the prime OAO mission of determining the ultraviolet properties of stars.

REFERENCES

Colegrove, F. D., Johnson, F. S. and Hanson, W. B. 1966, J. Geophys. Res. 71, 2227-2235.
Hays, P. B. and Roble, R. G. 1968a, Planet. Space Sci. 16, 1197-1198.
__________ 1968b, J. Atmos. Sci. 25, 1141-1153.
Hunt, B. G. 1966, J. Geophys. Res. 71, 1385-1397.