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We present here an explanation of the erroneous interpretations of spectroscopic sodium dayglow measurements which led to a large diurnal variation. In fact, the diurnal variation is proved to be either small or nonexistent. This result is confirmed by balloon-borne experimental measurements of the sodium twilight and dayglow intensities.

INTRODUCTION

The method which led to the first observation of sodium dayglow by *Blamont and Donahue* [1960, 1961] is based on the comparison of the profile of a Fraunhofer solar line with that of the scattered light at the same wavelength. The instrument used was a magnetic scanning spectrograph, or Zeeman photometer, initially conceived for the observation of the sodium twilight [*Blamont*, 1956]. Note that the high spectral resolution is obtained by using a resonance cell and the spectral scan by sweeping the magnetic field producing the Zeeman effect.

Among the difficulties encountered in the use of this instrument is its sensitivity to the polarization of the incident light, which for scattered sunlight varies during the day. This difficulty was first avoided by limiting the observations of dayglow to ±3 hours from local noon, when the plane of polarization is at 45° to the magnetic field: the light then behaves like unpolarized light. A more complete theoretical calculation of the behavior of the instrument, taking into account the polarization of Rayleigh-scattered light, allowed the use of all the daytime data and led to a study of the diurnal variation [*Albano et al.*, 1970]. These results were confirmed by *Gadsden and Purdy* [1970], using a polarizing filter in front of a Zeeman photometer: the diurnal variation was shown to be symmetric with respect to noon with the maximum at noon. The day to twilight ratios over a period of 5 years reported by *Blamont and Donahue* [1964] presented extreme values of 7 in June and 2 in December. The only measurements inconsistent with these results were the absorption data obtained by *McNutt and Mack* [1963] and by *Burnett et al.* [1972], which did not show any evidence of a diurnal variation. More recently, sodium soundings by laser showed no systematic difference in night, twilight, and daytime abundances [*Gibson and Sandford*, 1972].

All spectroscopic studies of the dayglow emission assume the similarity between direct and scattered solar profiles; we know now that this is not the case. In a separate article we have described the results of our measurements of light scattering by natural surfaces [*Chanin*, 1972]: these results present important consequences for the measurement of dayglow.

We will now present a critical view of the data obtained with the Zeeman photometer and a series of sodium dayglow observations from a high-altitude balloon platform (to reduce any contribution from Rayleigh scattering).

CRITICAL STUDY OF THE ZEEMAN PHOTOMETER DATA

As was mentioned before, the sodium dayglow intensity measurements were obtained from the difference between a direct sunlight profile and a scattered light profile. Within the limits where polarization effects would not affect the data, the total difference was attributed to the sodium resonance line. If one could scan the profile near the center of the Fraunhofer line, one would see if the difference between the profiles is due only to a resonance line. Such an analysis had been done by one of the authors for the potassium line [*Albano et al.*, 1970], and the difference was shown not to be due to the potassium resonance line. Later, such a spectral study on light scattered from the ground [*Chanin*, 1975] proved that the solar line is filled in by the scattering process. We will use the same notation as is used by *Chanin* [1975] and will call Δ the difference between the solar and the dayglow profiles.

We present in Figure 1 some typical profiles obtained on the dayglow for different local times and a direct solar profile measured on the same day (we comment on the conditions for obtaining a correct solar profile in the companion paper [*Chanin*, 1975]). From Figure 1 it is evident that at least part of the intensity of profile 4 is due to a resonance line, but we should try to see what part is not. To do so, we compared the quantities Δ to a family of hypothetical curves obtained by adding to the experimental solar profile different spectral distributions of light, from a pure resonance line to a complete continuum including a mixture of both. The absolute value of the added intensity was the same at the center of the line ($H = 0$) for all cases, and we chose it to be equal to the residual intensity of the Fraunhofer line (the theoretical curves are not affected by this choice because of the definition of Δ_n). In Figure 2 we show hypothetical curves and some experimental values obtained for the dayglow on days when the spectral profile was carefully measured; two samples of data have been identified as extreme cases: near twilight and on snow-covered ground. It is interesting to note that for very low solar elevation angles (between 0° and +10°) the profile comes closest to that of a pure resonance line, but already one third of the light is due to a continuum; for data obtained at higher values of solar elevation the contribution of the continuum increases to about ⅔ and can reach ⅘ if the ground is covered with snow. This is perfectly understandable if one remembers that the albedo is then very high (~0.8) and furthermore that the filling in of the Fraunhofer line by reflection on snow can be as high as 4% of the continuum [*Chanin*, 1975].

We did not obtain any experimental data which would agree either with a pure resonance line (the equipment is not sensitive enough to get a spectral profile of the twilight) or with a pure continuum (which was the case at the potassium wavelength). In brief, if no correction for the continuum, or albedo effect, is made, the intensity of the sodium dayglow can be too large by a factor of 3.

Let us examine in detail 1 day of measurements (e.g., October 15, 1969), for which the day to twilight ratio was found to be 3 when no correction was applied. The twilight intensity measurements were obtained with the Zeeman photometer according to the method described by ***Blamont*** [1956]. Figure 3 shows the twilight data obtained for this day. The spectral profiles of the dayglow data were already presented in Figure 1. For each profile we can make a rough estimate of the continuum contribution using the hypothetical curves of Figure 2. We obtain values varying from 66% (at noon) to 16% (4 hours after noon). Taking into account the values of Δ_0, which is found to vary from 38 to 75%, we conclude that the sodium emission really represents 12–63% of the residual intensity (instead of 38–75%). Then if only one third of the intensity at noon is due to sodium emission, the ratio of noon dayglow to twilight is reduced from 3 to 1. We have found similar results on randomly chosen representative days, showing that the diurnal variation is either very small or nonexistent.

However, the treatment described here cannot be systematically applied to correct the data because of the imprecision of the magnetic scanning spectra. In addition, a theoretical correction cannot be applied without more precise albedo data. To avoid depending upon these corrections, the sodium dayglow and its eventual diurnal variation were studied from a photometer placed in a balloon. The results of a series of such balloon observations are now presented.

BALLOON OBSERVATION OF THE SODIUM DAYGLOW

The method consists of a measurement of the dayglow intensity within a band pass of 35 mÅ centered on the sodium *D* lines and its comparison with the intensity on either side of those lines using a band pass of 75 mÅ. In order to isolate such narrow spectral intervals we made use of, as was done in the Zeeman photometer mentioned before, a resonance cell. The first channel of 35-mÅ band pass, defined by a sodium resonance cell of low optical thickness, was intended to detect the sodium resonance glow. The second channel contained successively a pressure-broadened resonance cell of 75-mÅ band pass and an absorption cell to eliminate all wavelengths corresponding to the resonance line: this channel was intended to measure the amount of parasitic light. It proved in fact to be of very little use because of the almost negligible intensity of the Rayleigh-scattered light at the altitude of the balloon (35 km).

Three successful flights took place between October 1971 and June 1972. The twilight and dayglow measurements were performed with a constant zenith angle of 30°, and the pointing direction was maintained normal to the solar excitation all along the flight by using a sun-pointing device: this meant a measurement toward the north for a morning flight (October 21, 1971) and one toward the south for an evening flight

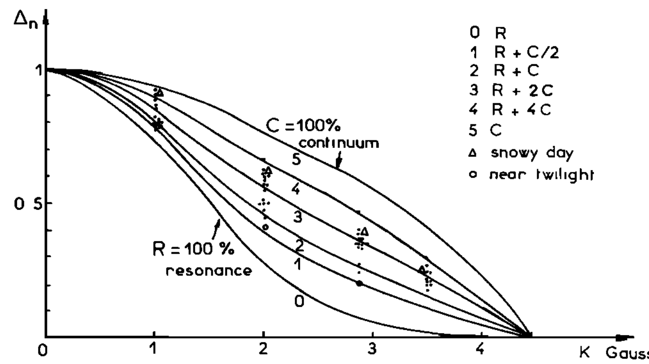

Fig. 2. Theoretical set of curves of the parameter Δ_n if the light profile superimposed on the experimental solar profile is the following: 0, pure resonance line *R*; 1, ⅔*R* + ⅓*C*; 2, ½*R* + ½ *C*; 3, ⅓*R* + ⅔*C*; 4, ¼*R* + ¾*C*; and 5, pure continuum *C*. Experimental data are for randomly chosen days (dots), for $-5° < \theta < +10°$ (circles), and for snow-covered ground (triangles).

(March 30 and June 24, 1972). Only the last flight was long enough to follow the variation of sodium intensity from twilight to 35° solar elevation angle. We present in Figure 4 an example of the experimental sodium data obtained for that flight, after correction for parasitic light and dark current; we have plotted all the experimental points and the average curve obtained by least mean squares. On Figure 5 we plotted only the average data for the three flights. The experimental data, represented by the solid curve, were extrapolated to local noon. All the experimental curves show a rapid change of intensity (by a factor of 3–3.5) between twilight and a solar elevation angle of $\theta = 10°$. The increase in the intensity is largely due to the variation with the solar elevation angle of the solar absorption through the sodium layer for low values of θ ($\theta < 10°$). For higher values ($\theta > 10°$) the slow increase of the sodium intensity is due to the increasing contribution of the albedo in the excitation of the sodium atoms at 90 km. In order to take into account that albedo effect we attempted to measure the albedo intensity, but the measurement was made with too small a field of view: while a surface of 1000 km is involved in the excitation of the sodium atoms, the balloon detector only looked at a surface 35 km in diameter. The albedo variation has been plotted with the sodium data in Figure 4; we note that (1) on the average it follows Lambert's law and (2) some of the sodium intensity fluctuations are correlated with albedo variations (at 0710 A.M., for example).

DIURNAL VARIATION FROM THE BALLOON OBSERVATIONS

In order to deduce the sodium abundance from the intensity measurements we have used the classical relationship between

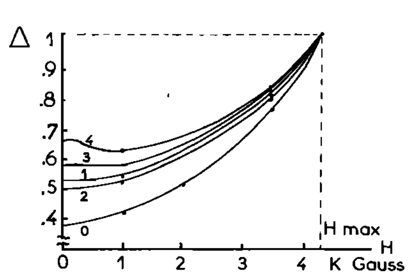

Fig. 1. Magnetic scanned profiles obtained on October 15, 1969: 0, direct sunlight; 1, dayglow at 1000 UT; 2, dayglow at 1200 UT; 3, dayglow at 1500 UT; and 4, dayglow at 1600 UT.

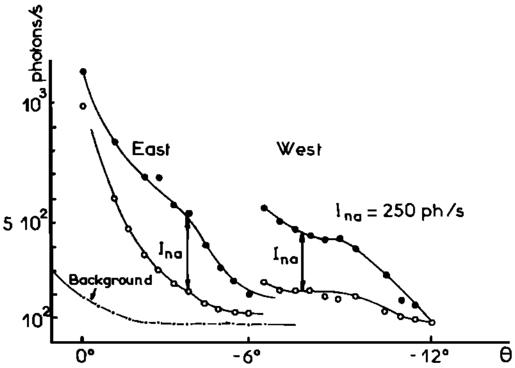

Fig. 3. Experimental twilight data for October 15, 1969.

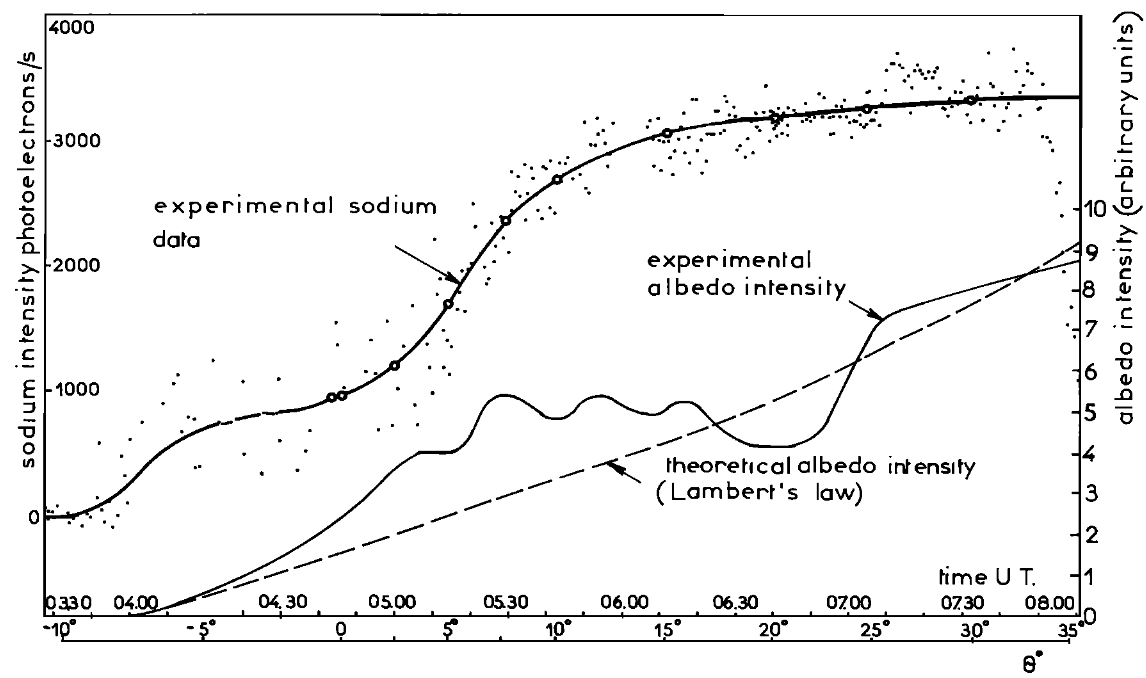

Fig. 4. Results of flight 3 on June 24, 1972. The points represent experimental sodium intensity data corrected for parasitic light and dark current. The heavy curve is the least mean squares fitting to the data. The light curve is the albedo intensity measurement. The dotted line is the theoretical albedo intensity according to Lambert's law.

the abundance and the density of excited atoms, and then we deduced the emission intensity. The theoretical results in the literature were concerned either with twilight [*Donahue and Stull,* 1959] or with dayglow [*Petitdidier,* 1969] for high solar elevation: $\theta > 10°$. As we measured the intensity continuously from twilight to dayglow, we had to complete the theoretical calculation for the missing interval, equal to $-2° < \theta < 10°$, taking multiple scattering into account. In order to deduce twilight abundance from the experimental results one has to assume a certain value of the day to twilight abundance ratio R: because of the self-absorption of solar excitation in the sodium dayglow layer before it reaches twilight regions of the earth, the daytime abundance influences the twilight glow. We took into account the additive contribution of the albedo, assuming that it varies according to Lambert's law. A more detailed description of the calculation is available [*Goutail,* 1974].

As a result of these calculations we obtained sets of curves giving the emission intensity as a function of solar elevation angle for different sodium abundances and for different values of the day to twilight ratio R and of the albedo A. In order to place the observed intensity data on these sets of curves we need to know the absolute intensity of the measured twilight glow. The balloon photometer was calibrated with the Zeeman photometer at the Observatory of Haute Provence, but it could not be used as an absolute calibration for two reasons: (1) we are not very confident of the absolute calibration of the Zeeman photometer, and (2) the electronic amplifier of the balloon experiment had to be changed between flights because of failures or poor performance. This makes even a comparison of data for the three flights impossible. Therefore we assumed for the values of the twilight abundances the average values over several years as published by *Gadsden et al.* [1966]. We assumed the following values for the three flights:

Flight 1 (October 21, 1971)

$$N = 6 \times 10^9 \text{ atoms/cm}^2$$

Flight 2 (March 30, 1972)

$$N = 5 \times 10^9 \text{ atoms/cm}^2$$

Flight 3 (June 24, 1972)

$$N = 3 \times 10^9 \text{ atoms/cm}^2$$

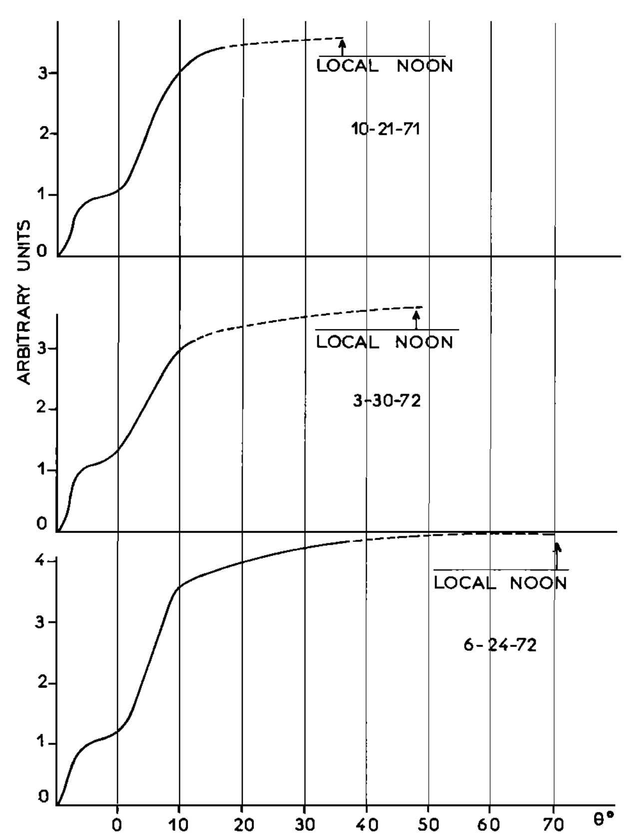

Fig. 5. Experimental results for the three flights. The dotted line is extrapolated.

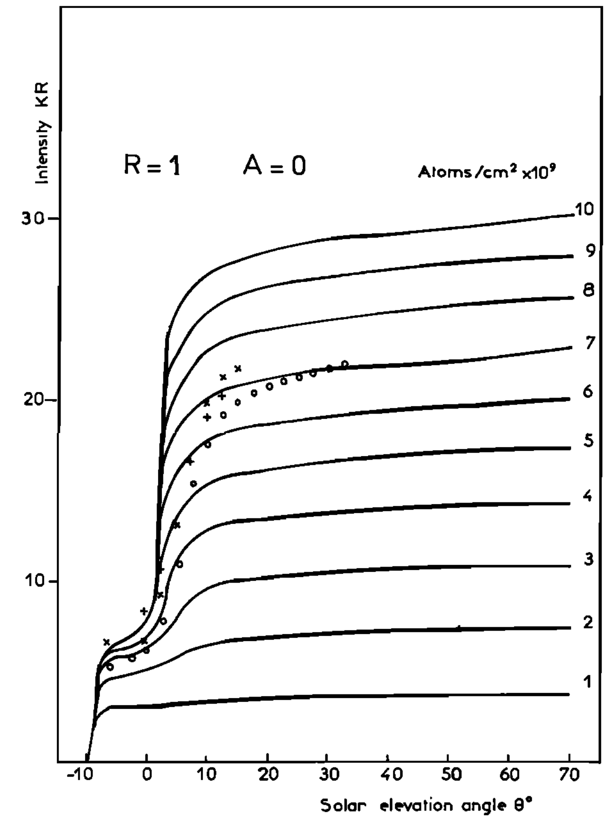

Fig. 6. Sodium intensity as a function of solar elevation angle and different abundances for $R = 1$ and $A = 0$.

By assuming these twilight values all the data were fitted to the different sets of theoretical curves corresponding to $R = 1, 1.5$, 2, and 3 and $A = 0$, 0.4, and 0.8. Let us first comment on the results if we neglect the albedo. With this hypothesis ($A = 0$) the variation in the intensity is only due to the decrease of self-absorption within the layer and occurs abruptly between $\theta = 0°$ and $\theta = 10°$; the intensity thereafter should stay constant if the diurnal variation is negligible. It is clear that the data do not follow the theoretical curves. Figures 6 and 7 correspond to the hypotheses $R = 1$ and $R = 1.5$, respectively.

In Figure 6 we assume no change of sodium abundance during the day for tracing the theoretical curves. Since the experimental data exhibit a small variation for flights 1 and 2 and a large one for flight 3, the results are incompatible with our assumption.

In Figure 7 we assume a regular change of abundance between $\theta = -6°$ and $\theta = +10°$ and a stable dayglow corresponding to 1.5 times the twilight abundance. For the first two flights the decrease in abundance is incompatible with this hypothesis. For the third flight the order of magnitude of the increase in abundance is correct until $\theta = 12°$, but the experimental abundance continues to increase after 12°.

A similar comparison of the data with the theoretical curves for $R = 2$, $R = 3$, and $A = 0$ shows complete incompatibility.

Let us now consider a more realistic value for the albedo: for the vegetation and ground concerned (forest and rocks) the average albedo (in the absence of snow) should be around 0.3. But from the filling in due to ground reflection [*Chanin*, 1973] the energy available at the center of the Fraunhofer line is increased by about 30%. In terms of the available energy for exciting the sodium atoms it is equivalent to an albedo of 0.4. With this hypothesis ($A = 0.4$) the slope of the set of curves is increased and becomes compatible with the data. If we assume $R = 1$, the data from flights 1 and 2 are in good agreement with the theoretical curves and indicate an absence of diurnal variation (Figure 8). In order to match the results of flight 3 we have to assume $R = 1.5$. The slow increase of intensity beyond $\theta = 12°$ is then in agreement with the theoretical curves (Figure 9).

We have tried to explain the data of flight 3 by increasing the albedo value to 0.8. Then the slope of the theoretical curves becomes such that experimental data would indicate a decrease of sodium abundance beyond $\theta = 12°$, which is not realistic. We had considered how other choices of twilight abundances would affect the results: for flights 1 and 2 the minimum twilight intensity for the seasons concerned could be 5 and 4×10^9 atoms/cm², respectively. This would lead to a maximum day to twilight ratio of 1.2. For the third flight, which occurred at a period of minimum sodium twilight, we obtain no diurnal variation if we take 4.5×10^9 instead of 3×10^9 atoms/cm² for the twilight abundance, and this is not unrealistic.

To summarize the results obtained from the balloon-borne photometer, one can say that the maximum diurnal variation observed is an increase of 50% over the sodium abundance. In two cases it could not be more than a 20% increase, and all data are compatible with a small or negligible diurnal variation.

REMARK

We have assumed a constant albedo of 0.3 for the interpretation of the three flights. But photographic cloud coverage obtained from meteorological satellites shows a different situation in the vicinity of the region of interest: dur-

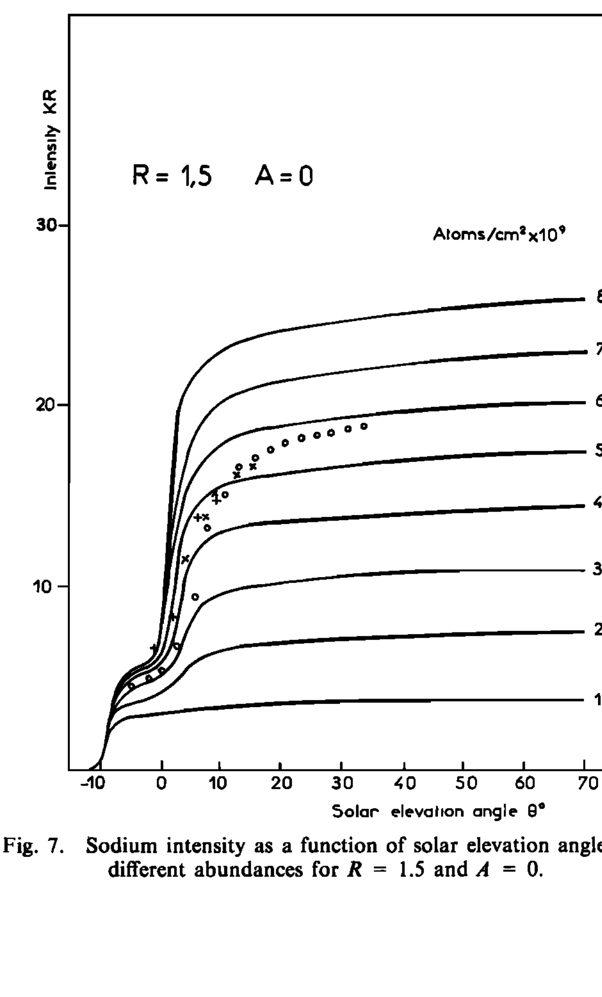

Fig. 7. Sodium intensity as a function of solar elevation angle and different abundances for $R = 1.5$ and $A = 0$.

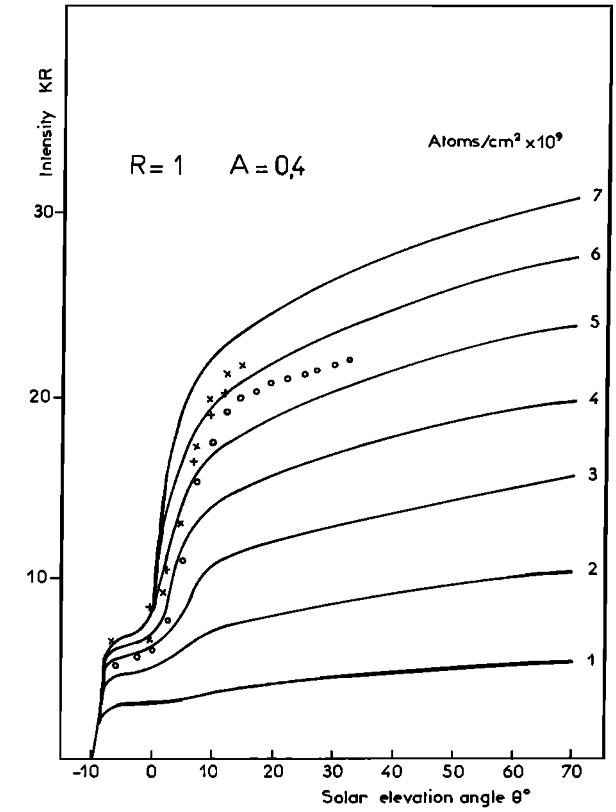

Fig. 8. Sodium intensity as a function of solar elevation angle and different abundances for $R = 1$ and $A = 0.4$.

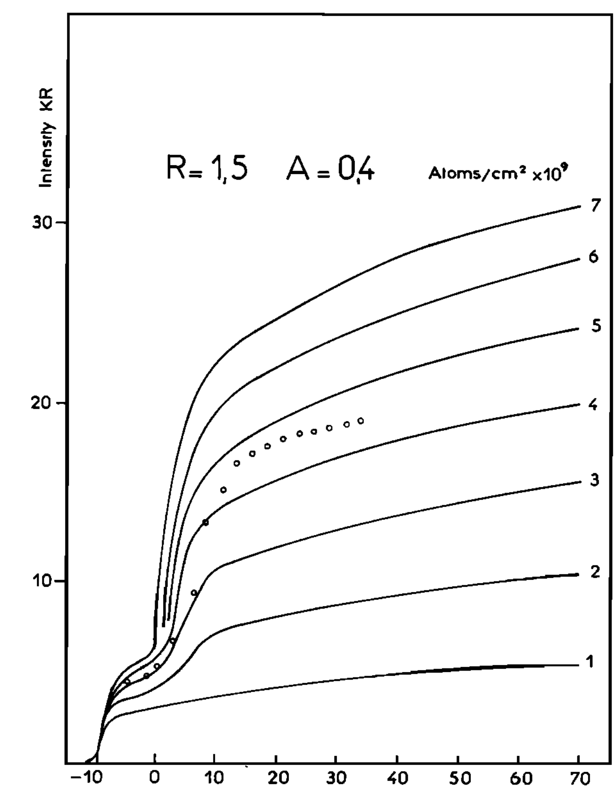

Fig. 9. Sodium intensity as a function of solar elevation angle and different abundances for $R = 1.5$ and $A = 0.4$.

ing the first two flights the sky was clear in a band of 1000 km along the balloon trajectory, while a variable cirrus-type cover was present during the last flight. This implies a higher and variable value of the albedo for that case and could be responsible for the higher values of the observed dayglow.

Conclusions

We can conclude both from the Zeeman spectral analysis and from the balloon observations that the diurnal variation of the sodium abundance is at the maximum 50% of the twilight value and may even disappear in most cases. A continuous monitoring of the albedo contribution to the dayglow excitation proved to be necessary for correct interpretation of dayglow measurements. We presented an explanation for the erroneous interpretation of the earlier spectroscopic emission data. Recent work by C. R. Burnett et al. (unpublished data, 1974) leads to the same conclusion, as do the laser dayglow data [*Gibson and Sandford,* 1972]. It may be expected that rapid progress can now be made by using the accurate technique of laser sounding in order to understand the still surprising behavior of sodium in the upper atmosphere.

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