INTENSITY DISTRIBUTION IN THE LYMAN-α LINE AT THE SOLAR LIMB

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Abstract. The distribution of the solar intensity in the Lyman α line has been measured close to the visible limb. It is compared to a computation including LTE departures (as evaluated by Y. Cuny). As far as the profile of the line and the intensity (integrated over the line) are concerned, the interspicular model of Coates is the only one which seems to agree with the observations.

1. Introduction

To date, models of the solar chromosphere have been deduced from eclipse flux measurements in the solar visible continuum, radio wavelength measurements and, more recently, far UV spectra of the Sun. Brightness measurements at the limb have been made in the Lyman α line during the eclipse of November 1966. The results are compared to theoretical computations including several models of the chromosphere. As a result, the agreement between computations and observations can be improved if the temperature gradient in the chromosphere is modified.

2. Experimental Data

The measurements were made from a rocket during the eclipse of November 1966, visible from the Southern Hemisphere. The rocket was launched from Argentina. The Service d'Aéronomie du C.N.R.S. (France) was responsible for the scientific payload.

The experimental results have been reported in [3]. The detector was a LiF window ionisation chamber filled with CS_2. The field of view was 2° and the flux was received from the whole disc. The bandpass was 1050–1250 Å. The measured flux ϕ is related to the phase of the eclipse through:

$$\phi(t) = \int_{\Sigma(t)} I(P)\, \mathrm{d}S$$

where $I(P)$ is the intensity over the band of the detector at point P on the disc. The integration is made over the whole uncovered area $\Sigma(t)$ of the disc at time t. Through inversion of this integral, one can obtain the value of $I(P)$.

A description of the inversion method used is given in [3] together with the different assumptions introduced in the mathematical processing of the data.

The net result is shown in Figure 1 where the emerging intensity I is plotted versus the position r on the solar disk, measured in arc sec. The origin of position is deduced from simultaneous flux measurements made during the same rocket flight in the in-

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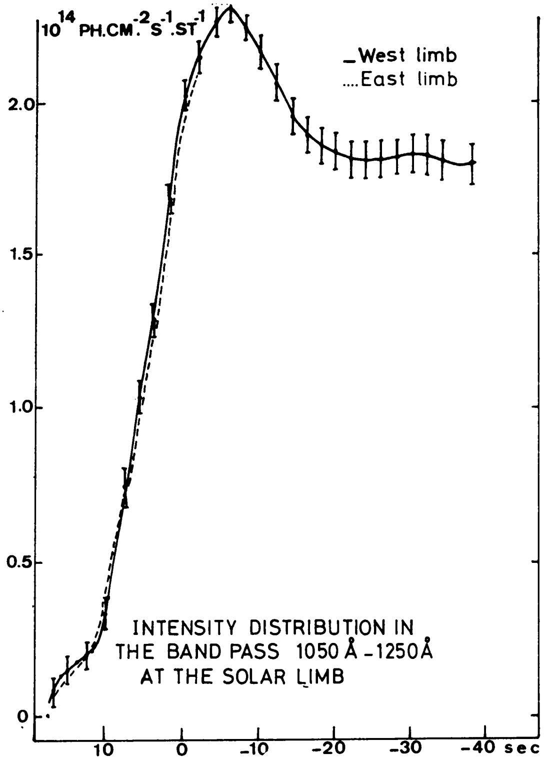

Fig. 1. Computed intensity integrated over frequency as a function of the distance to the visible limb in seconds of arc (from Blamont and Malique).

frared, with a photomultiplier. Figure 1 has been communicated to me by Blamont and Malique, before publication.

The curve of Figure 1 shows two important characteristic features:

(i) the position of the point of inflexion in the curve of variation of intensity at the limb is located 3″ of arc outside the visible limb, within an accuracy of $\pm\frac{1}{2}''$.

This position will hereafter be called 'Lyman α solar limb'.

(ii) the Sun is limb-brightened, the maximum being 6″ inside the visible limb.

This curve has been used to check the results of a computation using three solar models of the chromosphere and taking into account departures from LTE.

A description of these computations is given below.

3. Computation of the Emerging Intensity

A. METHOD OF COMPUTATION

The actual transfer equation in a spherically symmetrical medium is:

$$\frac{\mathrm{d}I}{\mathrm{d}s} = \mu_0 \frac{\delta I}{\delta r} + \frac{1-\mu_0^2}{r}\frac{\delta I}{\delta \mu_0} = k(I - S) \qquad \text{(see Kourganoff [8])}$$

where k is the absorption coefficient.

Close to the limb, the second term of the right-hand side of this equation cannot be considered as negligible in comparison to the first one.

The method we have used was also applied by Ambartsumyan [1] to the computation of the intensity emitted by prominences and by Pagel [10] for the computation of the continuous spectrum emitted in an optically thin medium.

The emergent intensity I at a given point in the line profile is

$$I_\lambda = \int_{-y_0}^{+y_0} k_\lambda S(y) \exp\left[-\int_{-y_0}^{+y} k_\lambda \, \mathrm{d}y'\right] \mathrm{d}y$$

where y measures the geometrical path along a line of sight at a given distance from the limb.

The absorption coefficient at wavelength λ is given by: $k_\lambda = k_{\lambda 0}\, H(a, v)$ where the subscript 0 refers to the line centre; $H(a, v)$ is the Hjerting function:

$$H(a, v) = \frac{a}{\pi} \int_{-\infty}^{+\infty} \frac{e^{-z^2}\, \mathrm{d}z}{a^2 + (v - z)^2}$$

with $a = \delta / \Delta\nu_\mathrm{D}$, where δ is the natural width; $\Delta\nu_\mathrm{D}$ is the Doppler width,

$$\Delta\nu_\mathrm{D} = \frac{\nu_0}{c} \sqrt{(2KT/m) + \xi^2}$$

and

$$v = \Delta\lambda / \Delta\lambda_\mathrm{D}\,.$$

T is the temperature and ξ the microturbulent velocity.

B. MODEL ATMOSPHERES

Three models have been used (Figure 2) to compute the source function and the optical depth.

1. *H.A.O. model* [2]

This model has been obtained from the continuum emission at 4760 Å and 3640 Å. It describes the atmosphere for a single set of parameters T_e, n_e, p (electron temperature, electron density and total pressure).

2. *Coates' model* [4]

This model is deduced both from eclipse measurements at 8.6 mm and from a scan of the disk at 4.3 mm.

The model attempts to describe the atmosphere by two sets of parameters T_e, n_e, p. For both measurements, the spatial resolution was not high enough to separate spicules from interspicular matter. One can just argue that the model thus established represents correctly the observations. In the interspicular matter, the model is characterized by the existence of a plateau between 3000 and 4000 km and then, a rapid increase in temperature.

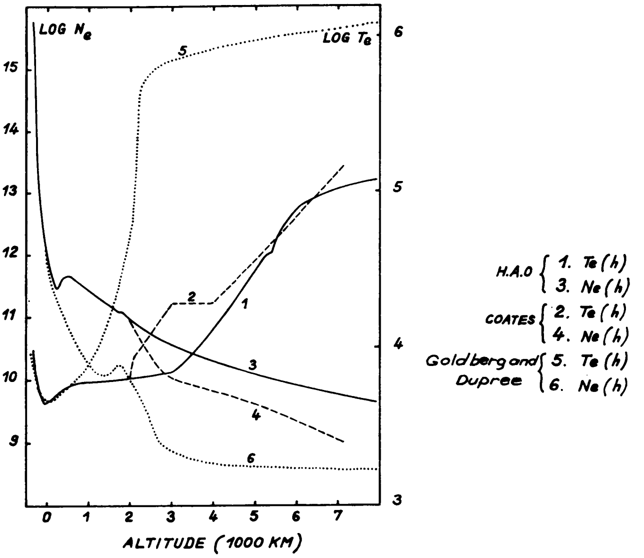

Fig. 2. 1–3 H.A.O. model; 2–4 Coates' model; 5–6 Goldberg and Dupree model; 1–2–5 electronic temperatures plotted vs. the altitude in the chromosphere; 3–4–6 electron densities versus the altitude in the chromosphere.

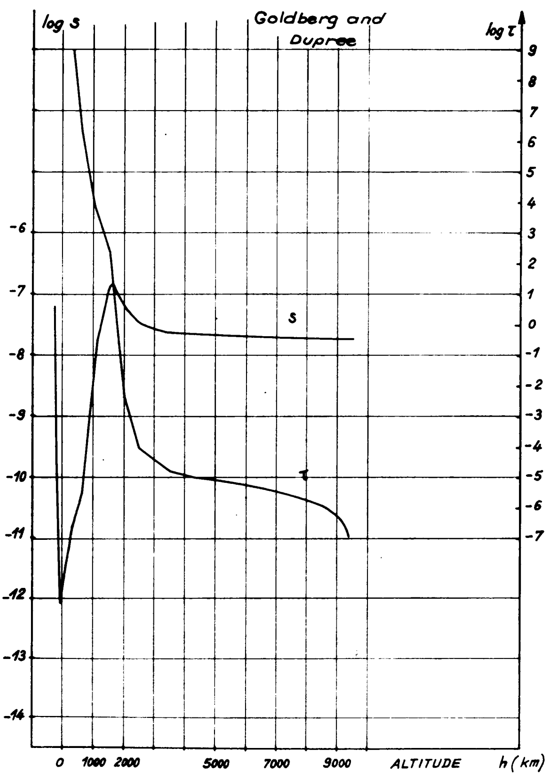

Fig. 3. For Goldberg and Dupree model, the source function S and the optical depth τ are plotted on logarithmic scale vs. altitude.

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Spicules are very cold (6400 K) and dense.
We have used, here, the interspicular model.

3. *Goldberg and Dupree model* [7]

This model was deduced from the recent OSO IV measurements of the solar UV intensity which is emitted in the chromospheric layers and the corona. It presents a sudden rise in temperature at about 2000 km that leads to coronal temperatures without any transition zone. Electron densities are consequently very low.

C. COMPUTATION OF THE SOURCE FUNCTION AND THE OPTICAL DEPTH

Y. Cuny's computing program has been used for the simultaneous resolution of the radiation transfer and statistical equilibrium equations which leads to the source function in the Lyman α line.

The source function S and the optical depth τ in the centre of the line are represented as functions of height in the chromosphere, on Figure 3, for the Goldberg and Dupree model.

4. Results of the Computation

A. INTENSITY RECEIVED AT 1 AU INTEGRATED OVER FREQUENCY

The calculation has been made for the first two models by Cuny [6]. The three computed values (Table I) lie higher than the value measured by Tousey of 6 ergs sec^{-1} cm^{-2} at the Earth, but they depend on the values of the electron collision cross-sections adopted for the computation and the width adopted for the line.

Coates' model leads to the best result with a value of 9.5 ergs sec^{-1} cm^{-2} at the Earth.

Table II indicates for Coates' model how the value of the flux does depend upon the wavelength interval of integration.

TABLE I

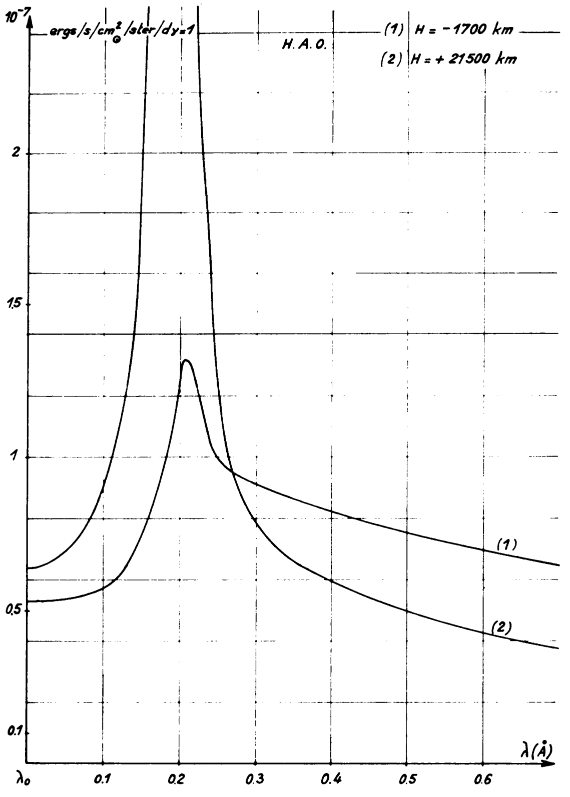
Intensity integrated over the disc and over the line profile within a bandpass of 5 Å in ergs sec^{-1} cm^{-2} at 1 AU

Model	H.A.O.	Coates	Goldberg and Dupree
Flux	24	9.5	9.95

TABLE II

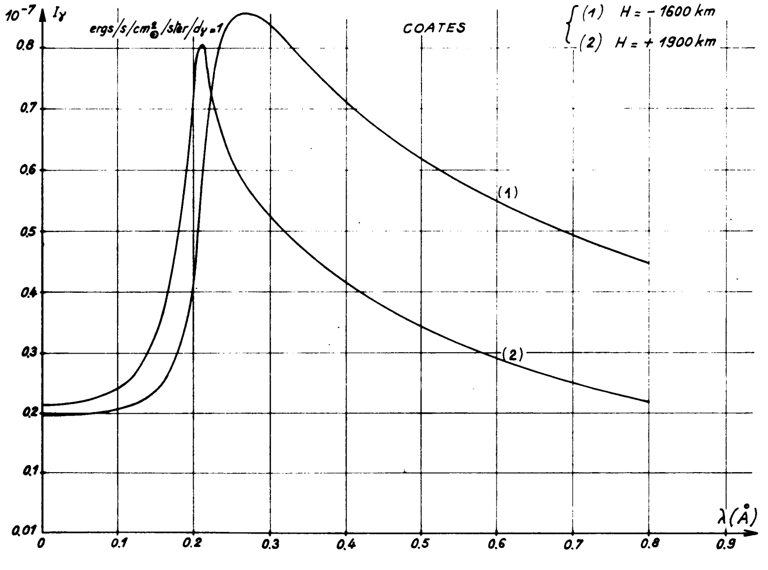
Coates' model
Variation of the intensity integrated over the disc and in the line with the width of the bandpass $\Delta\lambda$

$\Delta\lambda$ (Å)	I ergs sec^{-1} cm^{-2} at the earth
1.6	6.75
3	8.4
5	9.5
10	10.9



10^{-7}
ergs/s/cm$^2_\odot$/ster/dy=1
H.A.O.
(1) H = −1700 km
(2) H = + 21500 km
2
1.5
1
0.5
0.1
(1)
(2)
λ(Å)
λ$_0$
0.1
0.2
0.3
0.4
0.5
0.6

Fig. 4.



10^{-7} I_γ
ergs/s/cm$^2_\odot$/ster/dy=1
COATES
(1) H = − 1600 km
(2) H = + 1900 km
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.01
(1)
(2)
λ(Å)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Fig. 5.

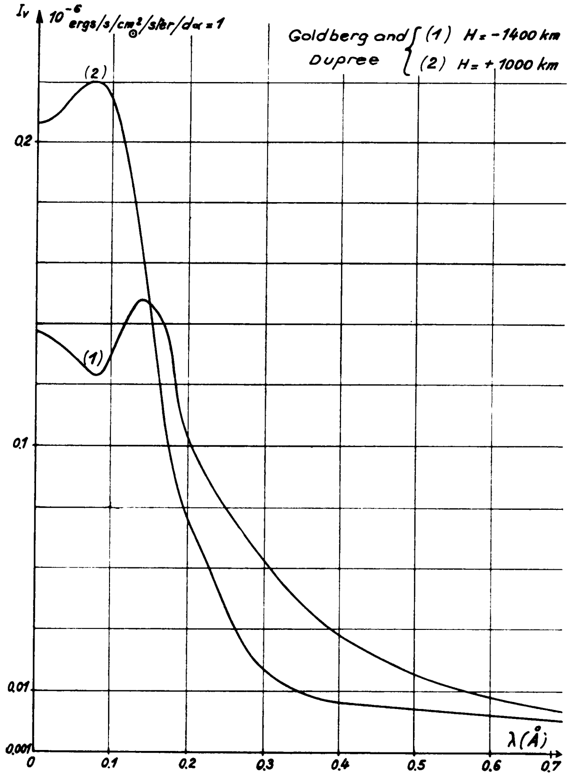


Fig. 6.

Figs. 4–6. Monochromatic intensity versus the distance from the centre of the line, at two positions on the disc close to the limb; (1) outside the visible limb; (2) inside the visible limb; (4) H.A.O. model; (5) Coates' model; (6) Goldberg and Dupree model.

The high values given by the H.A.O. model which are in complete disagreement with Tousey's measurements, are likely to be due to the high electron densities of this model. The Coates and Goldberg and Dupree models give values in better agreement with Tousey's measurements.

B. LINE PROFILE FOR VARIOUS POSITIONS ON THE DISC

The results are shown in Figures 4, 5 and 6.

TABLE III

Ratio of the intensities at the peak and at the centre of the line for the three models at the disc centre

Model	H.A.O.	Coates	Goldberg and Dupree
I_P/I_0	2.1	3.2	1.0

It can be noticed that all three models lead to broader and deeper profiles close to the limb, than at the centre of the disc, which is in agreement with Tousey's observations.

Let us take I_P as the intensity at a peak of the line.

In Table III we indicate the value of the ratio of the intensity emitted at the centre of the disc in the peak (I_P) to that emitted in the line centre.

It must be noticed that Tousey [11] gives a mean value for this ratio of 1.6. This measured value is intermediate between values computed with the H.A.O. and Goldberg and Dupree models but differs strongly from that given by Coates' model. This might be an indication that, as formerly noticed by Cuny [6], the steeper the temperature gradient for a given temperature, the lower the value of I_P/I_0.

On the other hand, the two first models lead to a distance between the peaks at the disc centre of 0.4 Å, in agreement with Tousey's observations [11].

That distance corresponds approximately to $\tau \sim 1$ for the altitude in the atmosphere where the source function is a maximum.

The Goldberg and Dupree model leads to special results: close to the limb, the line is reversed with a central emission peak and the distance between the peaks is about 0.3 Å. At the centre of the disc, the profile does not present any reversal, which contradicts the observations.

C. VARIATION OF THE INTENSITY INTEGRATED OVER THE LINE WIDTH AT THE LIMB

The results are given in Figure 7. They have to be directly compared to the observations. The interval of integration extends over 5 Å. All three models lead to a limb-brightening but none is able to represent the position of the maximum intensity according to observations.

H.A.O. Model: The 'Lyman α limb' is 4600 km above the minimum temperature or 4900 km above the visible limb, which corresponds to an angular distance of 7″, a value of the order of 2 greater than what is deduced from observations.

The brightening is 20% of the intensity at the disc centre.

Coates' model limb is 2900 km above the visible limb, i.e. $\simeq 4''$, in better agreement with observations. The brightening is very considerable and sharp (about 100% of the value at the centre of the disc).

It has also to be noticed that the intensity decreases continuously as one goes towards the centre.

Goldberg and Dupree model's 'Lyman α limb' is 2000 km above the visible limb and in good agreement also with observations. The model leads to oscillations in the intensity at the limb.

We have checked whether the results depend:

(1) on the interval of integration. If the intensity at the limb depends on $\Delta\lambda$ the position of the 'Lyman α limb' and of the maximum intensity remains fairly constant; so does the value of the intensity at the centre of the disc.

In figure 7, the curves 1, 2 and 3 correspond to an interval of integration of $\Delta\lambda \simeq 1.6$ Å whereas curve 2′ refers to Coates' model with $\Delta\lambda = 5$ Å. Here we can see how

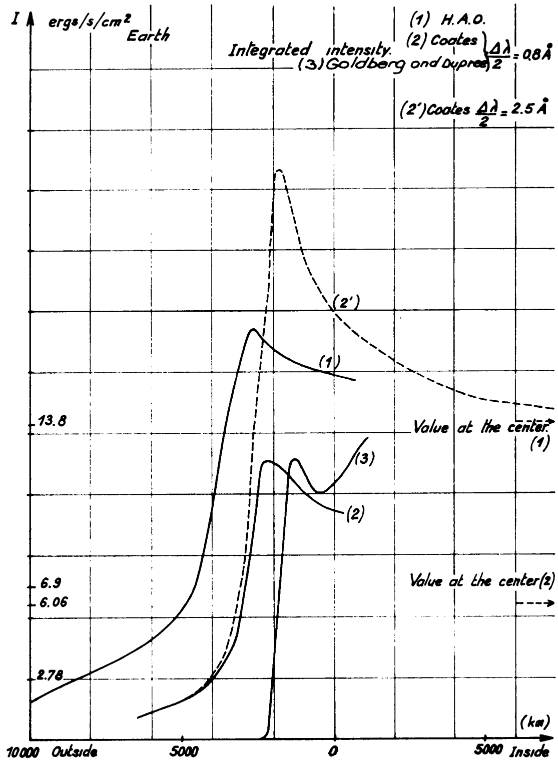


Fig. 7. Integrated intensity over frequency vs. the distance on the disc (on a band pass of 1.6 Å) (1) H.A.O. model; (2) Coates' model; (3) Goldberg and Dupree model; (2′) integrated intensity over 5 Å.

important would be the knowledge of measured values of the absolute intensity emitted by the Sun in order to discriminate the models. Unfortunately this value could not be obtained during the flight of Blamont and Malique.

(2) on the choice of the microturbulent velocity distribution. For this purpose we have tried out a model with a constant value of $\xi = 4$ km sec^{-1} all across the chromosphere, and another one for which $\xi = 20$ km sec^{-1} for $h > 2000$ km and $\xi = h/100$ for $h < 2000$ km.

We did not notice any important differences between the two results given by the two kinds of models.

5. Discussion

The comparison between the distributions of computed integrated intensities and Blamont and Malique's observations shows that the Goldberg and Dupree model would be satisfactory, for the position of the 'Lyman α limb'. Within the experimental error limits (about $\pm$ 350 km) Coates' limb agrees also with observations.

The Goldberg and Dupree model leads to a profile of the line at the limb which does not present any reversal at all. We see here the importance of detailed measured profiles for different regions on the disc. However, none of the models leads to any brightening inside the visible disc as that indicated by the observations.

Before incriminating the models, several sources of experimental error have to be discussed:

(1) the presence of an active region at the limb would affect the distribution of intensity and the position of the maximum. The only feature noticed is a facula appearing on the K line spectroheliogram taken on November 12, 1966. This feature was taken into account by Blamont and Malique who corrected their flux curve.

(2) The effect of other emission lines intercepted by the bandpass of the detector might affect the flux measurements, specially if they show a very intense limb-brightening, since about 80% of the flux emitted by the Lyman α line is concentrated in a band of 2 to 3 Å [12]. The only line which might be of some importance is that emitted by Si III at 1206 Å. The recent values measured on OSO-IV for the flux emitted in this line is 0.059 ergs cm^{-2} sec^{-1} at 1 AU (Noyes [9]). The brightening at 0.9 R is only 1.75 in units of the intensity emitted at the disc centre. Therefore, such a brightening is not large enough appreciably to modify the distribution of the Lyman α line intensity close to the limb.

6. Conclusion

The measurements reported in [3] can only give information on the position of the maximum source function. As a matter of fact, the position of the 'Lyman α limb' is closely related to the height of the maximum of the source function. As noticed by Cuny, the maximum takes place at heights where the electron temperature reaches a value of some 20000 K, which conditions the distance between the two peaks of the self reversal profile. The Goldberg and Dupree model fits this condition. However, it does not lead to any reversal except close to the limb, because at the altitude where the source function S is maximum, the optical depth is very low.

Coates' model might agree with measurements, as far as absolute intensity, distance between peaks a position of the Lyman α limb, are concerned. Furthermore, due to the plateau in temperature between 3 and 4×10^3 km of this model, the central reversal in the Lyman β line can be accounted for (Cuny [6]).

The value of the depression of the profile ($I_P/I_0 \sim 3$) is larger than that which was formerly measured by Tousey [11] in a quiet region of the active Sun ($I_P/I_0 \sim 1.6$), but agrees with the value measured, on August 22, 1962, in a quiet region of the quiet Sun ($I_P/I_0 \sim 3$) [11]. Anyway, a higher gradient of temperature above the plateau of Coates' model might reduce the importance of this depression.

However, one must keep in mind that the chromosphere is completely heterogeneous and that the experimental distribution of intensity reported by Blamont and Malique gives us information only in terms of an average model.

Therefore, further improvements have to be achieved in the direction of simultaneous observations and computations of the Lyman α and β profiles at a given position on the disc.

Acknowledgements

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Discussion

Deutsch: Does the geocoronal Lyman α interfere with the determination of the central intensity of the chromospheric line?

Vial: The geocoronal absorption is too narrow to have any influence on the intensity integrated over frequency.