Vertical cloud distribution in the Uranian atmosphere

N. M. Kostogryz

Main Astronomical Observatory of NAS of Ukraine, Zabolotnoho st., 27, 03680, Kyiv, Ukraine
`kosn@mao.kiev.ua`

In this work, the vertical cloud distribution in the Uranian atmosphere is investigated. We used the method of determinination of the deviation scope of the real atmosphere from homogeneity conditions. The idea of this methods is that the diffusely reflected radiations form at different effective depths in the atmosphere, namely: the strong absorption bands form higher in the atmosphere than weak ones. The same is for separate absorption bands: their centres form in higher atmospheric layers than other points of bands or lines contours. The relative methane concentration for all points of the contours of absorption bands will be the same only for a homogeneous atmosphere and will show the systematic deviation in the center and near the edge of the absorption bands in the case of an inhomogeneous atmosphere. It was obtained that Uranus' atmosphere has two cloud layers: the first one in the region with pressure within the range $1.5 - 1.8$ bar, and the second one in the region with the pressure $3.5 - 5.5$ bar. We also can conclude that aerosol was more abundant in 1981 compared to 1993 and 1995 which was found in our previous work.

Introduction

Visible and near infrared spectrum of Uranus is formed by the reflection of the sunlight from clouds and hazes, modulated mainly by the absorption of atmospheric methane. This spectral region is highly useful for determining the vertical cloud structure, since in the region of strong methane absorption only reflection from upper level hazes are observed, while in the regions of low absorption reflection from cloud layers down to 10 bars may be observed.

The vertical structure of Uranus has been the source of big debate. The Voyager 2 radio-occultation experiments [13] detected the presence of a thin cloud layer at 1.5 bars, assumed to be methane ice. Baines et al. [1] also deduced the presence of a thin cloud layer near 1.5 bars level, together with a second thicker cloud layer near 3 bars. Rages et al. [19] used Voyager 2 data and incorporated cloud physics calculations for the haze in the upper atmosphere. Methane was expected to form a cloud near 1.4 bars, and the Voyager occultation data [13] showed indication of a methane cloud. This approach produced models with one higher layer and two cloud layers below at the methane condensation level and near 3 bars. This model was modified by the inclusion of high resolution spectroscopy [2], Keck imaging [20], and near-infrared spectroscopy [6, 21].

The present work focuses on the vertical cloud distribution based on the data of Uranian geometric albedo [7, 8, 18] in the methane bands 887 nm, 727 nm, 619 nm, 543 nm using a technique of vertical structure deviations from the homogeneity conditions [14].

The method of calculations

The uncertainty of the atmospheric model choice during the analysis of spectral data of geometric albedo made us to find the technique which qualitatively demonstrates the deviation scope of the real atmosphere from the homogeneity. Such technique was proposed by Morozhenko [14]. The idea of this technique lies in the decreasing of probability of light quantum penetrations in the deep atmospheric layers depending on the single scattering albedo decreasing. It means, that the diffusely reflected radiation originates from different effective depths in the atmosphere, namely: the strong absorption bands form higher in the atmosphere than weak ones. The same is for separate absorption bands: their centers form at higher atmospheric layers than other points of bands or lines contours. The relative methane concentration for all points of the contours of absorption bands will be the same only for a homogeneous atmosphere and will show the systematic deviation in the center and near edge of the absorption bands in the case of an inhomogeneous atmosphere.

As model values of geometric albedo we used those calculated by Ovsak (private communication, part of calculations published in [15], p. 206) for a plane parallel, homogeneous semi-infinite layer illuminated by a parallel rays, with a three parameter Henyey-Greenstein phase function ($g_1 = 0.25$, $g_2 = -0.25$, $a =$

$0.5\,(x_1 = 0))$, where x_1 is the first coefficient of phase function series expansion in Legendre polynomials. We adopted that the atmosphere of Uranus is a homogeneous semi-infinite gas-aerosol layer. Comparing observed and calculated data on geometric albedo, we obtained $\ln[\frac{\tau_\nu+\tau_\kappa}{\tau_S}]$, $\ln\tau_S$ and $\ln\tau_\nu$. Here $\ln\tau_\nu$, $\ln\tau_\kappa$ are the absorption optical depth in the absorption bands and continuum, correspondingly, and $\ln\tau_S$ is the total (gas+aerosol) scattering optical depth.

The amount of methane NL along the line of sight is calculated using the following formula:

$$\ln NL = \ln\tau_\nu - \ln k_\nu. \tag{1}$$

The values of methane absorption coefficients k_ν were taken from [4] and redefined by [16] with regard for temperature-pressure dependence.

On Jupiter and Saturn, methane is expected to be uniformly mixed throughout the troposphere at all latitudes. Thus, the distribution of aerosol opacity can be directly inferred from methane band imaging. On Uranus, the methane mixing ratio in the upper troposphere varies vertically by three orders of magnitude. Unlike Jupiter and Saturn, The relative methane concentration changes from the upper to the deeper layers in the Uranian atmosphere. Thus, τ_R is determined in the following way:

$$\ln\tau_R = D\ln NL - \ln\gamma_0 - \ln\tau_{R_0}. \tag{2}$$

Here $D < 1$, γ_0 is the relative methane concentration at the atmospheric layer with $\ln NL = 0$, $\ln\tau_{R_0}$ is the value of $\ln\tau_R$ for hydrogen-helium mixture which extends up to 1 km-amagat at the 887 nm wavelength.

The atmospheric pressure is calculated with the following formula:

$$\ln p = \ln A + \ln\tau_R, \tag{3}$$

where A corresponds to the mean of pressure where $\tau_R(887.2\,\mathrm{nm}) = 1$.

In this work we used the following expression for depth dependence of the relative methane concentration proposed in [17]:

$$\begin{cases} \ln\gamma(p) = -9.98 + 2.68\Delta\ln p & \text{in the range} \quad 0.36 \le \ln p \le 1.55, \\ \gamma = 0.00382 & \text{in the range} \quad \ln p > 1.62. \end{cases}$$

In this case, expression (2) will look like:

$$\begin{cases} \ln\tau_R = -1.73 + 0.27\ln NL & \text{in the range} \quad -4.92 \le \ln NL \le -0.6, \\ \tau_R = 0.15 + \Delta NL/12.86 & \text{in the range} \quad NL \ge 0.55. \end{cases}$$

Results and conclusions

Using the technique of estimating the deviation scope of real atmosphere from the homogeneity, we can identify two cloud layers: the first one near $1.5 - 1.8$ bars (Fig. 2) and the second one near $\sim 3.5 - 5.5$ bars (Fig. 1). In Figure 1 a) the homogeneity conditions, i.e. clear gaseous atmosphere, are presented, while in Figure 1 b), c), d) the deviation scope from the homogeneity for different years of observations, i.e. real gas+aerosol atmosphere, are shown. In Figure 1 b),c),d) the scattering optical depths for 887 nm are very close to those for 727 nm, therefore we moved 887 nm band down to 0.5 values for better understanding. As it can be seen from the Fig. 1, the real atmosphere is quite different from clear gaseous atmosphere, especially in the pressure region $\sim 3.5 - 5.5$ bars. It means, that in this pressure region Uranus has a strong aerosol layer.

This result is in a good agreement with [20], where the presence of the second cloud layer at $4 - 5$ bars was detected, while in the other papers [5, 6, 22, 21] the presence of the second cloud layer some deeper in the atmosphere, from $6 - 8$ bars to $8 - 10$ bars, is discussed.

Figure 1 also shows the aerosol abundance in the atmosphere. As in the gaseous atmosphere (Fig. 1,a) the considerable differences are visible between red and blue wings of methane band, in the real atmosphere these differences are noticeably less. So, the less differences between red and blue wings are visible, the more aerosol abundance present in the atmosphere. We can conclude that in 1981 the aerosol was more abundant, than in 1993 and 1995. This result was obtained in our previous papers [11, 12] using quite different technique for aerosol abundance calculation.

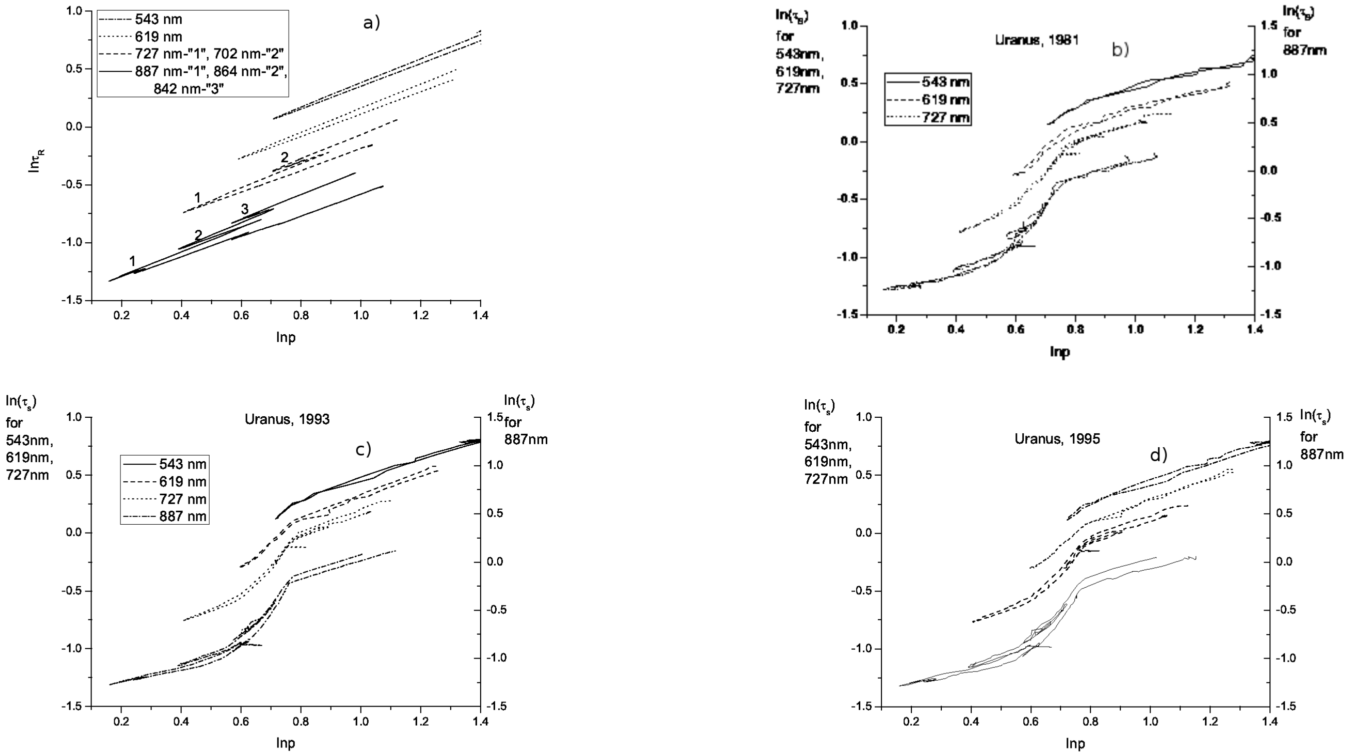

Figure 1: Logarithmic pressure dependence of the scattering optical depth: a) model of clear gaseous atmosphere, b) model of gas+aerosol atmosphere in 1981, c) model of gas+aerosol atmosphere in 1993, d) model of gas+aerosol atmosphere in 1995. In b), c), d) left vertical scale is for 543 nm, 619 nm, 727 nm, and right vertical scale is for 887 nm.

Upper cloud layer can be identified from Figure 2, which presents the logarithmic dependence of scattering optical depth from pressure for 887 nm methane band in 1981, 1993 and 1995. Fig. 3 shows minimum and maximum limits of errors for 1981. As one can see from Fig. 2 and 3, the upper cloud layer lies in the pressure region $\sim 1.5 - 1.8$ bars, and is much thinner than deeper layer. Because of the lack of near-infrared geometric albedo data, we have no possibility to conclude about upper limit of this layer, but we can conclude that at 1.5 bar this layer is present.

As the upper thin cloud layer assumed to be methane ice, and methane was expected to form a cloud near 1.4 bar, we obtained a very good agreement with this assumption. This result was confirmed by Voyager 2 radio occultation experiment [13] that detected the presence of a thin cloud layer at 1.5 bar and Rages et al. [19] who talked about methane cloud layer occupying 1.2-1.3 bars at 22.5° S, rising to 2.4 bar at 65° S and Karkoschka and Tomasko [9], who confirmed that Uranus has very small aerosol opacity above the 1.2 bar level, but much larger opacity below. But, in the same time, this result has some disagreements with [6, 22, 21]. These disagreements could be resolved by adjusting methane coefficients. Using new methane absorption coefficients from [10], Fry and Sromovsky [3] fitted Uranus near-IR spectra previously analyzed in [22, 21] using methane absorption coefficients from [5]. Because the new absorption coefficients usually result in higher opacities at the low temperatures seen in Uranus' upper troposphere, previously derived cloud altitudes were expected to generally rise to higher altitudes [3] and pressure of the upper tropospheric cloud to decrease to 1.6 bars (from 2.4 bars using Irwin coefficients [5]).

From our results we can conclude, that Uranus' atmosphere has two cloud layers: the first one is in region with the pressure from 1.5 bar to 1.8 bar, and the second one is the region with the pressure from 3.5 bar to 5.5 bar.

Acknowledgement

I would like to thank O. Morozhenko for the critical discussions on this work.

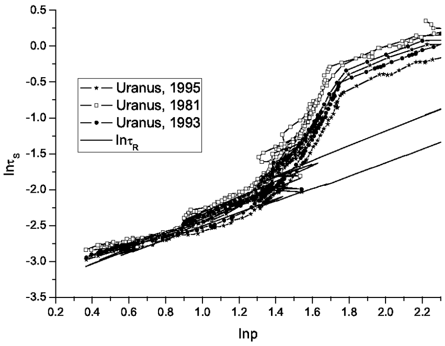

Figure 2: Logarithmic pressure dependence of scatering optical depth for 887 nm methane band in different years.

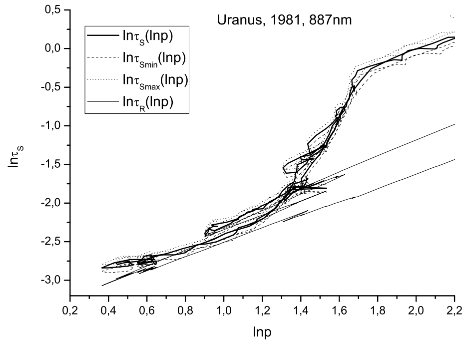

Figure 3: Logarithmic pressure dependence of scatering optical depth for 887 nm methane band in 1981 with upper and lower limits of errors

References

[1] Baines K. H., Bergstralh J. T. Icarus, V. 65, pp. 406-441 (1986)

[2] Baines K. H., Mickelson M. E., Larson L. E. et al. Icarus, V. 114, pp. 328-340 (1995)

[3] Fry P. M., Sromovsky L. A. DPS meeting, 41 (2009)

[4] Giver L. P., J. Quant. Spectrosc. and Radiat. Transfer, V. 19, pp. 311-322 (1978)

[5] Irwin P. G. J., Sromovsky L. A., Strong E. K. et al. Icarus, V. 181, pp. 309-319 (2006)

[6] Irwin P. G. J., Teanby N. A., Davis G. R. Astrophys. J., V. 665, pp. L71-L74 (2007)

[7] Karkoschka E. Icarus, V. 111, pp. 174-192 (1994)

[8] Karkoschka E. Icarus, V. 133, pp. 134-146 (1998)

[9] Karkoschka E., Tomasko M. Icarus, V. 202, pp. 287-309 (2009)

[10] Karkoschka E., Tomasko M. Icarus, V. 205, pp. 674-694 (2010)

[11] Kostogryz N. M. Kinematics and Physics of Celestial Bodies, V. 23, pp. 214-220 (2007)

[12] Kostogryz N. M. YSC'14 Proc. of Contributed Papers, eds.: Ivashchenko G., Golovin A., Kyivskyi Universytet, Kyiv, pp. 44-48 (2007)

[13] Lindal G. F., Lyons J. R., Sweetnam D. N. J. Geophys. Res., V. 92, pp. 14987-15001 (1987)

[14] Morozhenko A. V. Soviet Astr. Lett. (TR:PISMA) V. 10, pp. 323 (1984)

[15] Morozhenko A.V. Techniques and results of remote sensing of planetary atmospheres. Kyiv, Naukova dumka press (2004)

[16] Morozhenko A. V. Kinematika i Fizika Nebesnykh Tel, V. 22, pp. 138-153 (2006)

[17] Morozhenko A. V. Ovsak A. S. Kinematics and Physics of Celestial Bodies, V. 25, pp. 173-181(2009)

[18] Neff J. S., Humm D. C., Bergstralh J. T. et al. Icarus, V .60, pp. 221-235 (1984)

[19] Rages K., Pollack J. B., Tomasko M. G. et al. Icarus, V. 89, pp. 359-376 (1991)

[20] Sromovsky L. A., Fry P. M. Icarus, V. 192, pp. 527-557 (2007)

[21] Sromovsky L. A., Fry P. M. Icarus, V. 193, pp. 252-266 (2008)

[22] Sromovsky L. A., Irwin P. G. J., Fry P. M. Icarus, V. 182, pp. 577-593 (2006)